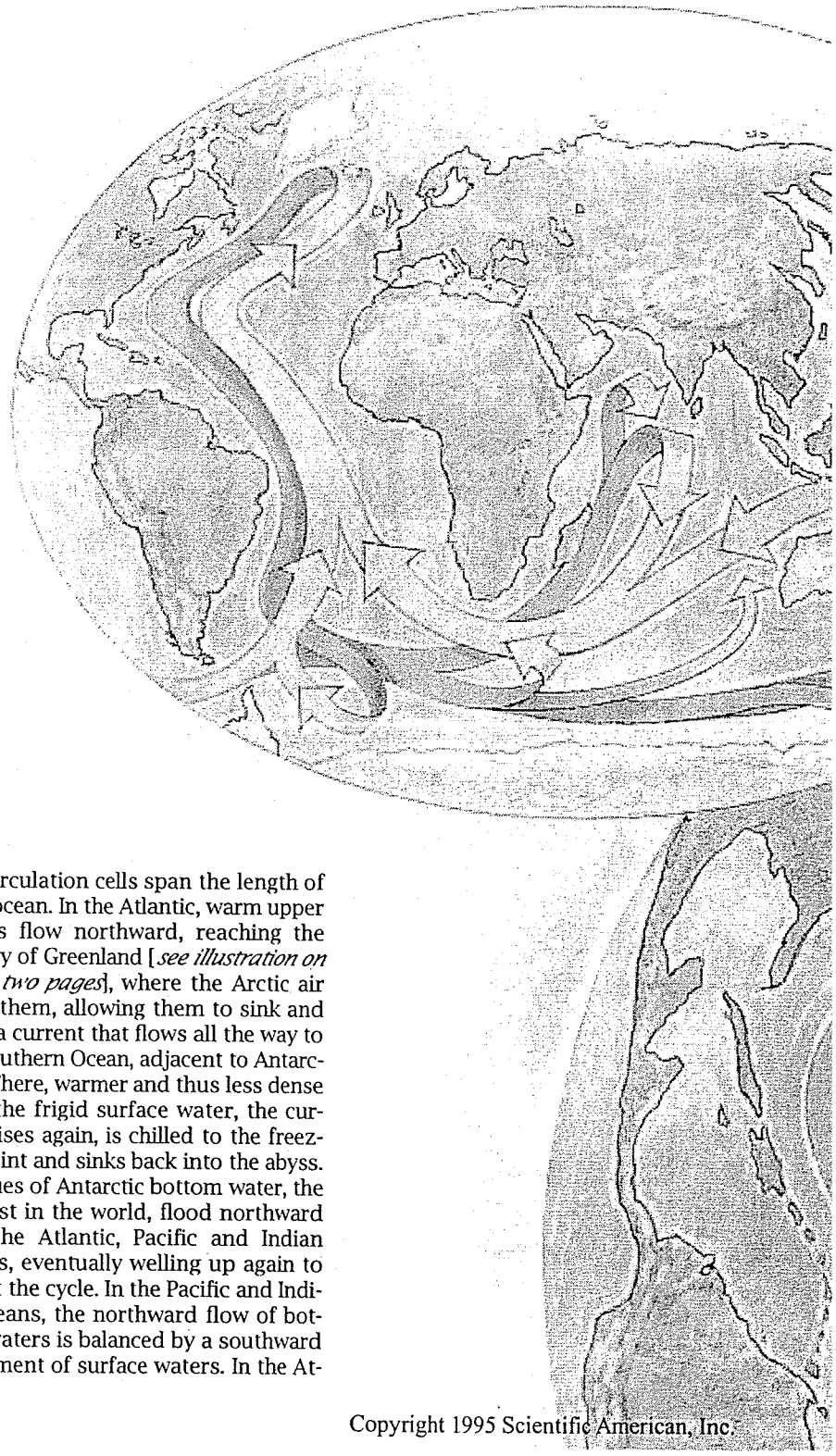
Chaotic Climate

Global temperatures have been known to change substantially in only a decade or two. Could another jump be in the offing?

by Wallace S. Broecker



The past 10,000 years are anomalous in the history of our planet. This period, during which civilization developed, was marked by weather more consistent and equable than any similar time span of the past 100 millennia. Cores drilled through several parts of the Greenland ice cap show a series of cold snaps and warm spells—each lasting 1,000 years or more—that raised or lowered the average winter temperature in northern Europe by as much as 10 degrees Celsius over the course of as little as a decade. The signs of these sudden changes can be read in the records of atmospheric dust, methane content and precipitation preserved in the annual ice layers.

The last millennium-long cold period, known as the Younger Dryas (after a tundra flower whose habitat expanded significantly), ended about 11,000 years ago. Its marks can be found in North Atlantic marine sediments, Scandinavian and Icelandic glacial moraines, and northern European and maritime Canadian lakes and bogs. New England also cooled significantly.

Further evidence is accumulating that the Younger Dryas's effects were global in scope. The postglacial warming of Antarctica's polar plateau came to a halt for 1,000 years; at the same time, New Zealand's mountain glaciers made a major advance, and the proportions of different species in the plankton population of the South China Sea changed markedly. The atmosphere's methane content dropped by 30 percent. Only pollen records from parts of the U.S. fail to show the period's impact.

The Great Conveyor

What lies behind this turbulent history, and could it repeat itself? Although no one knows for sure, there are some very powerful clues. A variety of models suggest that the circulation of heat and salt through the world's oceans can change suddenly, with drastic effects on the global climate. Giant, conveyor-like circulation cells span the length of each ocean. In the Atlantic, warm upper waters flow northward, reaching the vicinity of Greenland [*see illustration on these two pages*], where the Arctic air cools them, allowing them to sink and form a current that flows all the way to the Southern Ocean, adjacent to Antarctica. There, warmer and thus less dense than the frigid surface water, the current rises again, is chilled to the freezing point and sinks back into the abyss. Tongues of Antarctic bottom water, the densest in the world, flood northward into the Atlantic, Pacific and Indian oceans, eventually welling up again to repeat the cycle. In the Pacific and Indian oceans, the northward flow of bottom waters is balanced by a southward movement of surface waters. In the At-

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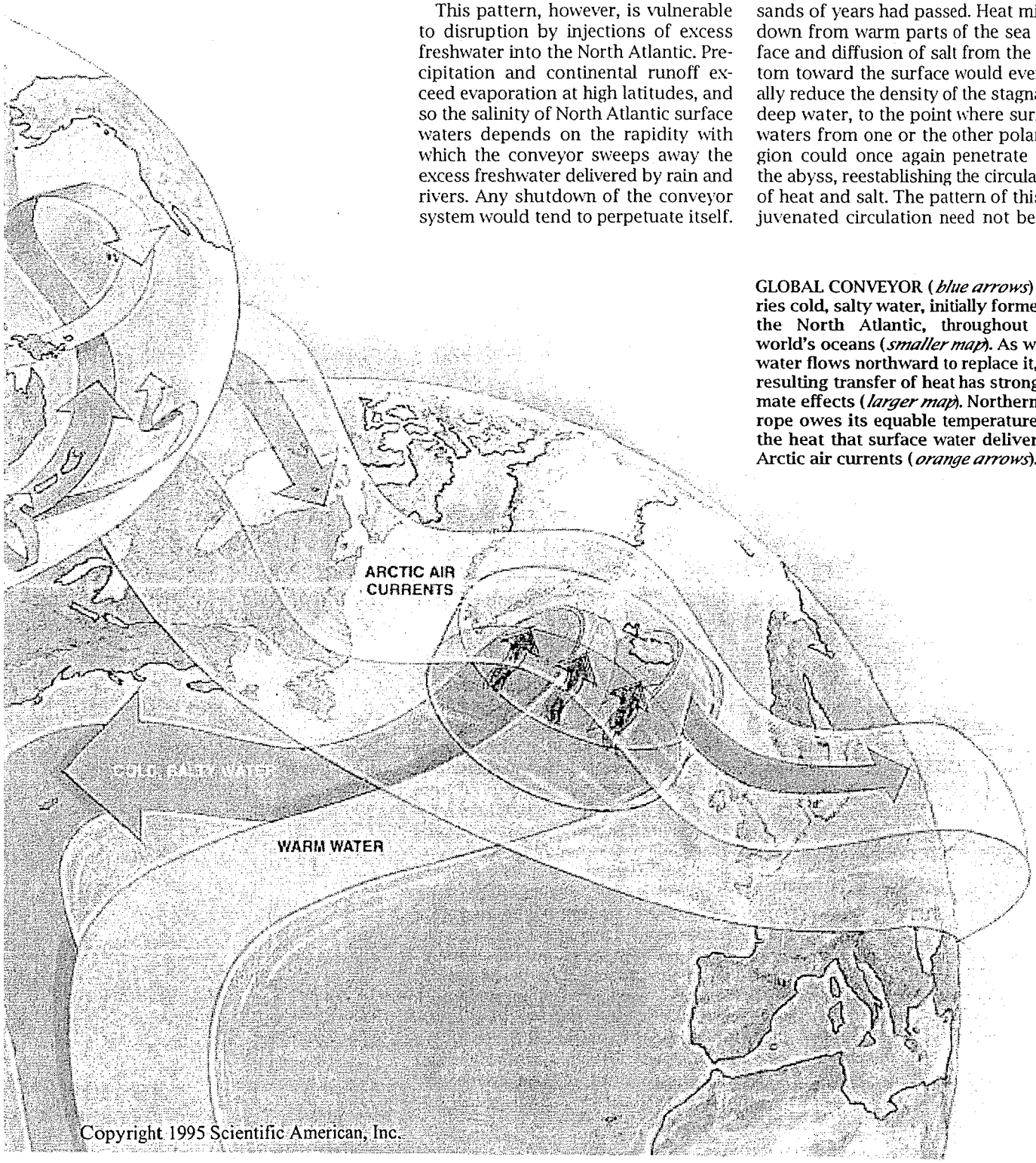
lantic, this northward counterflow is rapidly entrained into the much stronger southward current of the conveyor.

This so-called deep water forms in the North Atlantic—but not the Pacific—because surface waters in the Atlantic are several percent saltier than those in the Pacific. The locations of large mountain ranges in the Americas, Europe and Africa lead to weather patterns that cause the air leaving the Atlantic basin to be wetter than when it enters; the resulting net loss of water from the surface leads to an excess of salt. Salt makes the upper layers of water denser; as a result, they descend in the North Atlantic and begin a global circulation pattern that effectively redistributes the salt throughout the world's oceans.

The Atlantic's conveyor circulation, which has a flow equal to that of 100 Amazon Rivers, results in an enormous northward transport of heat. The water flowing north is, on average, eight degrees warmer than the cold water flowing south. The transfer of this heat to Arctic air masses over the North Atlantic accounts for the anomalously warm climate enjoyed by Europe.

This pattern, however, is vulnerable to disruption by injections of excess freshwater into the North Atlantic. Precipitation and continental runoff exceed evaporation at high latitudes, and so the salinity of North Atlantic surface waters depends on the rapidity with which the conveyor sweeps away the excess freshwater delivered by rain and rivers. Any shutdown of the conveyor system would tend to perpetuate itself. Were the conveyor to stop, winter temperatures in the North Atlantic and its surrounding lands would abruptly fall by five or more degrees. Dublin would acquire the climate of Spitsbergen, almost 1,000 kilometers north of the Arctic Circle. Furthermore, the shift would occur in 10 years or less. (Ice cores and other records suggest that the average temperature throughout the North Atlantic basin dropped about seven degrees during ancient cold snaps.)

Ocean modelers have shown that the oceanic conveyor would come back to life, but only after hundreds or thousands of years had passed. Heat mixed down from warm parts of the sea surface and diffusion of salt from the bottom toward the surface would eventually reduce the density of the stagnated deep water, to the point where surface waters from one or the other polar region could once again penetrate into the abyss, reestablishing the circulation of heat and salt. The pattern of this rejuvenated circulation need not be the



GLOBAL CONVEYOR (*blue arrows*) carries cold, salty water, initially formed in the North Atlantic, throughout the world's oceans (*smaller map*). As warm water flows northward to replace it, the resulting transfer of heat has strong climate effects (*larger map*). Northern Europe owes its equable temperatures to the heat that surface water delivers to Arctic air currents (*orange arrows*).

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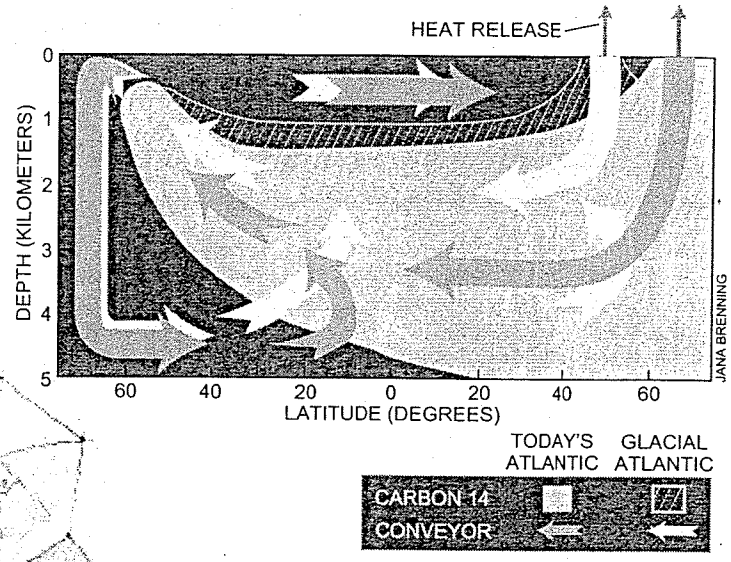
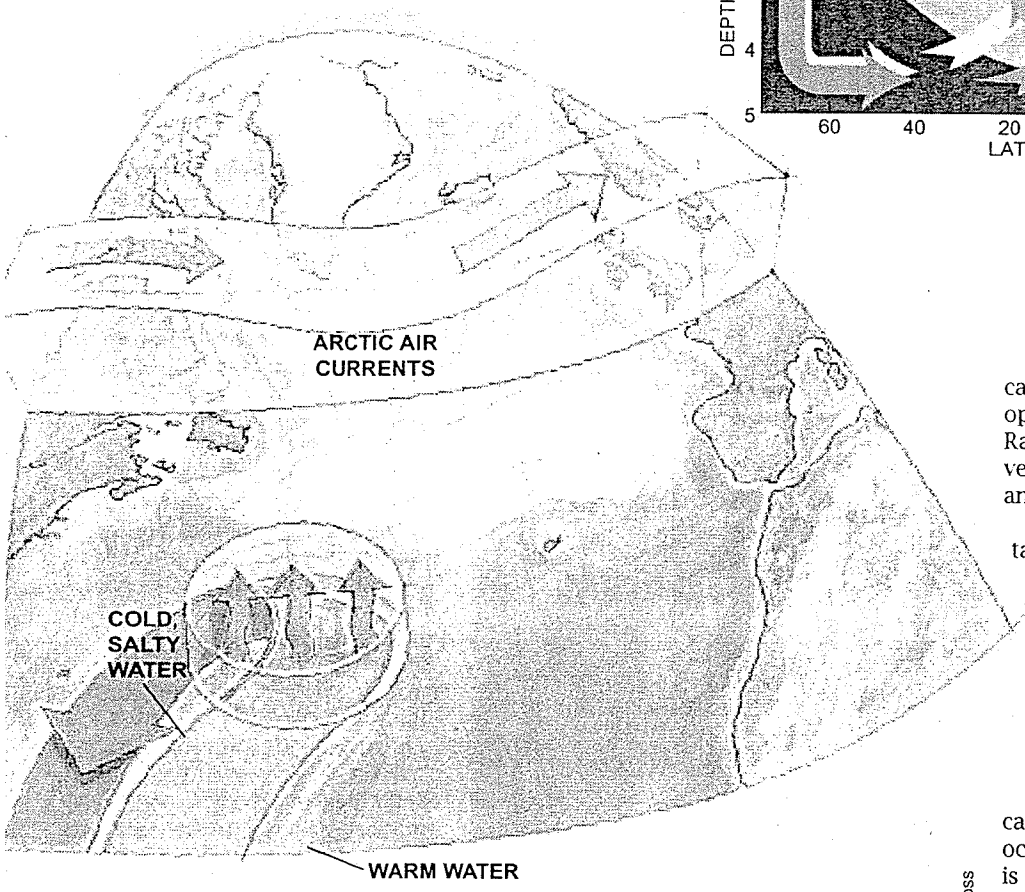
ALTERNATE CONVEYOR proposed by Stefan Rahmstorf of the University of Kiel (*below*) would operate at the latitude of southern Europe and so would not transfer heat effectively to North Atlantic winds. Temperatures in Europe during glacial times, when this conveyor was running, averaged as much as 10 degrees lower than today's. Shallow circulation characterized this alternate conveyor (*right*).





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same as that which existed before the shutdown, however. Instead it would depend on the details of the freshwater runoff patterns for each polar region.

More recently, modeling work by Stefan Rahmstorf of the University of Kiel has suggested that the shutdown of the primary conveyor system may be followed by the formation of an alternate circulation pattern that operates at a shallower depth, with deep water forming north of Bermuda instead of near Greenland. This shift renders the heat released far less effective in warming northern Europe. Rahmstorf's shallow conveyor can be knocked out of action by a pulse of freshwater, just like the primary one, but his model predicts a spontaneous reactivation after only a few decades. It is still not clear, however, how the ocean circulation might switch back from the shallow conveyor to the deeper one that operates today.

Two properties of Rahmstorf's model catch the eye of paleoclimatologists. First, the shallow draft of the alternate conveyor reproduces the ice age distribution of cadmium and carbon isotopes captured in the shells of tiny bottom-dwelling creatures called benthic foraminifera. Today the waters of the North Atlantic conveyor are poor in cadmium and rich in carbon 13, whereas deep waters in the rest of the ocean are rich in cadmium and poor in carbon 13.

This contrast reflects the fact that respiration by aquatic organisms depletes carbon 13 and enhances the concentration of cadmium (and other constituents whose history is not recorded in benthic shells). During cold episodes, cadmium levels dropped in the mid-depth Atlantic waters and rose dramatically in the bottom waters; the ratio of carbon 13 to carbon 12 displayed the opposite pattern—consistent with Rahmstorf's conclusion that the conveyor operated at a shallower depth and bypassed the bottommost water.

Second, the alternate conveyor maintains the movement of radiocarbon into the deep sea. If this transfer had ceased, radiochemical-dating methods based on carbon 14 decay would show huge distortions; in fact, the radiocarbon clock has been calibrated by other means and found to be imperfect but still basically valid.

Only about a quarter of the world's carbon currently resides in the upper ocean and atmosphere. The remainder is in the abyss. The distribution of radioactive carbon 14, which is formed in the atmosphere by cosmic rays, depends on the rate of oceanic circulation. In today's ocean, most of the radiocarbon reaching the deep sea does so via the Atlantic's conveyor circulation. During their traverse up the Atlantic, waters in the conveyor's warm upper limb are recharged with radiocarbon by absorption from the air. The conveyor then carries this radiocarbon down to the ocean depths. Although the deep water resurfaces briefly in the region around the Antarctic continent, little radiocarbon finds its way into solution there.

This state of affairs implies that even a slowdown of the conveyor would have a significant effect on the abundance of carbon 14 in both the atmosphere and the ocean. The ratio of carbon 14 to stable carbon 12 in the deep ocean is at present approximately 12 percent lower than the average for the upper ocean and the atmosphere because of the radioactive decay that takes place while the deep water is circulating. Meanwhile

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cosmic rays replenish 1 percent of the world's radiocarbon inventory every 82 years. As a result, if exchanges between the upper and deep ocean were to cease, the carbon 14 ratio in the upper ocean and the atmosphere would rise at the rate of 5 percent every century because carbon 14 was being added but not swept down into the deep sea. After a millennium of isolation, the atmosphere's carbon 14 ratio would rise by a third of its original value.

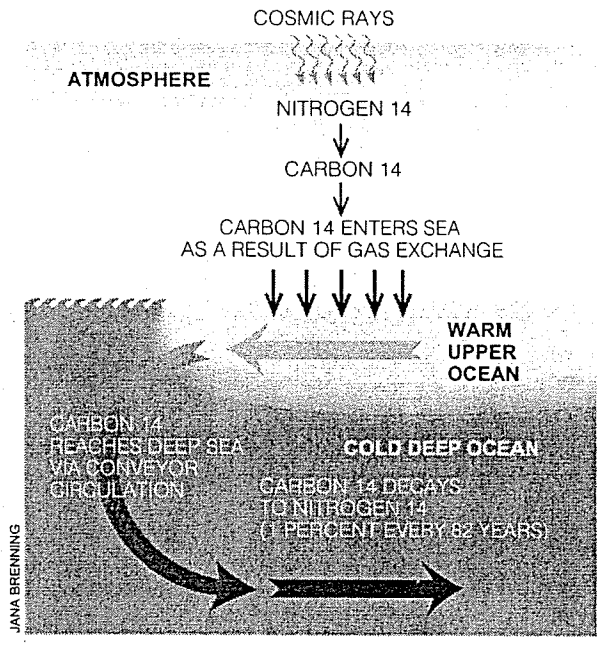
Such an occurrence would lead to a radical disturbance of the radiocarbon-dating record. Paleontologists determine the age of organic materials by measuring their residual carbon 14 content. The amount incorporated into a plant's structure while it is alive depends on the proportion of radiocarbon in the atmosphere (or ocean) at the time; the less carbon 14 that remains, the older a specimen must be. Plants that grew during a conveyor shutdown would incorporate the extra carbon 14 and appear younger than their true age. Then, when the conveyor started up again and brought atmospheric carbon 14 back down near its current level, the anomaly would disappear. Thus, plants from the cold times would appear—according to carbon dating—to be contemporary with warm-weather specimens that lived more than 1,000 years later.

Although the amount of carbon 14 in the atmosphere has varied somewhat over time, sequences of radiocarbon dates from marine sediments likely to have accumulated at a nearly uniform rate clearly demonstrate that no such sudden shock took place at any time during the past 20,000 years. Indeed, measurements on corals whose absolute ages have been established by uranium-thorium dating imply that during the end of the last ice age, when the conveyor should have been starting up again and drawing carbon 14 out of the atmosphere, the radiocarbon content of the atmosphere increased.

This record seems to be telling us that any conveyor shutdowns must have been brief—a century or less—and that they must have been matched by intervening intervals of rapid mixing. In particular, the Younger Dryas was apparently a time when overall ocean circulation increased rather than decreased, as would be expected if the cold snap were caused by a complete halt of the Atlantic conveyor. If the conveyor did shut down, some other method of transporting carbon 14 to the deep sea must have been in operation.

A Fleet of Icebergs

Assuming that changes in the conveyor mechanism did drive the abrupt changes found in the Greenland ice cores and other climate records, what might supply the excess freshwater needed to shut down transport of water into the abyss? The polar ice caps are the obvious sources for the jolts of freshwater needed to upset ocean circulation. Moreover, sudden changes appear to be confined to times when large ice sheets covered Canada and Scandinavia. Since the ice ages ended, global climate has remained locked in its present mode.



JANA BRENNING

DEEPWATER FORMATION PROCESS carries radioactive carbon 14, formed by cosmic rays, out of the atmosphere and upper ocean and into the abyss. Radiocarbon dating indirectly measures the state of the oceanic conveyor because any prolonged shutdown causes a buildup of carbon 14 in the atmosphere and scrambles the apparent ages of organic remains.

There is evidence of at least eight invasions of freshwater into the North Atlantic: seven armadas of icebergs released from the eastern margin of the Hudson Bay ice cap and a flood of meltwater from a huge lake that marked the southern margin of the ice sheet during glacial retreat. In the early 1980s, while he was a graduate student at the University of Göttingen, Hartmut Heinrich discovered a curious set of layers in the sediments of the North Atlantic. The layers stretch from the Labrador Sea to the British Isles, and their characteristics are most plausibly explained by the melting of enormous numbers of icebergs launched from Canada.

The debris dropped from this flotilla thins eastward from half a meter in the Labrador Sea to a few centimeters in the eastern Atlantic. Rock fragments characteristic of the sedimentary limestones and igneous bedrock from Hudson Bay and the surrounding area constitute most of the larger particles of the sediments. Shells of foraminifera are found only rarely in these layers, suggesting an ocean choked with sea ice; the low ratio of oxygen 18 to oxygen 16 in those shells that do appear provides an unambiguous marker that the animals lived in water much less salty than usual. (Rain and snow at high latitudes is depleted in oxygen 18 because the "heavy" water containing it condenses out of the atmosphere preferentially as air masses cool.)

The eighth freshwater pulse came from Lake Agassiz, a very large lake trapped in the topographic depression created by the weight of the retreating ice cap. Initially, the water from the lake spilled over a rock sill into the Mississippi River watershed and thence the Gulf of Mexico. About 12,000 years ago the retreat of the ice front opened a channel to the east, triggering a catastrophic drop in lake level. The water released during this breakthrough flooded across southern Canada into the valley now occupied by the St. Lawrence River and discharged directly into the region where deep waters now form.

The connection between these events and local climate changes is clear. Four occurred at times corresponding to significant changes in the climate of the North Atlantic basin. One of Heinrich's layers marks the end of the second-to-last major glacial cycle, and another that of the most recent cycle. A third layer appears to match the onset of glacial conditions in the North Atlantic, and the catastrophic release of water from Lake Agassiz coincided with the onset of the Younger Dryas. Each of the four remaining pulses caps a climate subcycle. Gerard C. Bond of the Lamont-Doherty Earth Observatory of Columbia University correlated Heinrich layers with the Greenland ice core record and found that the millennia-long cold events come in groups characterized by progressively more severe cold snaps, culminating with a Heinrich event that is followed in turn by a signif-

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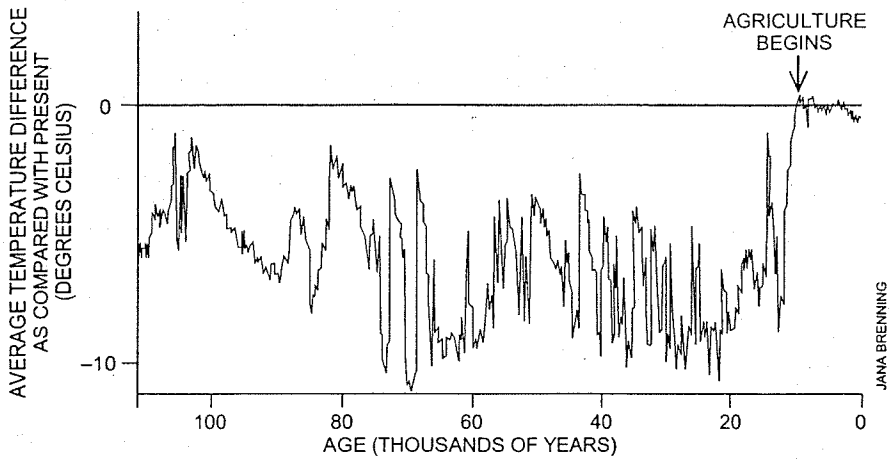

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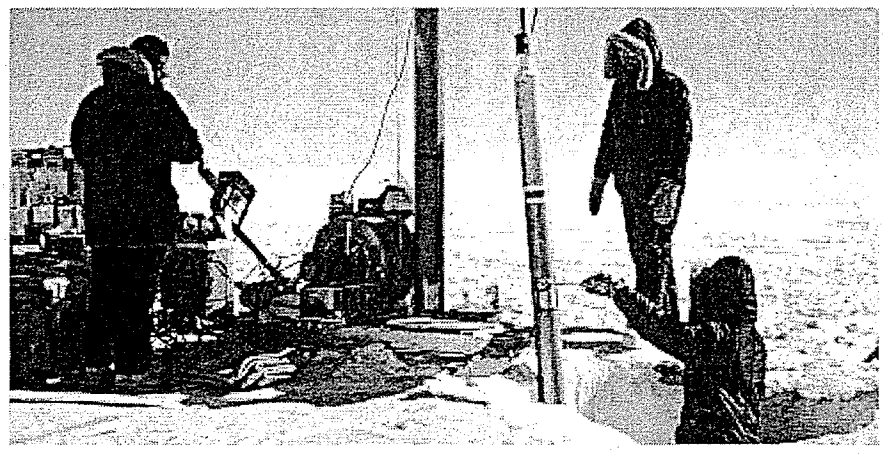

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ICE CORE DATA (*top left*) show the variability of the earth's climate during the past 100,000 years. Researchers drilled down to bedrock near the center of the Greenland ice cap (*above*) and measured the relative concentration of oxygen 18 and oxygen 16 in the samples they retrieved. (Cores awaiting analysis are shown in cold storage at the right.) The amount of oxygen 18 in atmospheric water vapor depends on air temperature: the colder the climate, the less water containing the heavy isotope is present. Microscopic views of an ice core section (*top right*) make individual ice crystals visible through their differing transmission of polarized light and highlight the trapped air bubbles that record the composition of the prehistoric atmosphere (*middle right*). The lowest layers (*bottom right*) have been distorted by the ice cap's flow over Greenland's uneven ground, making accurate measurements difficult or impossible.

icant warming that begins a new cycle.

The climate shifts of the Younger Dryas period were felt around the world. Is the same true of the 15 or so similar events that appear earlier in the ice core record? So far only two pieces of evidence point in that direction, but they are convincing ones. First, Jerome A. Chappellaz of the Laboratory of Glaciology and Geophysics of the Environment near Grenoble has analyzed air trapped in Greenland ice cores and found that cold periods were accompanied by drops in the atmosphere's methane content. Methane is produced mostly in swamps and bogs. Because those of the northern temperate region were either frozen or buried underneath ice during glacial times, methane present in the atmosphere must have come from the tropics. The fluctuations in the methane record imply that the tropics dried out during each of the northern cold intervals.

The second clue is an as yet unpublished study by James P. Kennett and Richard J. Behl of the University of California at Santa Barbara of a sediment core recovered from 500 meters below sea level in the Santa Barbara basin. The two found that bands of undisturbed sediment with clear annual layers alternated with sections more or less disturbed by burrowing worms. The presence of worms implies that the bottom water in the area contained significant amounts of oxygen, enough to support life; such periods display an uncanny correlation with cold spells in Greenland, implying that changes in ocean circulation reached around the globe.

More surprising is the finding that Heinrich events also appear to have had a worldwide imprint. Eric Grimm of the Illinois State Museum and his colleagues sampled pollen in the sediments of Lake Tulane in Florida and found one prominent peak in the ratio of pine to oak for each Heinrich event. Pine trees prosper in relatively wet climates, whereas oaks prefer dryer ones. Although the exact relation between pine-rich intervals and Heinrich events awaits more accurate radiocarbon dating, the Lake Tulane record suggests one wet interval per cycle. George H. Denton of the University of Maine and his co-workers found an even more distant connection: each of the four Heinrich events falling within the range of radiocarbon dating matches a sharp maximum in the extent of Andean mountain glaciers.

The finding that the massive calving

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of Canadian glaciers caused global impacts creates a paradox. Atmospheric models indicate clearly that climate shifts related to changes in the amount of heat delivered to the atmosphere over the North Atlantic would be limited to the surrounding regions. The evidence that has been found, however, demands a mechanism for extending these effects to the tropics, the southern temperate region and even the Antarctic.

The symmetrical distribution of these climate changes around the equator points to the tropics. Changes in the dynamics of the tropical atmosphere could easily have a far-reaching effect. The towering convection cells that form in the tropical atmosphere where the trade winds meet feed the atmosphere with its dominant greenhouse gas: water vapor. Although the link between ocean circulation and tropical convection is tenuous, it seems plausible that changed circulation patterns might alter the amount of cold water upwelling to the surface along the equator in the Pacific. This upwelling is an important part of the region's heat budget and thus its overall climate. Reduction of the equatorial upwelling, as occurs now during so-called El Niño periods, can cause droughts in some areas and floods in others.

Global Shifts

Support for such a scenario comes not only from Chappellaz's data showing drying in the tropics but also from the moisture histories of Nevada, New Mexico, Texas, Florida and Virginia. The most dramatic evidence comes from the Great Basin area of the western U.S.: immediately after the last Heinrich event about 14,000 years ago, Lake Lahontan in Nevada achieved its greatest size, an order of magnitude larger than today's remnant. Supporting such a large body of water requires immense amounts of precipitation, of the magnitude experienced during the record El Niño winter of 1982–1983. One way of thinking about the impact of these earlier occurrences, then, is as changes in the pattern of ocean circulation that led to El Niños lasting 1,000 years.

More recent findings, from Lonnie G. Thompson of Ohio State University, reinforce the evidence that tropical weather was extremely different during glacial times. Ancient ice cores from 6,000 meters up in the tropical Andes contain 200 times as much fine dust as more

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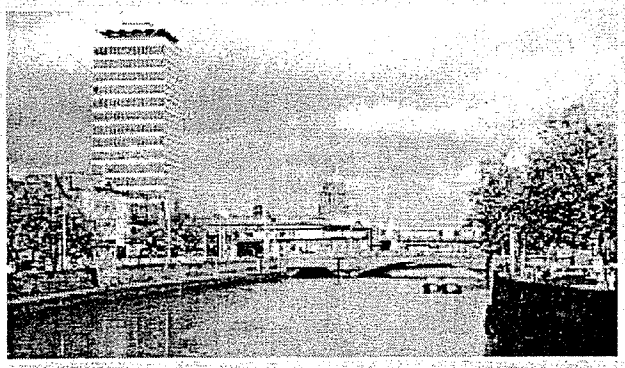

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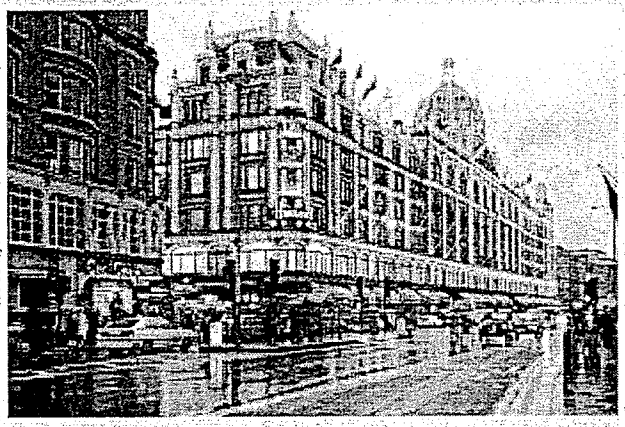

FRIDMAR DAMM Leo de Wys

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IMPACT ON EUROPE of a disruption in deepwater formation would be drastic and unpleasant. Dublin (*top left*) would have a summer climate of the kind currently characteristic of Spitsbergen in the high Arctic, and London (*bottom left*) would experience the winter cold that now grips Irkutsk in Siberia.

recent samples—dust probably carried by winds blowing up from an arid Amazonia. The older ice is also depleted in oxygen 18 as compared with ice formed more recently than 10,000 years ago, implying a temperature about 10 degrees lower than today. Taken with the observation that the Andean snow line reached down a full 1,000 meters closer to sea level during the ice ages, these data suggest that the tropics of glacial times were both colder and drier.

The conclusion that the earth's climatic system has occasionally jumped from one mode of operation to another is rock solid. Unfortunately, researchers have yet to pin down the cause of these abrupt shifts. Although large-scale reorganizations of the ocean's circulation seem the most likely candidate, it is possible that atmospheric triggers may be discovered as well.

A Fragile Balance

This situation leaves us in limbo with regard to climatic prediction. Might the current buildup of greenhouse gases set in motion yet another reorganization of the deepwater conveyor and the weather patterns that depend on it? On the one hand, the paleographic record suggests that jumps have been confined to times when the North Atlantic was surrounded by huge ice sheets, a situation that is now further from the case than ever. On the other hand, the greenhouse nudge promises to be far larger than any other forcing experienced during an interglacial interval, and there is no certainty that the system will remain locked in its present relatively benign mode.

A conveyor shutdown or comparable drastic change is unlikely, but were it to occur, the impact would be catastrophic. The likelihood of such an event will be highest between 50 and 150 years from now, at a time when the world will be bulging with people threatened by hunger and disease and struggling to maintain wildlife under escalating environmental pressure. It behooves us to take this possibility seriously. We should spare no effort in the attempt to understand better the chaotic behavior of the global climatic system.

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Further Reading

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