The Rising Seas

by David Schneider, *staff writer*

Many people were awakened by the air-raid sirens. Others heard church bells sounding. Some probably sensed only a distant, predawn ringing and returned to sleep. But before the end of that day—February 1, 1953—more than a million Dutch citizens would learn for whom these bells tolled and why. In the middle of the night, a deadly combination of winds and tides had raised the level of the North Sea to the brim of the Netherlands's protective dikes, and the ocean was beginning to pour in.

As nearby Dutch villagers slept, water rushing over the dikes began to eat away at these earthen bulwarks from the back side. Soon the sea had breached the perimeter, and water freely flooded the land, eventually extending the sea inward as far as 64 kilometers (nearly 40 miles) from the former coast. In all, more than 200,000 hectares of farmland were inundated, some 2,000 people died and roughly 100,000 were left homeless. One sixth of the Netherlands was covered in seawater.

With memories of that catastrophe still etched in people's minds, it is no wonder that Dutch planners took a keen interest when, a quarter-century later, scientists began suggesting that global warming could cause the world's oceans to rise by several meters. Increases in sea level could be expected to come about for various reasons, all tied to the heating of Earth's surface, which most experts deem an inevitable consequence of the mounting abundance of carbon dioxide and other heat-trapping greenhouse gases in the air.

First off, greenhouse warming of Earth's atmosphere would eventually increase the temperature of the ocean, and seawater, like most other substances, expands when heated. That thermal expansion of the ocean might be sufficient to raise sea level by about 30 centimeters or more in the next 100 years.

A second cause for concern has already shown itself plainly in many of Europe's Alpine valleys. For the past century or two, mountain glaciers there have been shrinking, and the water released into streams and rivers has been adding to the sea. Such meltwaters from mountain glaciers may have boosted the ocean by as much as five centimeters in the past 100 years, and this continuing influx will most likely elevate sea level even more quickly in the future.

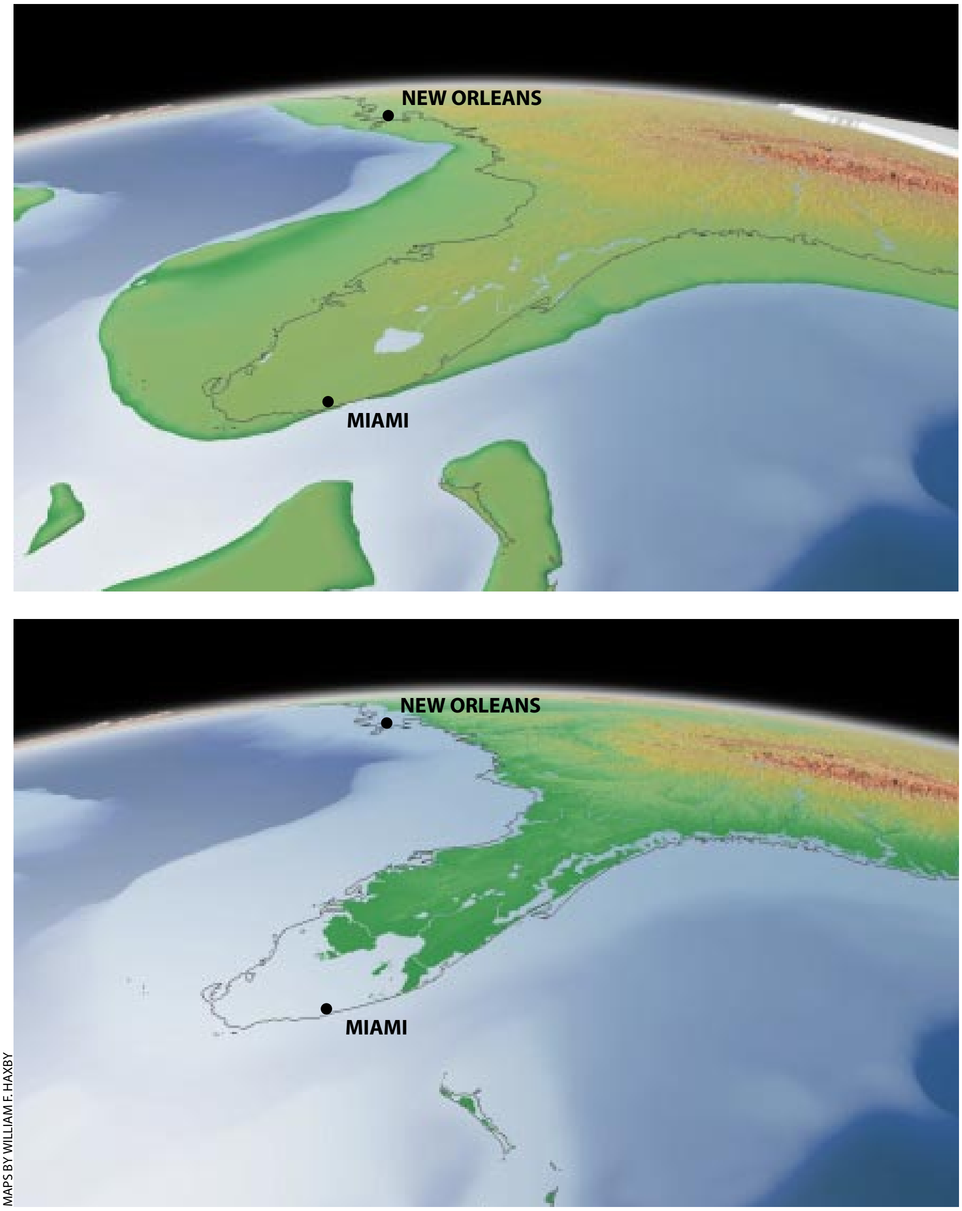
But it is a third threat that was the real worry to the Dutch and the people of other low-lying countries. Some scientists began warning more than 20 years ago that global warming might cause a precariously placed store of frozen water in Antarctica to melt, leading to a calamitous rise in sea level—perhaps five or six meters' worth.

Yet predicting exactly how—or whether—sea level will shift in re-

SEA DIKES protect low-lying areas of the Netherlands from the ocean, which rises well above the land in many places. The Dutch government must maintain hundreds of kilometers of dikes and other flood-control structures on the coast and along riverbanks.

Although some voice concern that global warming will lead to a meltdown of polar ice, flooding coastlines everywhere, the true threat remains difficult to gauge

NETHERLANDS MINISTRY OF TRANSPORT AND PUBLIC WORKS sponse to global warming remains a significant challenge. Scientists trained in many separate disciplines are attempting to glean answers using a variety of experimental approaches, ranging from drilling into the Antarctic ice cap to bouncing radar off the ocean from space. With such efforts, investigators have learned a great deal about how sea level has varied in the past and how it is currently changing. For example, most of these scientists agree that the ocean has been creeping upward by two millimeters a year for at least the past several decades. But determining whether a warmer climate will lead to a sudden acceleration in the rate of sea-level rise remains an outstanding question.



MAPS BY WILLIAM F. HAXBY

FLORIDA looked quite different 20,000 years ago, during the last ice age. At that time, vast amounts of water remained locked within continental ice sheets to the north, and sea level was nearly 120 meters lower than today (*top*). As the ice melted, the coastlines retreated inland to their present positions (*black line*). Future melting of ice in West Antarctica may yet raise sea level an additional five meters, inundating large areas (*bottom*).

Antarctic Uncertainties

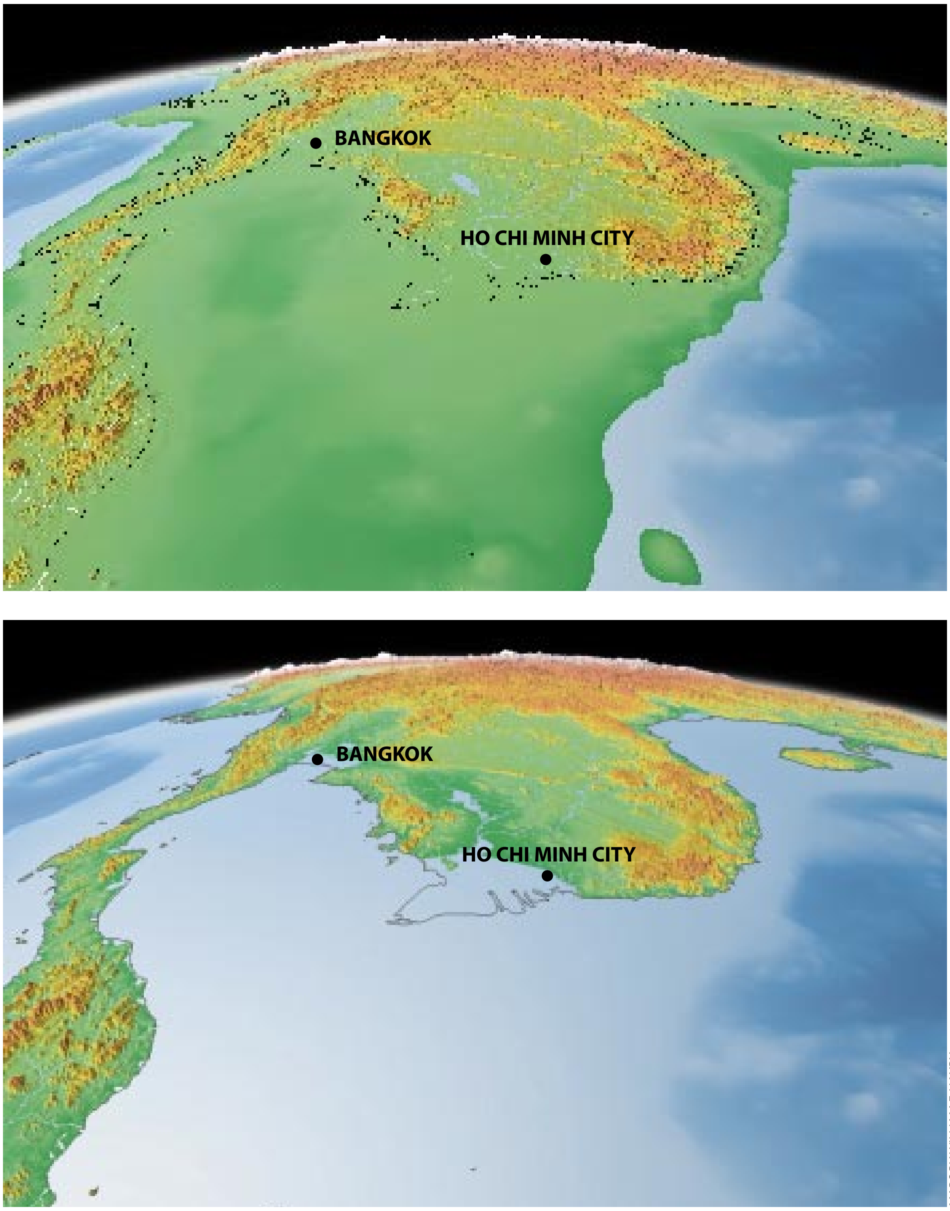
One of the first prominent geologists to raise concern that global warming might trigger a catastrophic collapse of the Antarctic ice cap was J. H. Mercer of Ohio State University. Because the thick slab of ice covering much of West Antarctica rests on bedrock well below sea level, Mercer explained in his 1978 article "West Antarctic Ice Sheet and CO_2 Greenhouse Effect: A Threat of Disaster," this marine ice sheet is inherently unstable. If the greenhouse effect were to warm the south polar region by just five degrees Celsius (by nine degrees Fahrenheit), the floating ice shelves surrounding the West Antarctic ice sheet would begin to disappear. Robbed of these buttresses, this grounded ice sheet—a vestige of the last ice age—would quickly disintegrate, flooding coastlines around the world in the process.

Mercer's disaster scenario was largely theoretical, but he pointed to some evidence that the West Antarctic ice sheet may, in fact, have melted at least once before. Between about 110,000 and 130,000 years ago, when the last shared ancestors of all humans probably fanned out of Africa into Asia and Europe, Earth experienced a climatic history strikingly similar to what has transpired in the past 20,000 years, warming abruptly from the chill of a great ice age.

That ancient warming may have achieved conditions a bit more balmy than those at present. The geologic record of that time (known to the cognoscenti as interglacial stage 5e) remains somewhat murky, yet many geologists believe sea level stood about five meters higher than it does now—just the additional dollop that would be provided by the melting of the West Antarctic ice sheet. If such a collapse had occurred in Antarctica during a slightly hotter phase in the past, some reason, the current warming trend might portend a repeat performance.

That possibility spurred a group of American investigators to organize a coordinated research program in 1990, to which they attached the title "SeaRISE" (for Sea-level Response to Ice Sheet Evolution). The report of their first workshop noted some ominous signs on the southernmost continent, including the presence of five active "ice streams" drawing ice from the interior of West Antarctica into the nearby Ross Sea. They stated that these channels in the West Antarctic ice sheet, where glacial ice flows rapidly toward the ocean, "may be manifestations of collapse already under way."

But more recent research suggests that the dire warnings expressed up to that time may have been exaggerated. In the early 1990s researchers using so-called global circulation models, complex computer programs with which scientists attempt to predict future climate by calculating the behavior of the atmosphere and ocean, began investigating how a warmed climate would affect the Antarctic ice cap. These researchers found that greenhouse heating would cause warmer, wetter air to



MAPS BY WILLIAM F. HAXBY

SOUTHEAST ASIA during the last ice age included a huge tract of land along what is now the Sunda Shelf. That terrain connected the mainland of Asia with the islands of Indonesia, forming one great continental mass (*top*). Should the West Antarctic ice sheet melt, the resulting five-meter rise in sea level would flood river deltas, including the environs of Ho Chi Minh City and Bangkok (*bottom*), substantially altering the present coast (*black line*).

reach Antarctica, where it would deposit its moisture as snow. Even the sea ice surrounding the continent might expand.

In other words, just as SeaRISE scientists were beginning to mount their campaign to follow the presumed collapse of the West Antarctic ice sheet, computer models were showing that the great mass of ice in the Antarctic could grow, causing sea level to drop as water removed from the sea became locked up in continental ice. "That really knocked the wind out of their sails," quips Richard G. Fairbanks, a geologist at the Columbia University Lamont-Doherty Earth Observatory.

Other observations have also steered the opinion of many scientists working in Antarctica away from the notion that sudden melting there might push sea level upward several meters sometime in the foreseeable future. For example, glaciologists now realize that the five major ice streams feeding the Ross Sea (named, rather uninventively, ice streams A, B, C, D and E) are not all relentlessly disgorging their contents into the ocean. One of the largest, ice stream C, evidently stopped moving about 130 years ago, perhaps because it lost lubrication at its base.

In fact, the connection between climatic warming and the movement of West Antarctic ice streams has become increasingly tenuous. Ellen Mosley-Thompson of the Ohio State University Byrd Polar Research Center notes that ice streams "seem to start and stop, and nobody really knows why." And her own measurements of the rate of snow accumulation near the South Pole show that snowfalls have mounted substantially in recent decades, a period in which global temperature has inched up; observations at other sites in Antarctica have yielded similar results.

But the places in Antarctica being monitored in this way are few and far between, Mosley-Thompson emphasizes. Although many scientists are now willing to accept that human activities have contributed to global warming, no one can say with any assurance whether the Antarctic ice cap is growing or shrinking in response. "Anybody who tells you that they know is being dishonest," she warns.

That uncertainty could disappear in just a few years if the National Aeronautics and Space Administration is successful in its plans to launch a satellite designed to map changes in the elevation of the polar ice caps with extraordinary accuracy—perhaps to within a centimeter a year. A laser range finder on this forthcoming satellite, which is scheduled to be placed in a polar orbit in 2002, should be capable of detecting subtle changes in the overall volume of snow and ice stored at the poles. (Curiously, a similar laser instrument now orbiting Mars may be charting changes in the frozen polar ice caps on that planet well before scientists are able to perform the same feat for Earth.) During the first decade of the 21st century, then, scientists should finally learn whether the Antarctic ice cap as a whole is releasing water to the sea or storing water away in deep freeze.

Other insights into West Antarctica's vast marine ice sheet may come sooner, after scientists drill deeply into the ice perched between two of the ice streams. The researchers planning that project (who have replaced the former moniker "SeaRISE" with the less alarmist acronym "WAIS"—for West Antarctic ice sheet) hope to recover ice, if it indeed existed, dating from the exceptionally warm 5e interval of 120,000 years ago. Finding such a sample of long-frozen West Antarctic ice would, in Mosley-Thompson's words, "give you some confidence in its stability."

Until those projects are completed, however, scientists trying to understand sea level and predict changes for the next century can make only educated guesses about whether the polar ice caps are growing or shrinking. The experts of the Intergovernmental Panel on Climate Change, a body established in 1988 by the World Meteorological Organization and the United Nations Development Program, have adopted the position that both the Antarctic and the smaller Greenland ice caps are most likely to remain constant in size (although they admit the possibility of substantial errors in their estimate, acknowledging that they really do not know whether to expect growth or decay).

Up or Down?

Whatever the fate of the polar ice caps may be, most researchers agree that sea level is currently rising. But establishing that fact has been anything but simple. Although tide gauges in ports around the world have been providing measurements of sea level for many decades, calculating the change in the overall height of the ocean is a surprisingly complicated affair. The essential difficulty is that land to which these gauges are attached can itself be moving up or down. Some regions, such as Scandinavia, are still springing back after being crushed by massive glaciers during the last ice age. Such postglacial rebound explains why sea level measured

Fertilize the Sea to Stop It from Rising?

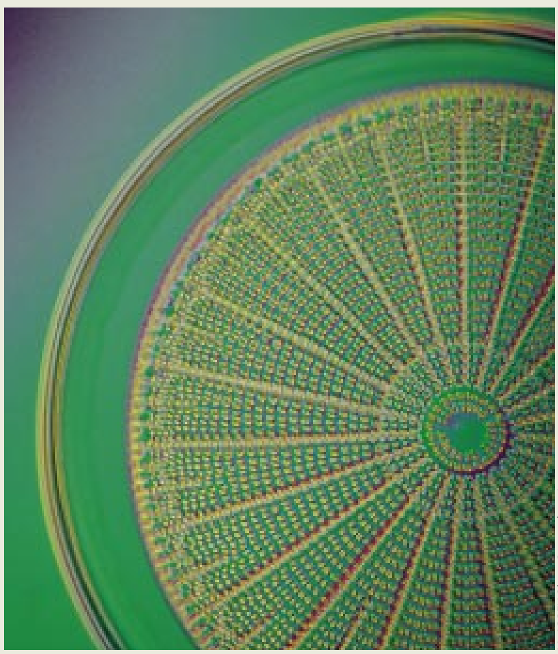
Discussions about ocean and global warming tend to focus on the threat of rising sea levels or the possibility that hotter tropical waters might spawn more frequent typhoons. But one also needs to remember that, in a fundamental sense, the oceans are important allies in the struggle against troubling climatic change. Of all the heat-trapping carbon dioxide that is released into the atmosphere every year from tailpipes and smokestacks, about a third goes into the sea, which scientists therefore recognize as an important "sink" for this gas.

The carbon dioxide dissolves in the shallow layers of the ocean, where, thankfully, it cannot contribute to warming the atmosphere. Much of the carbon transferred in this way is used by phytoplankton, the ubiquitous microscopic plants that grow near the surface of the water. After these short-lived organisms die, some of the carbon in their tissues sinks to great depths. Climatologists call this process the "biological pump" because it draws carbon out of the atmosphere and stores it deep in the sea. Naturally enough, some people have pondered whether this phenomenon could be artificially enhanced. This tactic would be the marine equivalent of planting more trees to isolate carbon in a form that does not contribute to greenhouse warming.

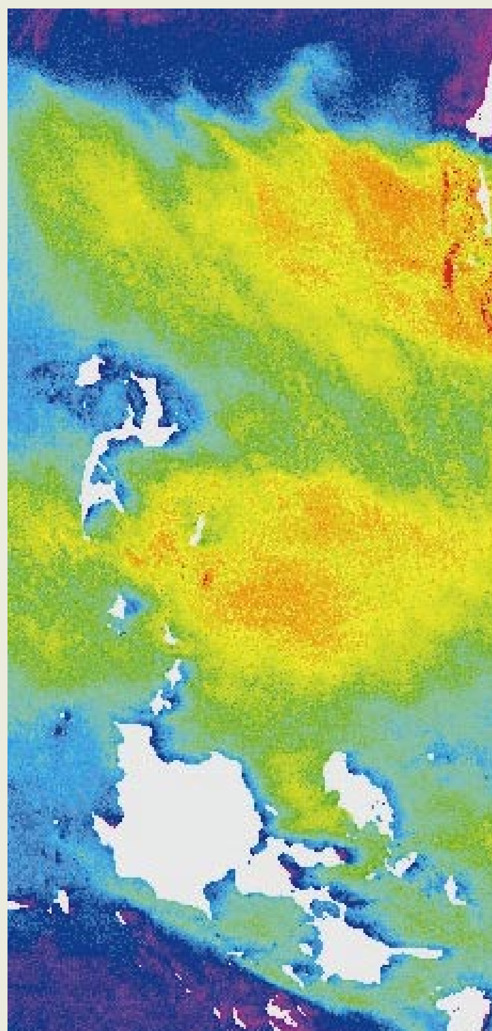
One researcher closely associated with this concept is the late John H. Martin of Moss Landing Marine Laboratories in California. Martin and his colleagues were aware that large oceanic regions contain high levels of nitrate (a normally scarce nutrient) but show low concentrations of the photosynthetic pigment chlorophyll. That combination was curious: with abundant nitrate to fertilize their growth, tiny marine plants should multiply rapidly, greening the sea with chlorophyll. Yet vast high-nitrate, low-chlorophyll areas can be found in the equatorial and northern Pacific and over large stretches of the southern oceans.

Martin and his co-workers knew that the growth of phytoplankton in these places was not limited by any of the major nutrients—nitrate, silicate or phosphate. They believed that the deficiency of a trace element, iron, was curbing the growth of phytoplankton, because experiments with cultures had shown that adding a dash of iron to water taken from these areas boosts its ability to support the growth of common types of phytoplankton.

They reasoned that this connection between iron and plant growth, if it indeed operated the same way in the ocean, would have profound consequences. For example, it could explain why carbon dioxide levels in the atmosphere were much lower during the last ice age: iron carried in dust blown off the cold, dry continents of the time would have fostered the growth of marine phytoplankton, which then acted to pump carbon from the atmosphere to the



M. ABBEY Photo Researchers, Inc.



SATELLITE OBSERVATIONS, such as this false-color image made with the Coastal Zone Color Scanner (*right*), reveal that the concentration of phytoplankton to the west of the Galápagos Islands is often much higher (*red*) than that in surrounding waters (*blue*). Such blooms of microscopic plants, typically diatoms (*above*), probably occur because iron-rich particles are carried westward from these volcanic islands by the prevailing winds and currents.

in Stockholm appears to be falling at about four millimeters a year, whereas it is rising by one and a half millimeters a year in Honolulu, a more stable spot.

In principle, one could determine the true rise in sea level by throwing out the results from tide gauges located where landmasses are shifting. But that strategy rapidly eliminates most of the available data. Nearly all the eastern seaboard of North America, for instance, is still settling from its formerly elevated position on a "peripheral bulge," a raised lip that surrounded the depression created by the great ice sheet that covered eastern Canada 20,000 years ago. What is more, local effects—such as the buckling that occurs at the edges of tectonic plates or the subsidence that ensues when water or oil is pumped from the ground—dominate in many tide gauge records, even in the tropics. In Bangkok, for example, where residents have been tapping groundwater at a growing rate, subsidence makes it appear as if the sea has risen by almost a full meter in the past 30 years.

Fortunately, geophysicists have devised clever ways to reconcile some of these discrepancies. One method is to compute the motions expected from postglacial rebound and subtract them from the tide gauge measurements. Using this approach, William R. Peltier and A. M. Tushingham,

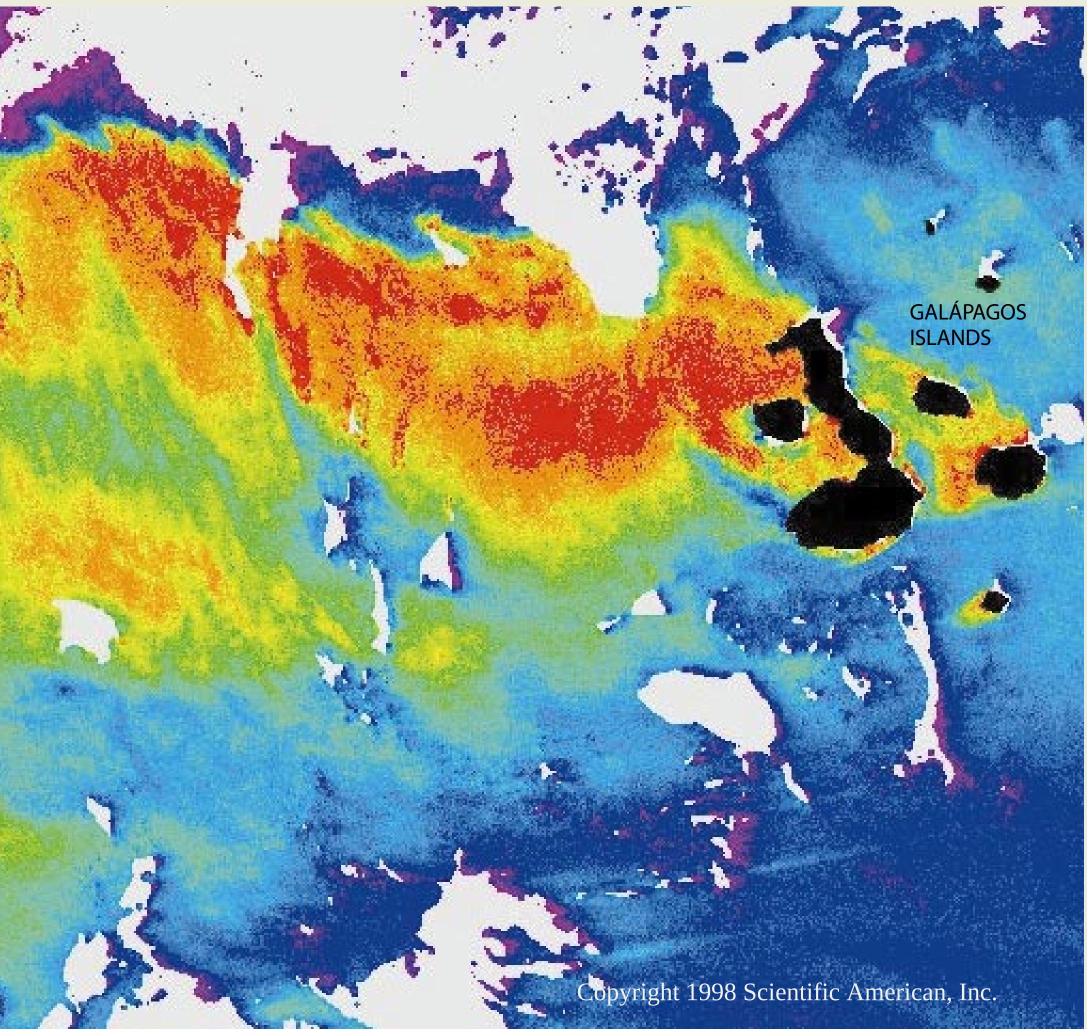
---

seafloor. When the continents became warmer and wetter at the end of the Pleistocene (roughly 10,000 years ago), the land gave off less dust to ocean-bound winds, robbing some marine phytoplankton of the iron needed for growth.

Although this argument was compelling, many other theories could also explain past changes in atmospheric carbon dioxide levels. To impress on some of his skeptical colleagues the importance of iron as a plant nutrient, Martin jokingly proclaimed in a lecture in 1988 that adding even modest amounts of iron in the right places could spur the growth of enough phytoplankton to draw much of the heat-absorbing carbon dioxide from the atmosphere. His often quoted jest "Give me a half a tanker of iron, and I'll give you an ice age" foreshadowed more serious considerations of actually using this approach to help cool the planet.

By 1991 other scientists had examined whether such a solution to global warming could be effective. Using computer models, they concluded that the most successful iron fertilization scheme would reduce carbon dioxide levels in the atmosphere by only about 20 percent at most. Still, the following year an influential panel from the National Academy of Sciences reported that such a program of geoengineering might provide a relatively cheap way to alleviate some of the expected greenhouse warming. But at that point, the very idea that adding iron to parts of the sea would enhance the growth of marine phytoplankton remained only a hypothesis.

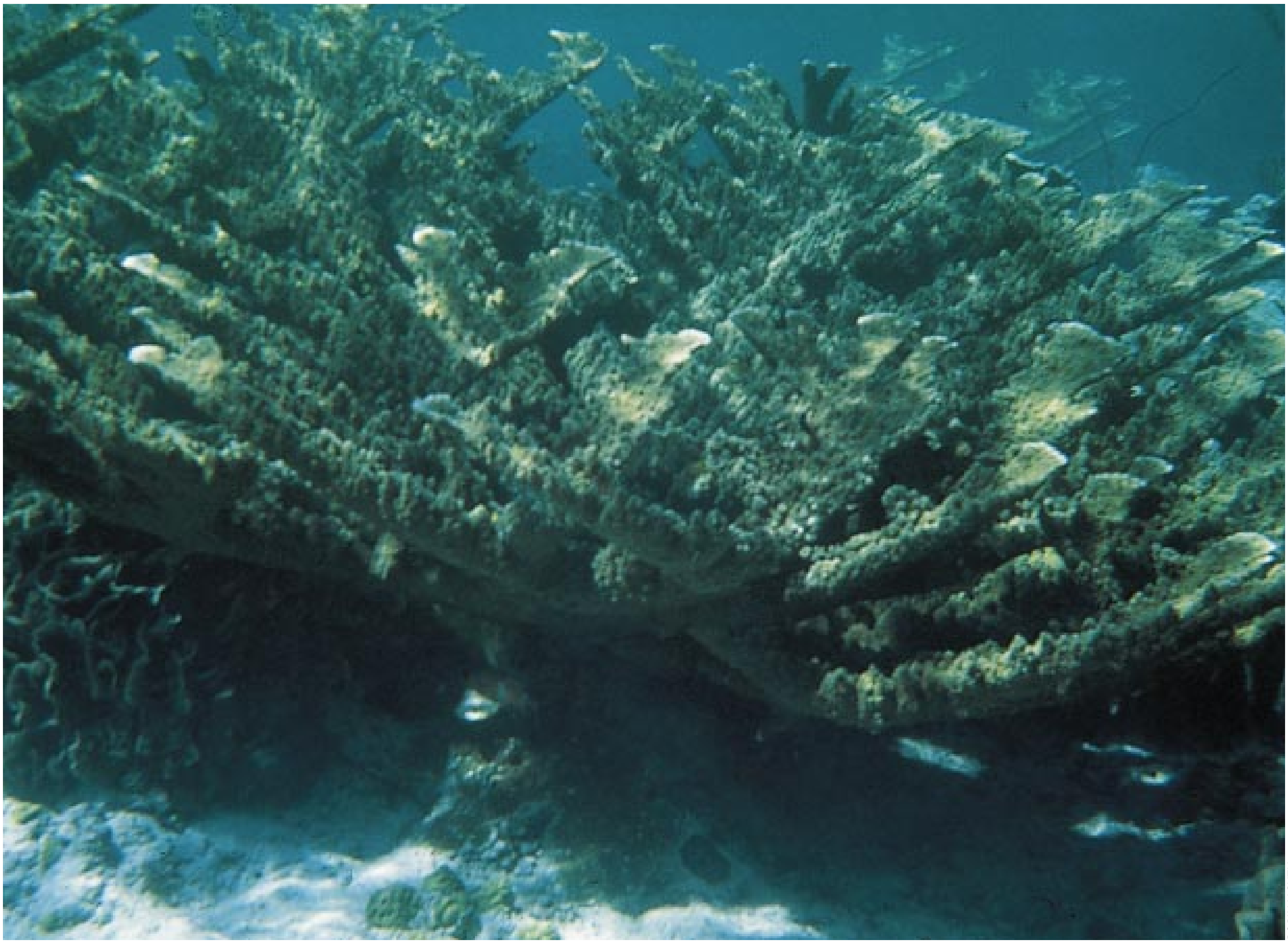
To test the basic theory better, Martin and his co-workers organized an expedition to the equatorial Pacific in 1993 to scatter a solution of iron over a 64-square-kilometer patch of open water. Promising results from this first experiment encouraged a second expedition to the region in 1995, which provided further evidence that iron indeed limits the proliferation of phytoplankton in these high-nitrate, low-chlorophyll waters.



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Martin died of cancer in June 1993, so he was not able to witness the success of these demonstrations. Yet even before the actual tests of his idea were carried out, he and many other oceanographers began to worry that performing planetary engineering on the scale required to put a dent in the problem could very well cause unforeseen environmental hazards in the sea—depleting oxygen disastrously in places, disturbing the marine food web and perhaps even worsening the buildup of atmospheric carbon dioxide in the long run.

In 1996 the Intergovernmental Panel on Climate Change concluded in their summary report that iron fertilization "is not a feasible mitigation tool, given our current knowledge of the potential ramifications of such a procedure." Nevertheless, several oceanographic expeditions to fertilize patches in the southern oceans with iron are now in preparatory stages, and these experiments will undoubtedly keep this controversial idea under debate for some time. *—D.S.*



ROBIN LIGHTY

NEAR-SURFACE-DWELLING CORALS of the species *Acropora palmata* help to determine past changes in sea level. By drilling into coral reefs and recovering ancient samples of this species from deep under the seabed, scientists have been able to reconstruct how sea levels rose as the last ice age ended.

both then at the University of Toronto, found that global sea level has been rising at a rate of about two millimeters a year over the past few decades. Many other investigators, using different sets of records from tide gauges, have reached similar conclusions.

Further confirmation of this ongoing elevation of the ocean's surface comes from more than half a decade of measurements by the TOPEX/Poseidon satellite, which carries two radar altimeters aimed downward at the ocean. Because the position of the satellite in space is precisely known, the radar measurements of distance to the sea below can serve as a spaceborne tide gauge. The primary purpose of the TOPEX/Poseidon mission is to measure water circulation in the ocean by tracking surface undulations caused by currents. But the satellite has also been successful in discerning overall changes in the level of the ocean.

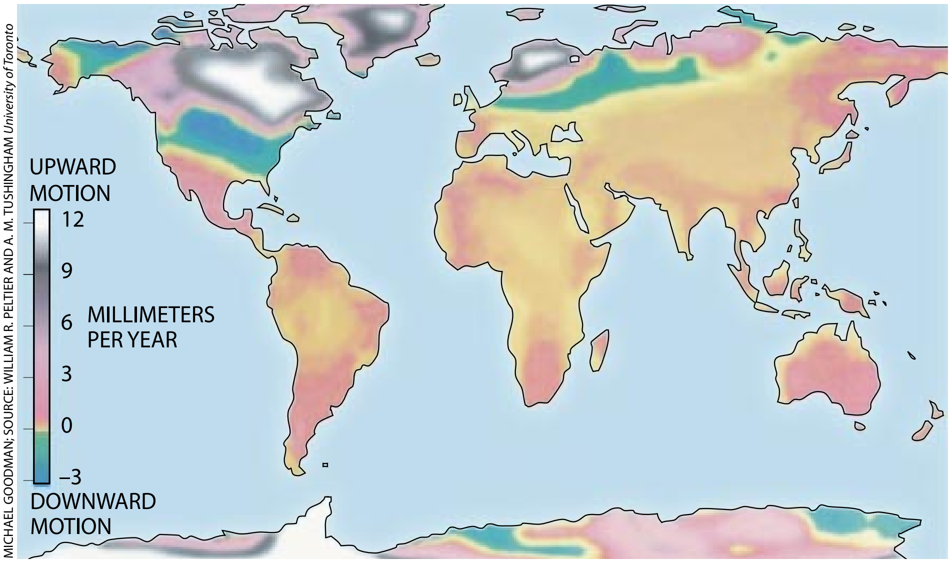
"When you average over the globe, you get much less variability than at an individual tide gauge," explains R. Steven Nerem of the Center for Space Research at the University of Texas at Austin. He had published results from the TOPEX altimeter that indicated that global sea level was rising at almost four millimeters a year—twice the rate previously determined. But, as it turns out, these were affected by a bug in the software used to process the satellite data. Subsequent analysis appears to confirm the land-based assessment of two millimeters a year in sea-level rise. "Of course, this estimate changes every time I put in some more data," Nerem admits, "but the current number is completely compatible with the estimates that have come from 50 years of tide gauge records."

Looking Backward

With few exceptions, scientists believe they have established a reliable value for the rate of recent rise in sea level: two millimeters a year. But the key question still facing these researchers—and civil planners—is whether this trend will hold steady or begin to accelerate in response to a warming climate. Geologists have helped address this problem by tracing how sea level has fluctuated in the past in response to prehistoric climate changes.

Columbia's Fairbanks, for example, has studied one species of coral that grows near the surface of the sea, particularly in and around the Caribbean. By drilling deeply into coral reefs in Barbados and locating ancient samples of this surface-dwelling species, he and his colleagues were able to follow the ascent of sea level since the end of the last ice age, when tremendous quantities of water were still trapped in polar ice caps and the oceans were about 120 meters lower than they are today.

Although his coral record shows episodes when the sea mounted by as much as two or three centimeters a year, Fairbanks notes that "these rates are for a very different world." At those times, 10,000 to 20,000 years ago, the great ice sheets that had blanketed much of North America and Europe were in the midst of melting, and the ocean was receiving huge influxes



MICHAEL GOODMAN; SOURCE: WILLIAM R. PELTIER AND A. M. TUSHINGHAM *University of Toronto*

POSTGLACIAL REBOUND, the slow recovery from the deformation caused by weighty ice sheets, accounts for the vertical movement of land in many parts of the world. These shifts, which have been continuing since the last ice age ended, affect relative sea level at the coastline in a manner that varies from place to place. Such movements can confound tide gauge records obtained from coastal sites and thus complicate efforts to track the overall change in global sea level.

of water. The more recent part of the sea-level record indicates a progressive decline in the rate of ascent, with the height of the ocean seemingly stagnating during the past few millennia. Thus, the current climatological regime would appear to be inclined toward a relatively stable sea level.

But this reassuring picture is called into question by John B. Anderson, a marine geologist at Rice University. The data collected by Fairbanks and his colleagues are "not accurate enough to see the kinds of events predicted by the glaciological models," Anderson contends. There were at least three episodes of sudden sea-level rise in the past 10,000 years, he elaborates, but these are invisible in the coral record simply because "there's a five-meter error bar associated with that method."

Anderson and his co-workers have garnered evidence from such places as Galveston Bay in the Gulf of Mexico, where sediment cores and seismic soundings reveal how that estuary has responded to rising sea level since the last ice age. A steady increase in sea level would have caused the underwater environments that characterize different parts of the estuary to move gradually landward. But the geologic record from Galveston Bay, Anderson points out, shows "very dramatic" features that indicate sudden flooding of the ancient strand.

The most recent episode of sudden sea-level rise that Anderson discerns occurred about 2000 B.C., when global climate was presumably similar to present conditions. His work indicates that sea level may have jumped considerably in just a few centuries. But so far Anderson has been unable to establish just how large a rise actually occurred.

Archaeologists should be able to help track ancient changes in sea level with further examination of coastal sites submerged by rising seas. Numerous analyses done so far in the Mediterranean, spanning only the past 2,000 years, indicate that sea level has risen an average of only two tenths of a millimeter a year. Unfortunately, those studies give little insight into whether the ocean may have suddenly mounted 4,000 years ago. Nor is the archaeological work yet adequate to discern exactly when sea level began to quicken in its rise, ultimately reaching the modern rate of two millimeters a year.

Despite many such troubling gaps in the scientific understanding of how sea level has varied in the past and how it could change in the future, the experts of the Intergovernmental Panel on Climate Change have provided some broad guidelines for what the world might expect by the end of the next century. The panel's forecasts for sea-level rise range from 20 centimeters to almost one meter. The low end of these estimates corresponds, in essence, to the rate of sea-level rise that has probably been occurring for the past century or two—since before humanity began releasing carbon dioxide and other greenhouse gases into the atmosphere with abandon. That is to say, the next century might see only a continuation of the natural rise in sea level that has long been tolerated. The high-end estimate of the panel represents a substantial acceleration that could plausibly happen but so far has not been evidenced.

Weathering the Future

Of course, responsible international authorities must take the full range of possibilities into account in planning for the future. Although the fivefold uncertainty in the amount of sea-level rise might trouble some, John G. de Ronde, the head of hydraulic modeling at the Ministry of Transport and Public Works in the Netherlands, seems unruffled by it. Whatever the eventual trend in global sea level, he is confident that his country can cope: "Sea-level rise—you can measure that, you can see it and do something about it."

Although the necessary expenditures might seem enormous, de Ronde reports that the cost of improving Dutch dikes and other waterworks to accommodate 60 centimeters of sea-level rise over the next century amounts to no more than what people there now pay to maintain their bicycle paths. He shows greater concern for poor, land-scarce coastal nations and for an aspect of future climate that is much more difficult to forecast than sea level: changes in the frequency and intensity of violent storms. "You would need 20 years to see a change in statistics," de Ronde notes, "then a bad storm could happen the next day."

So as long as the West Antarctic ice sheet remains reasonably behaved, the real question facing residents of coastal regions may be how greenhouse warming affects local weather extremes and the size of damaging storm surges. Yet for those kinds of changes, scientists are especially hard put to offer predictions.

Perhaps with the results of further research and more refined computer models, climatologists will eventually be able to pinpoint where conditions will deteriorate and where they will improve. But such precise forecasts may, in the final reckoning, prove unreliable. It may just be as de Ronde says, imparting a lesson that nature keeps forcing on him and his colleagues: "We have to live with things we don't know exactly." SA