Global warming could shut down an ocean current that warms the northern latitudes. The prospect underscores the oceans' power over climate, also featured in the Special Section beginning on page 189

Warming's Unpleasant Surprise: Shivering in the Greenhouse?

Wallace Broecker is worried about the world's health. Not so much about the fever of global warming but about a sudden chill. For more than a decade, the marine geochemist has been fretting over the possibility that a world warming in a strengthening greenhouse might suffer a heart attack, of sorts: a sudden failure to pump vital heat-carrying fluids to remote corners of Earth. If greenhouse warming shut down the globe-girdling current that sweeps heat into the northern North Atlantic Ocean, he fears, much of Eurasia could within years be plunged into a deep chill. In the mid-1980s, that prospect and its alarming consequences prompted Broecker, a longtime researcher at Columbia University's Lamont-Doherty Earth Observatory in Palisades, New York, to start urging his colleagues to examine records of the climate system's past behavior for clues to its future health.

The data pouring in from ice cores and marine sediments are only fueling Broecker's fears—and worrying many of his colleagues too. At a conference* last month in Snowbird, Utah, researchers heard overwhelming evidence that the so-called "conveyor belt" current that warms northern Europe and adjacent Asia has repeatedly slackened and at times even shut off during the past 100,000 years, in concert with dramatic climate shifts around the hemisphere. And computer models suggest that, ironically, the greenhouse world's moister air could also squelch the conveyor belt.

At first, Broecker's colleagues weren't much concerned about the relevance of past climate shifts to the greenhouse future. But given the powerful new evidence that shifts in ocean circulation have jolted climate, many now wonder about the unpredictable course that climate change may take. "Wally is occasionally wrong … but for the most part he's remarkably prescient," says paleoceanographer Jerry F. McManus of the Woods Hole Oceanographic Institution in Massachusetts, who calls his colleague's disquietude "scientifically justified."

A sudden cooling of the Northern Hemisphere, even by only a few degrees on average, could throw a monkey wrench into the societal works. Farmers may have to contend with unseasonable cold, drought, and floods—an unsettled climate that could jerk one way and the other from year to year. Says glaciologist Richard Alley of Pennsylvania State University in University Park, "Humanity would continue, but a lot of us would be very unhappy."

Cool customer. Past climate flips may portend a big chill in the Northern Hemisphere due to global warming, contends Columbia's Broecker.

JEAN-LOUIS ATLAN

A hair-trigger climate

With climate-change debates polarized by hyperbole from both ends of the political spectrum, mainstream scientists have tended to avoid raising alarms. But recent findings show that global climate patterns flip-flopped every few thousand years—sometimes violently—during the last ice age. Climate indicators such as dust and isotope ratios in ice cores from Greenland reveal 24 so-called Dansgaard-Oeschger events, marked by 10° temperature swings that sometimes occurred in just a few years. North Atlantic sediments reveal that great flotillas of icebergs have sailed southward no fewer than six times in the past 100,000 years, each followed by plunging surface temperatures in the Atlantic.

Just as the last ice age was giving way to the thaw of the current Holocene Epoch 10,000 to 15,000 years ago, a prolonged climate swing sent temperatures plummeting again in Greenland and Europe in a matter of decades. The 5° to 10°C temperature drop replaced Europe's newly emerged forests with glacial tundra for 1000 years before the Holocene brought the forests back for good, and the cooling had a noticeable effect on parts of the rest of the hemisphere—from the dustiness of the Gobi Desert to the strength of the Arabian monsoon.

No one knows for sure what's at the root of these climate swings, but shifts in ocean circulation are a leading candidate. In the Atlantic, climate records preserved in bottom sediments suggest that surface water temperatures changed in step with changes in the ocean's conveyor belt, a term Broecker coined for the current whose upper loop carries warm, shallow waters from the North Pacific across the Indian Ocean, around Africa, and up the Atlantic. With a flow equaling that of 100 Amazon Rivers, the conveyor delivers enough heat to the North Atlantic's northern half to equal 25% of the solar energy reaching the surface there. Off Labrador and north of Iceland, frigid winds absorb that heat and carry it downwind, easing the chill on Europe and adjacent lands by as much as 10°C. Winds not only steal the North Atlantic's warmth but also boost its saltiness by evaporating freshwater, making surface waters dense enough to sink. The colder and saltier deep water flows southward, completing the conveyor belt loop.

Scientists have long suspected that this crucial artery can be totally shut down; now they have persuasive evidence, from an analysis of carbon-14 preserved in sediments of the southern Caribbean's Cariaco basin. Carbon-14, a radioactive isotope, is produced from nitrogen by cosmic rays striking the atmosphere. Sinking conveyor waters in the North Atlantic carry carbon-14, in the form of carbon dioxide, into the deep sea. So, if the conveyor were shut down, carbon-14

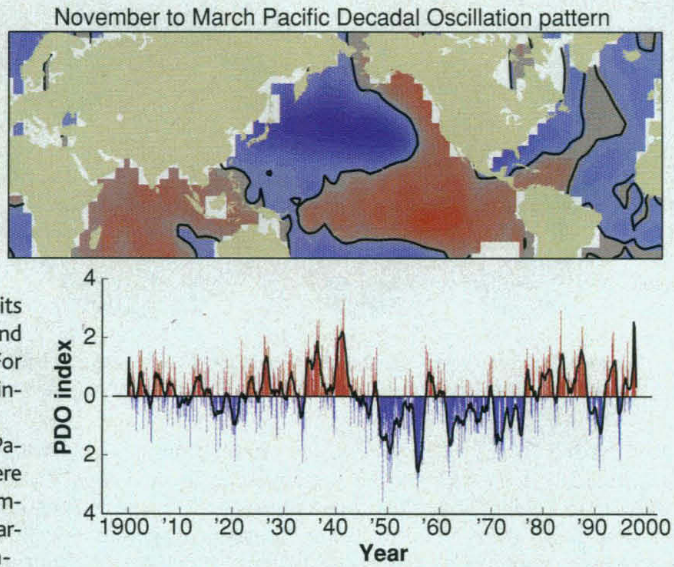
* Mechanisms of Millennial-Scale Global Climate Change, 14–18 June 1998. For further information, see www.agu.org/meetings/cc98dcall.html

As the Oceans Switch, Climate Shifts

While climate scientists ponder the ocean's possible wildcard role in the next couple of centuries of greenhouse warming (see main text), other researchers are considering how the ocean and atmosphere shift climate in our lifetime. Last winter's El Niño—an unusual warming of the tropical Pacific that altered weather patterns worldwide—was a prime example of ocean and atmosphere conspiring to bring climate change. But the tropical Pacific is likely not the only puppeteer pulling the strings. Oscillations in the North Pacific and the North Atlantic have long been suspected of shifting climate from decade to decade, and others are on the table.

It's one thing to indict ocean-atmosphere interplay as a suspect in these "decadal" climate shifts, however, and quite another to convict it. "Research into ocean climate is in its infancy," says oceanographer Lewis Rothstein of the University of Rhode Island, Narragansett. "It's a fully nonlinear system in which the human mind trying to figure out cause and effect doesn't work very well. Everything interacts with everything else."

In sorting out the complex interactions driving decadal climate change, researchers look to the ocean because only it can set such a leisurely pace. During an El Niño, for instance, tropical winds blowing from the east that draw deep, cold water to the surface may weaken, allowing surface waters to warm; the ocean warming further weakens the easterly winds. This ocean-atmosphere interaction can bring on a full-blown El Niño in a matter of months, but swings from El Niño to its opposite number, the cool La Niña, and back take between 3 and 7 years. For that kind of pacing, researchers must invoke the ocean's tremendous inertia.



In full swing. The newly identified Pacific Decadal Oscillation's ocean temperature patterns *(above)* can bring storms to the Pacific Coast, warming to Alaska, and freezes to Florida.

MANTUA *ET AL* / UNIVERSITY OF WASHINGTON

While an ocean like the tropical Pacific may set the pace, the atmosphere can extend an ocean's reach. For example, El Niño may be just part of a near-global daisy chain that loosely connects three oceans. Oceanographer James Carton of the University of Maryland, College Park, and his colleagues have used a computer model to merge 50 years of temperature and salinity observations into a complete and consistent picture of an evolving world ocean. By analyzing this motion picture, they can pick out oscillations in water temperature—and their possible connections—throughout the ocean.

This picture showed that before El Niño revs up in the Pacific, the tropical Indian Ocean warms. Then, like spectators in a stadium doing "the wave," warming appears in the tropical Pacific, setting off a full-blown El Niño. About 9 months after El Niño's wind shifts have leaped South America, they change the circulation of the tropical Atlantic to warm the ocean there, sometimes bringing drought to the Sahel of Africa and the coffee-growing region of northeast Brazil. "There's definitely a tropical connection," says Carton. "It's through the atmosphere from one basin to the next." The nearly global link stops there, after about 4 years and more than 30,000 kilometers.

The newly emerging ocean-atmosphere oscillations aren't confined to the tropics. The tropical Atlantic's own ocean-atmosphere–driven oscillation, a pair of researchers believes, extends beyond the tropics to include more than 11,000 kilometers of the Atlantic, from at least as far south as the mid–South Atlantic to beyond Iceland.

The proposed "pan-Atlantic decadal oscillation" or PADO, described in the 15 June issue of *Geophysical Research Letters* (*GRL*) by meteorologists Shang-Ping Xie of Hokkaido University in Sapporo and Youichi Tanimoto of Tokyo Metropolitan University, fluctuates on a 10- to 15-year time scale. At one extreme, east-west bands of alternately warmer or cooler water span the length of the Atlantic accompanied by changes in atmospheric circulation; at the other extreme, the temperature anomalies reverse. Guided by computer modeling, Xie and Tanimoto suspect that the ultimate driver for the PADO may be decadal variations of the North Atlantic Oscillation, a seesaw of atmospheric pressure between Iceland and the Azores (*Science*, 7 February 1997, p. 754).

The chain of oscillations doesn't stop there. According to an analysis in the 1 May *GRL* by meteorologists David Thompson and J. Michael Wallace of the University of Washington, Seattle, the strength of a swirling vortex of winds circling the Arctic in the wintertime stratosphere influences the lower atmosphere right down to the surface, including the far northern North Atlantic. Varying from day to day and decade to decade, the oscillation is a natural response of the atmosphere to the random jostlings of the ocean-atmosphere system, the way a drum has a natural tone when struck. Depending on where it is in its cycle, the Arctic Oscillation warms or cools northern Europe and Siberia.

The Arctic gong also reverberates in the far North Pacific, where oceanographer David Enfield of the National Oceanic and Atmospheric Administration in Miami is finding that on a decadal scale, the far northern reaches of the Pacific and the Atlantic seem to be varying in lockstep. The connection must be through the atmosphere, he says, and the Arctic Oscillation is a likely agent.

Another high-latitude oscillation may bring the global interplay full circle to the tropics. In 1977, the North Pacific seemed to flip to a whole new mode of operation (*Science*, 20 March 1992, p. 1508). It cooled and the atmospheric low-pressure center off the Aleutian Islands intensified and shifted eastward, bringing more storminess to the West Coast, warming to Alaska, and periodic winter freezes to Florida, among a raft of environmental changes.

Last year, meteorologist Nathan Mantua of the University of Washington, quantitative biologist Steven Hare of the International Pacific Halibut Commission in Seattle, and their colleagues dubbed this climate shift the Pacific Decadal Oscillation, or PDO, after finding evidence that shifts also occurred around 1947 and 1925. In the spirit of "everything interacts with everything else," Mantua and his colleagues note that the PDO appears to have close ties to El Niño—which seems to have shifted to another, warmer mode in 1977. Whether El Niño triggered the shift in the PDO or vice versa, they can't say. Determining just how many climate oscillations exist and how tightly they are linked should keep meteorologists and oceanographers busy well into the greenhouse world.

–R.A.K.

that would have entered the deep sea should build up in the atmosphere. Such an increase would leave a trace in ocean sediments.

Paleoceanographer Konrad Hughen of Harvard University and his colleagues have now found a carbon-14 buildup in Cariaco sediments deposited during the first 200 years of the Younger Dryas, the cold snap at the end of the last ice age 13,000 years ago. The rise was so rapid that the conveyor must have been shut down for that 200 years, the group concluded. For the remaining 1100 years of the Younger Dryas, a less efficient conveyor kicked in before regaining its full steam about 12,000 years ago.

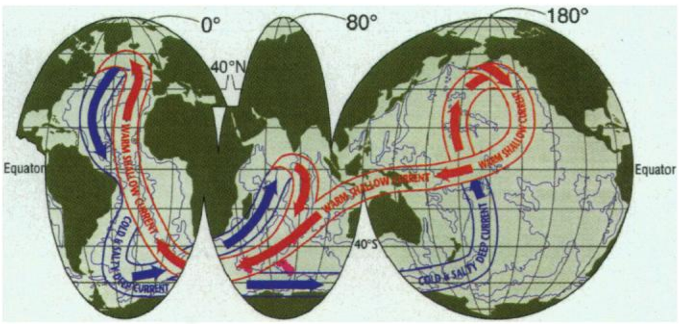
Researchers say that the ultimate cause of the conveyor's shutdown 13,000 years ago was the gradual warming of the Arctic at the end of the last ice age due to Earth's changing tilt toward the sun. Freshwater gushing from melting glaciers, they reason, would have spread a layer of less salty and therefore less dense water across the far northern North Atlantic, eliminating the extra density that drives the conveyor. A sudden diversion of conveyor-halting meltwaters to the St. Lawrence River and the North Atlantic might account for the abruptness of the Younger Dryas.

Freshwater messed with the conveyor at other times during the ice age, too. During six Heinrich events, ice sheets collapsed and sent armadas of melting icebergs across the North Atlantic (*Science*, 6 January 1995, p. 27). And in Dansgaard-Oeschger cycles, Broecker has suggested, the freshwater flushing of the North Atlantic could have been part of an endless oscillation of freshening that slows the conveyor and stagnation that lets salinity build back up and accelerate the conveyor.

In at least some of these events, freshwater jammed the conveyor completely, argued climate modeler Thomas Stocker of the University of Bern and his colleagues at Snowbird. They determined the timing of climate shifts around Antarctica and Greenland relative to one another, using as a benchmark the fluctuations of atmospheric methane trapped in ancient ice of both poles. Stocker's group found that during two or three of the biggest Dansgaard-Oeschger events, as well as during the Younger Dryas, the cooling in Greenland came at the same time as a warming in Antarctica. Later, when Greenland warmed a bit, Antarctica was cooling.

Opposite responses at opposite poles is just the pattern expected from a complete shutdown of the conveyor, because while a strong conveyor carries heat to the Northern Hemisphere, it draws heat away from the Southern Hemisphere. Turn off the conveyor, on the other hand, and the heat-starved north will cool while heat piles up in the south. The absence of an obvious out-of-phase relation during smaller, shorter Dansgaard-Oeschger climate swings suggests to Stocker and his colleagues that the conveyor slowed during those events or was restricted to the North Atlantic but did not shut down.

Although the conveyor may have faltered and even stopped during the last ice age, today it is almost rock steady. Climate records from ice and sediments show that subtle oscillations lasting roughly 1600 years seem to have persisted through the Holocene (*Science*, 27 February, p. 1304). But these oscillations can't compare with the ice age climate swings; the latest may have been the Little Ice Age of the 17th and 18th centuries, but it brought cooling of only about 1°C. "All the evidence we have for large flips comes from times when we had ice melting, dumping freshwater into the North Atlantic," says modeler Thomas Crowley of Texas A&M University in College Station. "It hasn't flipped in 8000 years, so modest perturbations aren't enough. You have to kick it harder."



Alarming current events. A shutdown of the globe-girdling "conveyor belt" current could blight Ireland's green fields and lead to agricultural anarchy elsewhere.

W. J. SCHMITZ JR., *REVIEWS OF GEOPHYSICS* 33, 151 (1995)

Calculating cooling's consequences

Broecker's worry is that greenhouse warming will kick the Holocene conveyor into its next big flip. This time, however, the villain is not expected to be melting glaciers alone. Instead, the warming would deliver more freshwater to high latitudes by increasing the load of water vapor that the atmosphere can carry from lower latitudes. The far North Atlantic would then receive a torrent of freshwater flowing into it from rain, snow, and swollen rivers.

In a sophisticated computer simulation of this kick, climate modelers Syukuro Manabe of the Institute for Global Change Research in Tokyo and Ronald Stouffer of the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey, raised carbon dioxide concentration in a model atmosphere over 140 years until it plateaued at four times the preindustrial levels, which might be reached in the real world by the 22nd century. They found that the high-latitude North Atlantic freshened and the conveyor slowed to a near standstill about 60 years after the quadrupling. In a recent extension of that simulation to more than 5000 years from now, Manabe and Stouffer were startled to find that over the next couple of thousand years of continuing warmth, the conveyor recovered completely. "I don't understand why," says Stouffer. "It's not exactly satisfying." Others share that discontent, adds Woods Hole's McManus: "We're learning that the climate system often responds in an unpredictable fashion."

Predicting the effects of the next conveyor shutdown is equally problematic. If it were like the Younger Dryas, Reykjavik would be bulldozed into the sea by the Iceland Ice Cap, Ireland's green fields would be blighted into the barrenness of present-day Spitsbergen, and Scandinavian forests would be replaced by treeless tundra. But Broecker notes that the Younger Dryas cooling started in a world cooler than today's, and a greenhouse-driven shutdown would come after perhaps several degrees of warming.

Broecker's best guess is that around the North Atlantic a shutdown would trigger a climate shift as large as the Younger Dryas's—reversing a century's worth of greenhouse warming and driving areas like Europe several degrees colder than present. And the cooling could take as little as several decades. If that weren't disruptive enough, the transition could be peppered with climate "flickers" lasting 5 to 10 years during which climate would whipsaw between extremes. Around the rest of the hemisphere, the cooling might just be a temporary relief from the greenhouse, notes Broecker, but the altered rainfall patterns could be just as disruptive as the temperature changes.

The capricious nature of past climate changes is exactly why Broecker says he has sounded the alarm. Given current knowledge, "there's nothing to do but guess" at the chances the conveyor will flip again soon, he says. To make those guesses more informed, says Broecker, "we should be doing much more in the polar regions" to understand why water sinks there and to track the conveyor's behavior. For his part, Penn State's Alley hopes to learn more about past climate flips by more finely analyzing the Greenland ice core records. And McManus wants to check older marine sediments from times even warmer than the present to see if extreme warmth really can destabilize the conveyor. Perhaps soon Broecker will be able to relax—if not cool off.

–RICHARD A. KERR