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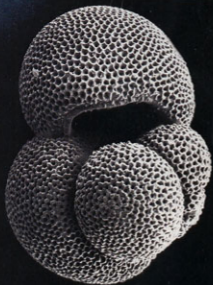
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Worried about global warming?
Talk to a few scientists at Woods Hole.
Oceanographers there are seeing big trouble with
the Gulf Stream, which warms both North America and Europe

BY BRAD LEMLEY



GLOBIGERINOIDES SACCULIFERA



UVIGERINA PEREGRINA



CIBICIDOIDES WUELLERSTORFI



GLOBIGERINOIDES RUBER

Chemical analysis of fossilized foraminifera, shell-building one-celled creatures, helps climate researchers determine oceanic temperatures during a mini-ice age hundreds of years ago. *G. sacculifera* and *G. ruber* are planktonic organisms that spend their lives floating near the surface but fall like sand grains to the bottom of the ocean when they die. *U. peregrina* and *C. wuellerstorfi* are benthonic organisms that live and die on or in sediments on the seafloor.

WILLIAM CURRY IS A SERIOUS, SOBER CLIMATE SCIENTIST, NOT AN art critic. But he has spent a lot of time perusing Emanuel Gottlieb Leutze's famous painting "George Washington Crossing the Delaware," which depicts a boatload of colonial American soldiers making their way to attack English and Hessian troops the day after Christmas in 1776. "Most people think these other guys in the boat are rowing, but they are actually pushing the ice away," says Curry, tapping his finger on a reproduction of the painting. Sure enough, the lead oarsman is bashing the frozen river with his boat. "I grew up in Philadelphia. The place in this painting is 30 minutes away by car. I can tell you, this kind of thing just doesn't happen anymore."

But it may again. Soon. And ice-choked scenes, similar to those immortalized by the 16th-century Flemish painter Pieter Brueghel the Elder, may also return to Europe. His works, including the 1565 masterpiece "Hunters in the Snow," make the now-temperate European landscapes look more like Lapland.

Such frigid settings were commonplace during a period dating roughly from 1300 to 1850 because much of North America and Europe was in the throes of a little ice age. And now there is mounting evidence that the chill could return. A growing number of scientists—including many here at Curry's base of operations, the Woods Hole Oceanographic Institution on Cape Cod in Massachusetts—believes conditions are ripe for another prolonged cooldown, or small ice age. While no one is predicting a brutal ice sheet like the one that covered the Northern Hemisphere with glaciers about 12,000 years ago, the next cooling trend could drop average temperatures 5 degrees Fahrenheit over much of the United States and 10 degrees in the Northeast, northern Europe, and northern Asia.

COLD BRUTALITY

Should a little ice age arrive, its impact will be told in human suffering, not scientific terminology. *The Little Ice Age* (Basic Books, 2000), by anthropology professor Brian Fagan of the University of California at Santa Barbara, is replete with tales of woe depicting the plight of European peasants during the 1300 to 1850 chill: famines, hypothermia, bread riots, and the rise of despotic leaders brutalizing an increasingly dispirited peasantry. In the late 17th century, writes Fagan, agriculture had dropped off so dramatically that "Alpine villagers lived on bread made from ground nutshells mixed with barley and oat flour." Finland lost perhaps a third of its population to starvation and disease.

Life was particularly difficult for those who lived under the constant threat of advancing glaciers in the French Alps. One, the Des Bois glacier on the slopes of Mont Blanc, was said to have moved forward "over a musket shot each day, even in the month of August." When the Des Bois threatened to dam up the Arve River in 1644, residents of the town of Chamoniex begged the bishop of Geneva to petition God for help. In early June, the bishop, with 300 villagers gathered around him, blessed the threatening glacier and another near the village of Largen-tière. For a while, salvation seemed at hand. The glaciers retreated for about 20 years, until 1663. But they had left the land so barren that new crops would not grow. —B. L.

"It could happen in 10 years," says Terrence Joyce, who chairs the Woods Hole Physical Oceanography Department. "Once it does, it can take hundreds of years to reverse." And he is alarmed that Americans have yet to take the threat seriously. In a letter to *The New York Times* last April, he wrote, "Recall the coldest winters in the Northeast, like those of 1936 and 1978, and then imagine recurring winters that are even colder, and you'll have an idea of what this would be like."

A drop of 5 to 10 degrees entails much more than simply bumping up the thermostat and carrying on. Both economically and ecologically, such quick, persistent chilling could have devastating consequences. A 2002 report titled "Abrupt Climate Change: Inevitable Surprises," produced by the National Academy of Sciences, pegged the cost from agricultural losses alone at \$100 billion to \$250 billion while also predicting that damage to ecologies could be vast and incalculable. A grim sampler: disappearing forests, increased housing expenses, dwindling freshwater, lower crop yields, and accelerated species extinctions.

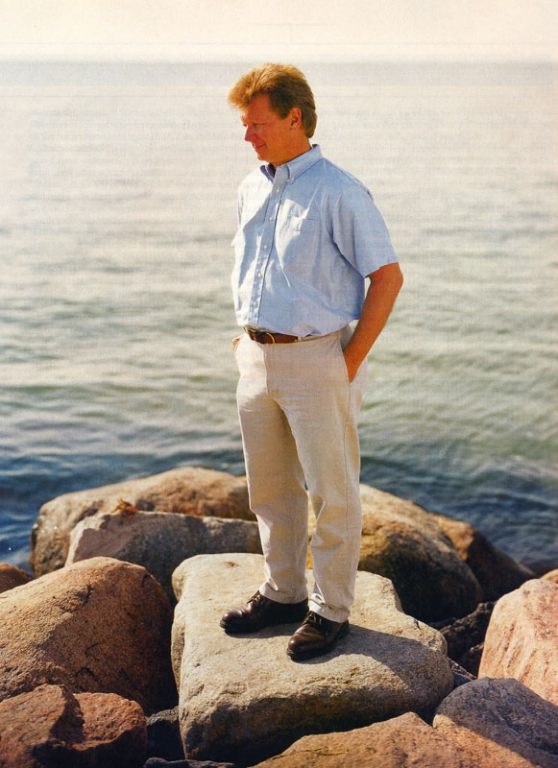
The reason for such huge effects is simple. A quick climate change wreaks far more disruption than a slow one. People, animals, plants, and the economies that depend on them are like rivers, says the report: "For example, high water in a river will pose few problems until the water runs over the bank, after which levees can be breached and massive flooding can occur. Many biological processes undergo shifts at particular thresholds of temperature and precipitation."

Political changes since the last ice age could make survival far more difficult for the world's poor. During previous cooling periods, whole tribes simply picked up and moved south, but that option doesn't work in the modern, tense world of closed borders. "To the extent that abrupt climate change may cause rapid and extensive changes of fortune for those who live off the land, the inability to migrate may remove one of the major safety nets for distressed people," says the report.

Still, climate science is devilishly complex, and the onslaught of a little ice age is not certain, at least at this stage of research. Scientists the world over are weighing the potential for rapid North Atlantic cooling, but perhaps nowhere in the United States is more energy, equipment, and brainpower directed at the problem than here at Woods Hole. The oceanographers on staff subsist largely on government grants and are beholden to no corporation, making the facility "uniquely independent," says David Gallo, director of special projects. Consequently, it should be as likely as any research facility or university to get at the truth.

The task is huge. Down on the docks where the institution keeps its three research ships, gulls swoop around a collection of massive metal frameworks; these are core samplers that, dropped over a ship's side, can extract long columns of layered sediments from the undersea muck. In a workshop nearby, technicians tinker with arrays of multiple independent water samplers, which at four feet long and eight inches thick look rather like giant scuba tanks. Out on the water, researchers drop these instruments into the North Atlantic, hoping to get a sharper

Opposite: "As we continue to pile on atmospheric carbon dioxide, we're going to have more unintended consequences," says William Curry, a climate scientist. "We need to seriously consider steps to curb greenhouse gases."



A prime suspect in the freshening trend is melting Arctic ice,

picture of the potential for a little ice age. A sense of urgency propels the efforts. "We need to make this a national priority," says Joyce. "It's a tough nut to crack, but with enough data, I think we can make a more specific and confident prediction about what comes next." Policymakers armed with a specific forecast could make adjustments to prepare for the inevitable.

BUT FIRST THINGS FIRST. ISN'T THE EARTH ACTUALLY WARMING?

Indeed it is, says Joyce. In his cluttered office, full of soft light from the foggy Cape Cod morning, he explains how such warming could actually be the surprising culprit of the next mini-ice age. The paradox is a result of the appearance over the past 30 years in the North Atlantic of huge rivers of freshwater—the equivalent of a 10-foot-thick layer—mixed into the salty sea. No one is certain where the fresh torrents are coming from, but a prime suspect is melting Arctic ice, caused by a buildup of carbon dioxide in the atmosphere that traps solar energy.

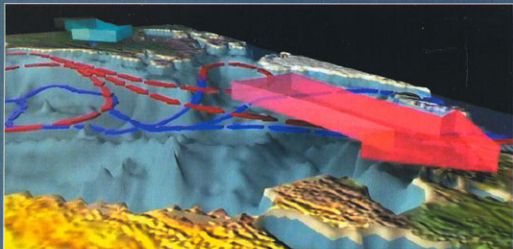
The freshwater trend is major news in ocean-science circles. Bob Dickson, a British oceanographer who sounded an alarm at a February conference in Honolulu, has termed the drop in salinity and temperature in the Labrador Sea—a body of water between northeastern Canada and Greenland that adjoins

the Atlantic—"arguably the largest full-depth changes observed in the modern instrumental oceanographic record."

The trend could cause a little ice age by subverting the northern penetration of Gulf Stream waters. Normally, the Gulf Stream, laden with heat soaked up in the tropics, meanders up the east coasts of the United States and Canada. As it flows northward, the stream surrenders heat to the air. Because the prevailing North Atlantic winds blow eastward, a lot of the heat wafts to Europe. That's why many scientists believe winter temperatures on the Continent are as much as 36 degrees Fahrenheit warmer than those in North America at the same latitude. Frigid Boston, for example, lies at almost precisely the same latitude as balmy Rome. And some scientists say the heat also warms Americans and Canadians. "It's a real mistake to think of this solely as a European phenomenon," says Joyce.

Having given up its heat to the air, the now-cooler water becomes denser and sinks into the North Atlantic by a mile or more in a process oceanographers call thermohaline circulation. This massive column of cascading cold is the main engine powering a deepwater current called the Great Ocean Conveyor that snakes through all the world's oceans. But as the North Atlantic fills with freshwater, it grows less dense,

BLOWING HOT AND COLD



A three-dimensional computer schematic of the Atlantic seafloor, viewed from a hypothetical vantage point in space, reveals how heat is transferred from ocean currents to air currents. As the warm surface currents of the Gulf Stream (small red arrows) flow up to the North Atlantic from the equator, the prevailing westerly winds (large blue arrow) blow across them, picking up their warmth (large red arrow) and lofting it to Europe. The now-cooler, denser water (small blue arrows), produced as the warm currents lose heat to the atmosphere, then sinks a mile or more. The process is called thermohaline circulation.

caused by a buildup of carbon dioxide gas in the atmosphere

making the waters carried northward by the Gulf Stream less able to sink. The new mass of relatively fresh water sits on top of the ocean like a big thermal blanket, threatening the thermohaline circulation. That in turn could make the Gulf Stream slow or veer southward. At some point, the whole system could simply shut down, and do so quickly. "There is increasing evidence that we are getting closer to a transition point, from which we can jump to a new state. Small changes, such as a couple of years of heavy precipitation or melting ice at high latitudes, could yield a big response," says Joyce.

In her sunny office down the hall, oceanographer Ruth Curry shows just how extensive the changes have already become. "Look at this," she says, pointing to maps laid out on her lab table. "Orange and yellow mean warmer and saltier. Green and blue mean colder and fresher." The four-map array shows the North Atlantic each decade since the 1960s. With each subsequent map, green and blue spread farther; even to the untrained eye, there's clearly something awry. "It's not just in the Labrador Sea," she says. "This cold, freshening area is now invading the deep waters of the entire subtropical Atlantic."

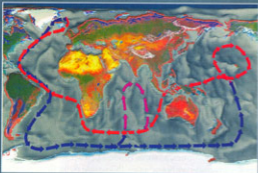
"You have all this freshwater sitting at high latitudes, and it can literally take hundreds of years to get rid of it," Joyce says. So while the globe as a whole gets warmer by tiny fractions of 1 degree Fahrenheit annually, the North Atlantic region could,

in a decade, get up to 10 degrees colder. What worries researchers at Woods Hole is that history is on the side of rapid shutdown. They know it has happened before.

ON THE NORTHWEST SIDE OF WOODS HOLE'S QUISSSET CAMPUS, IN A DIM laboratory that smells like low tide, about 24,000 polycarbonate tubes full of greenish-tan mud rest in wire racks, as carefully cataloged as fine wines. They are core samples collected from seafloors, many collected during expeditions by the *Knorr*, one of Woods Hole's three largest research ships. Each core tells a story about time and temperature spanning thousands of years.

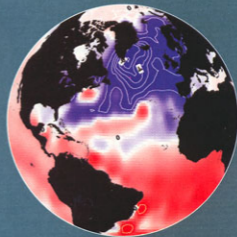
But one particular core, kept carefully refrigerated at 39 degrees Fahrenheit, was pivotal for reaching the conclusion that little ice ages can start abruptly. The Canadian ship *CSS Hudson* collected the core in 1989 from a seafloor plateau called the Bermuda Rise in the northern Sargasso Sea, roughly 200 miles northeast of Bermuda. "It's a peculiar place on the seafloor where mud accumulates rapidly," says Lloyd Keigwin, a senior scientist in the Woods Hole Geology and Geophysics Department. Most of the sediment was washed out of Canadian rivers before settling, so it bears witness to the vagaries of climate in the North Atlantic.

Seafloor sediments are peppered with tiny invertebrates called foraminifera, which Keigwin describes as "amoebas with



ABOVE: Thermohaline circulation in the North Atlantic is the main engine powering the Great Ocean Conveyor, a twisting, swirling current that winds through all of the world's oceans. Deep currents travel around the globe to the Indian and Pacific Oceans and return as warm surface currents. If the freshening trend in the North Atlantic continues, thermohaline circulation could shut down, altering or even stopping the Great Ocean Conveyor's flow.

RIGHT: Researchers Syukuro Manabe and Ronald Stouffer of the Geophysical Fluid Dynamics Laboratory in Princeton, N.J., have predicted that thermohaline shutdown could precipitate a sudden drop in North Atlantic water temperatures of up to 13 degrees Fahrenheit. That in turn would bring colder temperatures to the landmasses on either side of the ocean.



-12 -9 -6 -3 0 3
Temperature Anomaly (Fahrenheit)

If the National Weather Service has trouble predicting tomorrow's weather, how can anyone forecast a change in global climate a few years hence?

shells," that can yield clues about the temperature of the ocean in which they lived. Clay and silt from the Nova Scotia region cause the little creatures to accumulate in neatly distinguishable layers, which means a wealth of information.

Keigwin subjected the foraminifera in various layers of this core to mass spectroscopic analysis. By measuring the proportions of oxygen isotopes—especially the ratio of oxygen 16 to oxygen 18—he was able to peg the temperature at which the tiny animals in each layer formed their calcium carbonate shells to an accuracy of less than 1 degree Fahrenheit. He coupled that with carbon dating to determine each sediment layer's age.

Keigwin had expected to find evidence of climate swings during the past few thousand years. But in the CSS *Hudson's* prize sample, which was drilled with a more precise corer than oceanographers had used previously, he uncovered plenty of data about abrupt temperature changes over the past 1,000 years, including for a little ice age that averaged about 4 degrees Fahrenheit colder than the present. "And because the Sargasso Sea is pretty well mixed, the cooling must have been widespread," Keigwin says. More ominously, "I found evidence that proves the climate cycles continue right up until today."

Clearly, the little ice age from 1300 to 1850 wasn't kicked off by humans releasing greenhouse gases into the atmosphere. But natural climate cycles that melted Arctic ice could have caused thermohaline circulation to shut down abruptly. "We are almost certain that this was the cause of the last little ice age," says Ruth Curry, "although we'd need a time machine to be sure."

"I was aware that this could be a bombshell, but I stuck my neck out," says Keigwin, who first published his findings in 1996. Since then, similar high-sediment locations have bolstered his early conclusions. "As it turns out, there are probably at least 10 places in the North Atlantic that can give you pretty good core evidence of mini-ice-age cooling," he says.

A more recent event is perhaps better evidence that a climate can cool quickly because of thermohaline shutdown. In the late 1960s, a huge blob of near-surface fresher water appeared off the east coast of Greenland, probably the result of a big discharge of ice into the Atlantic in 1967. Known as the Great Salinity Anomaly, it drifted southward, settling into the North Atlantic in the early 1970s. There it interfered with the thermohaline circulation by quickly arresting deepwater formation in the Labrador Sea. It continued to drift in a counterclockwise direction around the North Atlantic, re-entering the Norwegian Sea in the late 1970s and vanishing soon after.

"I believe it shut the system down for just a few years. The result was very cold winters, particularly in Europe," says Ruth Curry.

That fresher-water mass, fortunately, was small enough to disperse in a short period of time. The one accumulating up there now, however, "is just too big," says Joyce.

CLIMATE SCIENCE IS EXTRAORDINARILY COMPLEX BECAUSE IT IS dependent upon the gathering and interpretation of millions of data points. If the National Weather Service has trouble predicting tomorrow's weather, how can anyone forecast a change in global climate a few years hence? One answer is even more data. At the moment, there are about 450 floating sensors bobbing around in the Atlantic monitoring temperature and salinity changes, and that is not enough, says Ruth Curry. "The models don't have enough resolution to capture all the physics yet. Prediction is tough."

Or maybe Woods Hole researchers are adhering to a flawed model. That's the view of Richard Seager, a climate scientist at Columbia University's Lamont-Doherty Earth Observatory. In a paper titled "Is the Gulf Stream Responsible for Europe's Mild Winters?" to be published this year in the *Quarterly Journal of the Royal Meteorological Society*, he casts doubt on the notion that warmth transported by the Gulf Stream has a significant impact on either continent. Europe would be warmer, he says, "even if the Atlantic were just a big, stagnant ocean" because the prevailing westerly winds would still blow heat stored in the Atlantic in the summer to Europe in the winter. Transported Gulf Stream heat, he says, accounts for less than 10 percent of England's warmth relative to the United States.

In Seager's view, prolonged winter warmth is more likely than a little ice age. "The thousand-pound gorilla in eastern North America and Europe is the North Atlantic Oscillation," he says. This is a complex, poorly understood variation in the strength of air-pressure cells over Iceland and the Azores. When pressure over Iceland is high, the pressure over the Azores tends to be low, and vice versa. During the winter, a lower-than-usual low over Iceland and a higher-than-usual high over the Azores forces cold air to eastern Canada and warm, moist air to northwestern Europe and the eastern United States.

That's precisely what has happened from the 1960s to the late 1990s, says Seager, which gave rise to relatively balmy winters in the high-population regions on both sides of the Atlantic. "If this phase continues, as some models predict will occur as the result of rising greenhouse gases, this would make these changes in winter climate persist for years to come," he says.

Seager's viewpoint is in the minority. In other models, and climate science is ultimately a battle of different computer models, the Gulf Stream is a major source of warmth for the lands that border the North Atlantic. In Ruth Curry's view, the science as it stands is more than strong enough to warrant thinking ahead.

"We can't know the point at which thermohaline shutdown could actually start," she says. "But we should plan for it." ☐

Opposite: "The physics of El Niño are simple compared to the physics of this climate change," says Terrence Joyce, chairman of the Woods Hole Department of Physical Oceanography, with Ruth Curry, one of the lead researchers.

