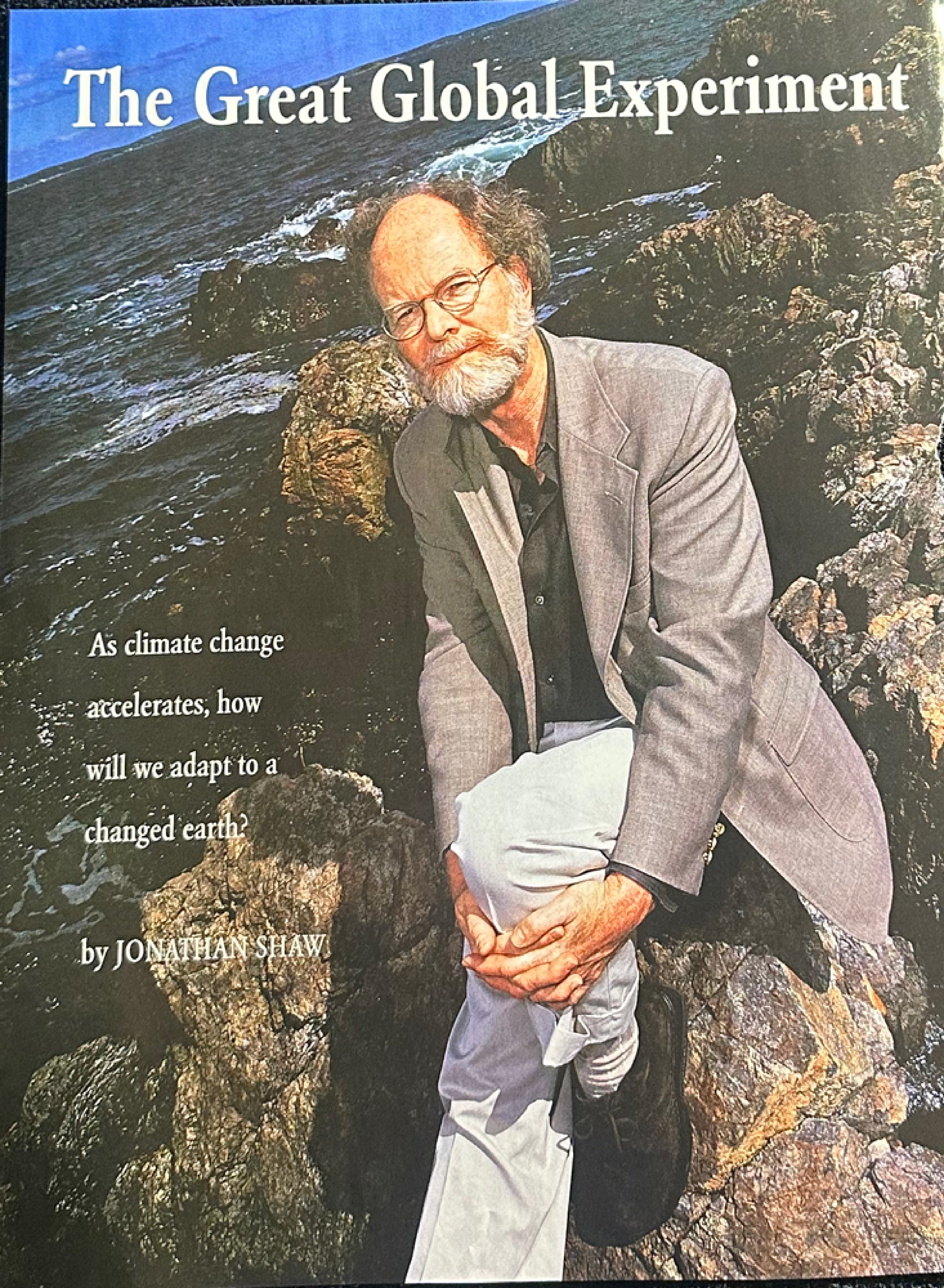
The Great Global Experiment



As climate change accelerates, how will we adapt to a changed earth?

by JONATHAN SHAW

During a recent Alaska study cruise cosponsored by the Harvard Museum of Natural History, James J. McCarthy stopped at several islands with small native communities—Little Diomede, for example, with 150 inhabitants. At each village, McCarthy asked the elders if climate had changed in their lifetimes. In one village after another, he relates, "They said, 'Well, my grandfather said the ice used to come in November, and now it doesn't come until January.'" Wherever he went, the story was the same: "My grandfather said it used to leave in June. Now it goes out in March."

"Those are just anecdotes," says McCarthy, the Agassiz professor of biological oceanography. But even as he distinguishes anecdote from scientific evidence, McCarthy shares with virtually all his colleagues who study climate change the firm conviction that our world is warming rapidly. Understanding the rate of change, its causes, and the consequences for humans and nature engages researchers around the planet—including prominent scientists in Harvard laboratories. With the scientific consensus coming into clearer focus, policy analysts in the University, as elsewhere, are struggling to devise appropriate responses—a task revealing sharp differences of opinion over fairness and efficiency, and even wider gaps between the worldviews of biologists and economists.

Biological oceanographer James J. McCarthy has been a leader in the international effort to assess the risks to human and natural systems posed by global climate change.

McCarthy's experience demonstrates the sweep of the global-warming challenge. The former director of the Museum of Comparative Zoology has studied the processes that control biological production in the upper waters of the North Atlantic, the equatorial Pacific, and the Arabian Sea. Inevitably, those inquiries have led him, in the past two decades, to consider the overall condition of the marine environment—where half the planet's biological production occurs—and more recently, to investigate the diminished extent of sea ice; altered ocean-atmosphere exchange of energy, air, and moisture; and the likelihood of changing ocean-circulation patterns.

In 1997, McCarthy was tapped to cochair the Working Group on Impacts, Adaptation, and Vulnerability for the Intergovernmental Panel on Climate Change. The IPCC, created in 1988 by the World Meteorological Organization and the United Nations Environmental Programme, is the mechanism for winnowing the myriad of published research to achieve consensus on what aspects of climate change scientists are most confident about. It's a conservative process, involving comments from thousands of scientists worldwide. McCarthy describes meetings at which four-fifths of the papers were rejected for insufficient data. "The possibility of having anything radical get through this process is virtually nil," he says. His panel's effort represents the work of more than 400 authors: their report of 1,000 or so pages documents the mainstream scientific consensus on climate change. The result, McCarthy maintains, "is the one that stands up to all the tests, the one that you cannot refute with published scientific findings."

The full IPCC report, released last year (see www.ipcc.ch), confirmed that the average global temperature is rising, and concluded that human activity propels climate change.

What's more, McCarthy says, a warming world is a *changing* world. Average temperature rose a little more than 1 degree Fahrenheit during the past century—but on Alaska's north slope and in northwestern Canada, during the same period, temperatures have *already* risen 4 to 7 degrees. That impact dramatically illustrates a key research finding: the effects of climate change vary widely by region, and may be far more powerful than average figures suggest. It is no particular comfort that the data confirm the Little Diomede villagers' anecodotal testimony: subsistence lifestyles throughout the far north are threatened by warmer winters. All over the planet, says McCarthy, scientific work reviewed by the IPCC shows warming-induced changes "in geographic distribution of many species, and in the timing of flowering, egg laying, migrations, et cetera."

The Arctic Meltdown

How did we reach this point? The largest contributor to recent global warming, scientists believe, is carbon dioxide (CO_2), a "greenhouse gas" that allows visible light from the sun to reach the earth's surface, but then retains some of that emitted light as heat in the lower atmosphere, and hence warms it. This gas occurs naturally in the environment: we exhale it, and plants absorb it during photosynthesis, releasing oxygen. The problem is that we have been adding more CO_2 to the atmosphere than can be absorbed by the biosphere and the ocean, slowly but surely, since the beginning of the Industrial Revolution. When fossil fuels such as oil, coal, or natural gas are burned, they release their carbon content to the atmosphere as CO_2. Atmospheric concentrations of the gas are now well beyond the steady level of 280 parts per million (ppm) that persisted from A.D. 1000 until the early 1800s. Ice cores from around the globe tell most of the story, and direct measurements were added in 1958. The concentration of CO_2 began increasing about 150 years ago and is now at 370 ppm, one-third higher than the historic level—and rising. Because these additions of CO_2 will persist in the atmosphere for a century or more, mitigating action taken now won't reduce concentrations for generations. These actions, however, will *slow* the rate of greenhouse gas warming.

Surface temperature in the last thousand years (according to evi-

Photograph by Jim Harrison

dence from tree rings, corals, ice cores, and isotopes), has been variable, but if anything was *decreasing* slightly, on average, until about 1900. That is what might have been expected based on historic cycles of glaciation: we are at a point in the cycle where we might anticipate beginning a long period of gradual cooling. Instead, temperatures have been *rising* since the turn of the twentieth century. The rate of warming in the last century was probably the fastest of any hundred-year period in the last millennium, and the trend appears to be accelerating. Since 1976, the World Meteorological Organization reports, global average temperature has risen approximately three times faster than the century-long trend. Nine of the 10 warmest years in the last 140 years have occurred since 1990—and 2002 is on track to be the warmest ever.

Looking beyond instruments, scientists have found other evidence of warming. In close to 100 areas in the Northern Hemisphere, data exist covering at least a century, often based on newspaper reports of contests and wagers to guess the ice-out date of lakes and rivers. In 95 percent of these cases, the ice-free season has lengthened an average of about two and a half weeks.

Another piece of the puzzle comes from the top of the world. Nuclear submarines have been transiting the North Pole beneath the Arctic ice since the 1950s, and measuring its thickness. When the data were declassified at the end of the Cold War, they showed that thickness had decreased by 40 percent between the late 1950s and the 1990s. Satellite data show a 10 percent reduction in the extent of the icepack over the last two decades. The United States Navy, pondering the implications for national security, worries about "scientific models [that] consistently suggest seasonal sea lanes through a formerly ice-locked Arctic may appear as soon as 2015. Summertime disappearance of the ice cap could be possible by 2050 if the trend continues."

Extending the speculation, what will happen to all the organisms adapted to life in a frigid Arctic? Algae that live on the underside of polar sea ice, McCarthy explains, constitute the base of an arctic food web that ultimately supports the "signature creatures" commonly associated with the far north: fish, seals, and polar bears. Loss of ice threatens the chain from the bottom to the top, where entirely carnivorous polar bears stalk seals' breathing holes. Without ice, seals don't need breathing holes and polar bears will go hungry. "One might imagine that while this is bad for polar bears, it is good for seals," says McCarthy. But "this year, in the Gulf of St. Lawrence, many harp seal pups drowned when there was no stable ice for them to rest on. That is a massive recruitment failure."

In the summer of 2000, McCarthy got a glimpse of what the Arctic's future may look like. He and other scientists aboard the 75,000-horsepower Russian icebreaker *Yamal* arrived at the North Pole only to find open water in every direction for miles. All along their 500-mile journey they had encountered unusually thin ice, with large areas of open water visible at every point of the compass. That same season, a Canadian ship transited the legendary, once-impassable, Northwest Passage without touching ice. The Arctic meltdown is well under way.

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The Great Carbon Sink

Although the tangible evidence of global warming is clearest at high northern latitudes, other important factors are at work much closer to home, in the forested middle latitudes where many of the industrialized world's people live. We know this in part because of work pioneered by Steven C. Wofsy, Rotch professor of atmospheric and environmental science, who has been studying the role of the terrestrial biosphere—mostly forests—in absorbing atmospheric carbon as he tries to ferret out the magnitude of the CO_2 problem. "The world use of fossil fuels amounts to about six and half billion tons of carbon per year," he says. "There's a magic number that I teach my Science A-30 class: it takes 2.1 billion tons of carbon to raise the atmospheric CO_2 concentration by one part per million." If all the CO_2 we pumped into the atmosphere stayed there, the concentration would be rising by more than three ppm per year—but it is actually rising only one and a half ppm annually. Scientists began to search for the missing carbon, and guessed that it was going into the oceans or being taken up by forests or soils.

Of the three-billion-plus tons missing from the atmosphere each year, it turns out the oceans absorb half (for an explanation of how the "biological pump" moves carbon into the deep ocean, see "The Ocean Carbon Cycle," page 40). The rest almost certainly ends up sequestered in forests.

The process of plants taking CO_2 out of the atmosphere and storing it as organic matter has accelerated in the last 20 years—a surprise, given how much one hears about deforestation. (In his lectures, Wofsy calls it a miracle.) Could it be that the terrestrial biosphere is responding to the rising CO_2? If we knew why, might we control the process and use it as a management tool? He set out to understand exactly what is happening in the woods.

"There are three explanations worth mentioning," says Wofsy. "One is that when you add CO_2 to the atmosphere, plants grow better." In fact, experiments conducted at Harvard have shown that plants exposed to double concentrations of CO_2 usually grow faster: the so-called CO_2 fertilization effect. Of course, the actual rise in atmospheric CO_2 since the pre-industrial era has been only about 30 percent. "If that is enough to stimulate extra uptake of CO_2," says Wofsy, "it really is a miracle."

A second possibility is that forests are growing better because they are being fertilized by pollution. "Trace metals, the oxides of nitrogen that form smog, and the sulfate aerosols that cool the earth (and kill people) are actually all fertilizers," he explains.

"Finally," he says, "it may be that what is happening is an historical artifact. In the eighteenth century a lot of forests were cut down as we converted the land to agricultural use; in the nineteenth century many forests in Northern Europe were logged." Because of modern agricultural practices that boost crop yield per acre, marginal lands have been abandoned to forest. This is true in most of the eastern United States. "In the most extreme case," says Wofsy, "if you went to New Hampshire in 1680, 95 to 100 percent of the land was in forest. In 1880, only 15 percent of the land was forested. If you go there today, it's 85 percent. In South Carolina, huge areas that were used to grow cotton now support forests that yield wood fiber for paper companies. Much the same has happened in northern Europe." And organic matter has accumulated in forests for the last hundred years as fires have been suppressed in the western United States.

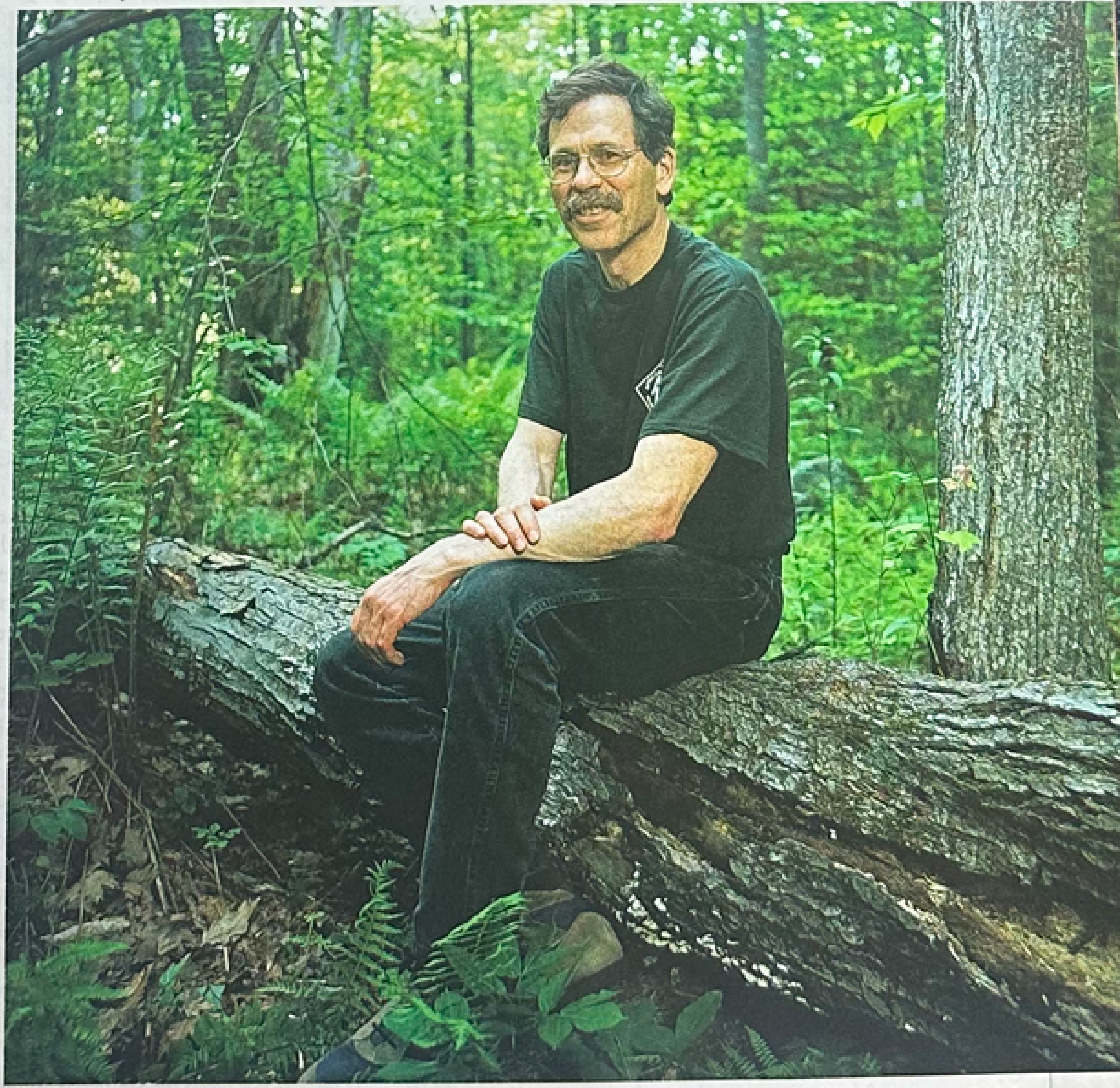
Which of the three likely explanations is actually responsible for the increased uptake of carbon? A Princeton analysis found no significant increase in forest growth rates during the last 40 years, suggesting that the effect of any kind of fertilization on these forests has so far been negligible. The study attributed half the carbon uptake to fire suppression and called the other half an historical artifact.

But Wofsy, suspecting that the story was more complex, devised a direct experiment. Thinking about just how much carbon a forest absorbs, he began to wonder what else happened in the woods besides the growing of live trees. After all, he reasoned, when the New England forests were fields, there was no dead wood lying around, and even the soils had been depleted of organic matter by cultivation. He was also interested in how global warming might be affecting forest growth. "Growing seasons have gotten longer in the middle latitudes of the Northern Hemisphere," he says, "and I wanted to understand whether that was a factor."

Using techniques he had deployed for short-term measurements in Brazil and Canada, Wofsy and his research group of 15 to 20 young scientists set up a long-term experiment at the Harvard Forest in Petersham, Massachusetts, in 1989. They found that the Harvard Forest was taking up a *lot* of carbon. "It is 60 years old," Wofsy says of the prevalent vegetation, "and a lot of models said that it should have stopped absorbing carbon by then, but even though it is a full-height forest, the trees are still growing." He discovered first that less than half the carbon absorbed by the forest is going into the living trees. The rest is going to deadwood in the soils, and accumulating there. (The forest is also undergoing "succession": as oak replaces pine, the denser wood of the successor species holds more carbon.)

He also learned that the forest responds strongly to climate variations. In a long growing season, it will take up more carbon. In a dry growing season, carbon sequestration increases as well. "It has nothing to do with the trees' uptake of carbon," Wofsy explains, "but rather with the decomposition process of deadwood, which is slowed down when the forest dries out."

Having established that northern mid-latitude forests are sequestering vast quantities of carbon, Wofsy decided to run the same longer-term experiment in a boreal forest in central Canada and in a tropical forest in Brazil. He learned that those ecosystems are quite different.



Northern mid-latitude forests, like the Harvard Forest in Petersham, Massachusetts, currently absorb one quarter of all the carbon dioxide emitted as the result of human activities, says atmospheric scientist Steven C. Wofsy. But these "carbon sinks," he warns, could become future sources of CO_2 and should be carefully managed.

In boreal forests, growing seasons are short, there is very little rainfall, nutrients are few, and the trees don't get very big. But underlying the forest there is a lot of peat, the remains of moss that has been building up for 5,000 to 7,000 years. The moss grows slowly, but it accumulates because the soils tend to be saturated with water or to be frozen as part of a discontinuous permafrost.

Photograph by David Carmack

"We call this a cold desert," says Wofsy, "because it gets only about 11 inches of rainfall a year, but the climate is cold enough that evaporation is even less." The combination of cold and wet preserves the peat. Recently, however, the climate has warmed in this area, and there is a good chance that the peat is no longer stable over the long term.

Why should that matter? "If you took all the peat in Canada and Russia and turned it into CO_2," by burning, Wofsy says, "you would double the amount of CO_2 in the atmosphere. It took 5,000 years to make it, but it doesn't take much to get rid of it," because it can catch fire. Intense conflagrations burn all of the dried peat in a forest. "Usually, just a foot or so of peat is dry enough to burn, but if all two meters dry out as climate warming trends continue," he cautions, "the full accumulation could be released to the atmosphere over perhaps 50 years."

Given that threat, Wofsy is now studying boreal forest hydrology, or water balance, in order to gauge the peat's long-term stability. He already has temperature measurements dating back to 1994 of the permafrost in the immediate area where he has been working. They show that temperatures deep in the soil are rising. "It is only one spot," he cautions, "and it is not something that we would be able to extrapolate to the whole region, but we don't think it is atypical."

Far to the south, in a tropical setting, he is duplicating the experiment as part of a cooperative program among NASA, the United States, and Brazil. One would expect that a mature tropical forest wouldn't be taking up any carbon on average, he says, because any organic matter decays quickly in the heat and humidity despite the tremendous growth. And in fact, his data show that the forest neither loses nor gains carbon. The miracle, then, is that the mid-latitude forests over much of North America, Europe, and some parts of Asia, all generally 50 to 100 years old, *are* acting as a giant carbon sink, and prior land use changes are a major factor in that.

Can we solve the carbon problem by growing more forests? "No," says Wofsy, "that is not an entire solution. But I strongly advocate the idea that *managing* forests for carbon should be part of a much broader strategy of managing forests for multiple gain. Forests provide a variety of economic goods, including fiber, watershed protection, and wildlife habitat. Lengthening the cycle of rotation or changing the tree species to higher-quality hardwoods would add to the amount of carbon stored there and simultaneously increase the value of the product." Sequestration of carbon by forests is "an important matter to keep in mind," says Wofsy. "But if you want a magic bullet, I don't have one—I don't think anybody does."

Under the tutelage of Rotch Professor of atmospheric environmental science Steven Wofsy and doctoral candidate Lucy Hutyra (in bandanna), students in a Harvard Forest summer program learn to measure tree growth by recording the expansion of encircling metal bands and to track the quantity of organic matter falling to the forest floor.

Spreading Seas

Not everyone is compelled by Wofsy's and McCarthy's data. But owners of oceanfront property confronted by rising sea levels are increasingly aware of global warming. Contrary to popular belief, most global sea-level rise to date is caused by thermal expansion, not melting of ice. As ocean waters warm, they expand at a predictable rate in response to temperature. During the twentieth century, driven by warming waters, the global sea level rose 4 to 8 inches. This century, sea level is expected to rise between 4 and 35 inches, according to the IPCC, with mid-range values (a little more than 18 inches) more likely than either extreme. Sea levels will continue to rise for centuries, even if new emissions of CO_2 were limited tomorrow, because to date, only a fraction of the ocean—the warmest water that lies on the surface—has been warmed by higher temperatures. It will take hundreds or thousands of years for all the water in the ocean to be exposed to our warmer planet, so coastal inundation, erosion, storm damage, contamination of freshwater supplies, and rising water tables are problems that will be around for a long time.

Melting of land-based freshwater glaciers and ice sheets also contributes to sea-level rise. (Melting sea ice doesn't—because it floats, sea ice already displaces ocean water. The 12,000-year-old, half-a-trillion ton, Rhode Island-sized chunk of the Larsen B ice shelf that collapsed so spectacularly this spring off the Antarctic peninsula was sea ice.) Worldwide, 90 percent of alpine glaciers are retreating. Glacier National Park, for example, is not likely to have any glaciers by 2070. But by far the greatest reserves of fresh water on the planet are frozen in Greenland and Antarctica, where the ice forms sheets up to two miles high. At those elevations, temperatures remain consistently below freezing. Today, Antarctica has the least precipitation of any continent—but that might change as the world warms. Warmer air has the potential to hold more water, and if moisture-laden winds found their way into the polar vortex, that might actually *increase* snowfall at the South Pole—thereby acting as a small brake on sea-level rise.

But there are indications that the Antarctic ice sheets partially melted as recently as 14,000 years ago, and that sea levels rose 70 feet in a few hundred years. No climate model predicts melting of any of these massive ice sheets in the next 100 years, yet no model today can explain the melting of the past. Clearly, the two biggest variables governing sea-level rise—what happens to the ice in Antarctica and in Greenland—are subjects for further research.

Photographs by David Carmack

Doomsday scenarios aside, even the incremental rise in sea level already in evidence and forecast to continue at an accelerated rate is potentially catastrophic. The horizontal extent of beach erosion is typically 50 to 200 times the rise in sea level. Mid-range IPCC estimates of sea-level rise during the next century therefore imply a corresponding loss of 75 to 300 feet of shoreline, threatening coastal settlements everywhere. In the span of one lifetime, many U.S. beaches would disappear. Low-lying areas like the Mississippi River delta (think of New Orleans) and Chesapeake Bay would suffer further inundation. Coastal habitat, including wetlands, would vanish and some species would become extinct. Millions of people in developing countries—Bangladesh, for example—would be at risk from rising waters. By 2090, lower Manhattan would be under several feet of water during storm surges every few years unless something were done (as it likely would be: the real estate is simply too valuable, the inhabitants too affluent, to do nothing).

To the Extremes

Not that it is safe to assume all such changes will be as "gentle" or as gradual. Another "robust conclusion" of the recent IPCC report is that extreme weather events have become "more frequent, more intense, and more persistent" in the last 50 years: higher maximum temperatures and more hot days over nearly all land areas; higher minimum temperatures over all land areas; an increased heat index (a combination of temperature and humidity); more intense rain over land areas; and increased summer drying and risk of drought in some areas. The projections show a broadening and intensification of these trends, plus increased tropical-storm peak winds and intensified peak precipitation; more droughts and floods associated with El Niño events; and increased Asian summer monsoon variability. "One can argue that a little bit of warmer weather may be bad for the ski industry and good for the citrus industry," James McCarthy acknowledges, "but hardly anyone can find good news in any of this because extreme events are inherently destructive."

The increased frequency and intensity of floods is the strongest sign of this tendency toward more extreme weather. "One has to be careful," McCarthy says, "because most of the floods that we hear about, including those in the news this summer in Central and Eastern Europe, are in systems that have been heavily modified by human use—floodplains, for example, have been developed." But one need only look at the last five years to see the increased frequency in century-scale storms, like the one in Europe. "Tropical storm Allison in Texas a year ago was the costliest precipitation disaster in U.S. history," says McCarthy. "And 1999's Hurricane Mitch—which wasn't a hurricane by the time it reached Honduras because the wind energy was gone—was a warm air mass that lifted up slowly and dumped its moisture, resulting in more than 10,000 lives lost. It was the biggest precipitation disaster in Central American history. One year later in Venezuela, in December, more than 25,000 lives were lost in the greatest precipitation disaster in South American history." In the last five years, he continues, "in China, in North Korea, in India—even places that are preadapted to flooding—people have experienced flooding beyond any historical proportions."

Might warmer temperatures increase the global food supply, offsetting coastal property losses? To a point, yes, McCarthy explains, but other problems of distribution and inequity arise in the IPCC's vision of the future. Net gains in agricultural productivity are most likely to take place in North America and Northern Eurasia with a moderate rise in temperature. But neither of those places is food-limited today. So the bounty will accrue where the people *aren't*, while the populous tropics and subtropics will see net *declines* in agricultural production. The notion of environmental refugees streaming north out of Africa is one that European nations are taking very seriously.

Further, any projected increase in crop yields assumes temperature increases of no more than 4 to 6 degrees Fahrenheit. Beyond that, productivity drops off sharply everywhere. Not surprisingly, most of the crops humans have selected over time are grown in regions near the optimum temperature for maximum food production. A detailed analysis in the *U.S. Climate Action Report–2002* (www.epa.gov/globalwarming/publications/car/index.html), the official federal summary of observed and anticipated domestic climate-change impacts, notes, for example, that with rising temperatures, barley should benefit, but wheat will not. The report (McCarthy calls it "an excellent document...the science is accurately represented") also illustrates graphically what will happen to agriculture in one state by "moving" Illinois south to the latitude of Oklahoma and North Carolina. Beyond agriculture, the government report acknowledges that "some of the goods and services lost through the disappearance or fragmentation of natural ecosystems are likely to be costly or impossible to replace"; that alpine meadows in the Rockies, and some barrier islands, will likely disappear; and that southeastern forests are likely to experience major species shifts or break up into a mosaic of grasslands, woodlands, and forests.

But what if global warming somehow reinforces itself, *accelerating* climate change—or in fact triggers a sudden, sharp shock to earth's systems? McCarthy says the models that purport to predict agricultural yields "presume a very linear change, that we will gradually get warmer and warmer and warmer. [But] we know from the record in the past that climate doesn't gradually shift from one stage to another. It does so with large swings, and one manifestation of these swings is in extreme events."

An example of such reinforcement occurs in the Arctic. When sunlight hits ice or snow, 90 to 95 percent is reflected. But when the snow melts or the ice retreats, almost the inverse is true: only 5 or 10 percent of the sun's energy is reflected. As the sun warms bare ground and open ocean, this warms adjacent areas of snow and ice, causing further melting and increased absorption of the sun's rays. "This drives a greater pace of change in the Artic," says McCarthy. Another imponderable feedback—he calls it "the juggernaut in all this"—is what will happen to cloud cover. A warmer atmosphere is able to hold more moisture. But will there be more clouds? If so, will they be dark clouds that absorb heat, or reflective clouds that reduce sunlight that reaches earth, thereby miti-

The report also illustrates graphically what will happen to agriculture in one state by "moving" Illinois south to the latitude of Oklahoma and North Carolina.

gating the impact of global warming? Nobody knows. And what kind of impact will an ice-free Arctic Ocean have on world ocean-circulation patterns and the variety of their oscillations and harmonics, most of which are poorly understood? "It is an experiment that is really wide open," says McCarthy, "and many of us wish we were doing it in a laboratory rather than in the real world."

"Climate Switches" and a Permanent El Niño

Butler professor of environmental studies Michael B. McElroy focuses on just such questions of larger-scale effects from climate change, a principal interest of Harvard's Center for the Environment, which he directs. The center, an interfaculty initiative, includes experts in oceanic ecosystems, development, governance, public health, and atmospheric chemistry.

"The IPCC approach," he says, "has been to focus in large measure on the ability of models to reproduce the global average temperature changes that were observed in the last 150 years." When early models overstated temperatures, some scientists were concerned. But McElroy wouldn't throw the models out—he just wouldn't ask so much of them: "I don't believe that any of these models should be expected to reproduce in detail what happened over the last 150 years because there is natural variability in the climate system."

He focuses less on the *degree* of warming, which could easily be higher or lower than IPCC estimates, he says, and more on the *risk of sudden changes* to the climate system. There are indications that some of the major circulation patterns that drive that system are starting to change, with potentially serious consequences.

One hint comes from a general circulation model—a giant climate simulator running on a supercomputer—produced by the Hadley Centre in Britain. The Hadley model, one of several worldwide, "though not necessarily a uniquely credible projection," stresses McElroy, "is as good an indicator of the changes that could happen in the future as any that we have." What it shows (see

The Ocean Carbon Cycle

Of all the carbon dioxide (CO_2) *emitted* into the atmosphere, one quarter is taken up by land plants, another quarter by the oceans. Understanding these natural mechanisms is important in forecasting the rise of atmospheric CO_2 because even though plants and bodies of water now absorb surplus greenhouse gas, they could become new trouble spots. The ocean absorbs CO_2 from the atmosphere in an attempt to reach equilibrium by direct air-to-sea exchange. This process takes place at an extremely low rate, measured in hundreds to thousands of years. However, once dissolved in the ocean, a carbon atom will stay there, on average, more than 500 years, estimates Michael McElroy, Butler professor of environmental science.

Besides the slow pace of ocean turnover, two more factors determine the rate at which the seas take up carbon dioxide. One is the availability of carbonate, which comes from huge deposits of calcite (shells) in the upper levels of the ocean. These shells must dissolve in ocean water in order to be available to aid in the uptake of CO_2, but the rate at which they dissolve is controlled by the ocean's acidity. The ocean's acidity does rise with increased CO_2, but the slow pace of ocean circulation prevents this process from developing useful momentum. It takes a long time for the increased acidity to reach the vulnerable calcite deposits, to dissolve them, and then to bring the carbonate cations to the surface where they can combine with CO_2 in the surface waters of the ocean. There is no hope, says McElroy, that this process will take place fast enough to help control the build-up of CO_2.

Another process, called "the biological pump," transfers CO_2 from the ocean's surface to its depths. Warm waters at the surface can hold much less CO_2 than can cold waters in the deep. "This is the 'soda bottle on a warm day' effect," says Agassiz professor of biological oceanography James McCarthy, "and is not unique to carbon dioxide; it applies to all gases dissolved in water. There is a higher capacity to hold a gas with a lower temperature than with a higher temperature." This means that when deep ocean waters rise to the surface as part of normal ocean-circulation patterns, the water heats up and actually releases CO_2.

The biological pump works in the opposite direction. One-celled plants, the remains of organisms that feed on them, and fecal matter sink, by force of gravity, into the deep ocean. This phenomenon was first described in the late 1800s by Harvard's Alexander Agassiz, who referred to it as the "rain of detritus." Its effect is to pull carbon out of the upper ocean and cause it to rain down into the depths, where bacteria and other organisms metabolize and release it back into the water as CO_2, enriching carbon dioxide in the deep ocean. (Either way, the chance is very small that a carbon atom in the ocean will be incorporated into organic matter or chemically combined with a carbonate cation to form calcium carbonate that will end up sequestered in sediments, where it might remain for hundreds of millions of years.)

For complex reasons, the fertilization effect of CO_2 (see "The Great Carbon Sink," page 36) does not stimulate biological production in the oceans as it can on land. What regulates these plants' growth is light (of which there is plenty near the surface) and the availability of nutrients. Patterns of circulation control both these parameters. For example, plankton does not thrive in sinking water masses such as those found deep in the North Atlantic, because it is pulled down and away from the light. Similarly, warm surface waters don't hold much in the way of nutrients such as nitrogen and phosphorus. What these plants require is an upwelling of cold, nutrient-rich waters from lower levels of the ocean, and then a particular stratification of waters of different temperatures, in order to thrive.

"These upwellings follow natural cycles," says McCarthy, "which is why there are seasonal blooms of plankton in different places near ocean-circulation features. Here in New England, we see a spring bloom off Georges Bank that feeds the great cod and haddock fisheries."

Nobody knows how climate change will affect currents, stratification, and nutrient supply. "But to say that the ocean will continue working just the way it is, and that the biological pump will continue to work the way it does at present—this is sophistry," says McCarthy. "We know that it will not."

graphic on page 42) runs counter to the conventional wisdom on climate change—that the highest temperature increases will occur at the highest latitudes. McElroy was sufficiently impressed by the model that he put it on the cover of his latest book, *The Atmospheric Environment: Effects of Human Activity.* "This shows what the world might look like 50 years from now, with temperature changes of 7 to 11 degrees, and in some places 14 to 18 degrees, which are bigger than the interglacial changes that occur in nature," he says. "But what is really notable about this projection is that it shows significant warming, and simultaneous drying, in areas of the equatorial tropics, such as the Brazilian rainforest."

"The way the tropics work at the moment," he explains, "is that you have the strongest rainfall over Indonesia." Warm, moisture-laden air releases rain over the region as it rises into cooler heights of the atmosphere. This fountain of air, once drained of its moisture, descends over the Pacific, where the cycle begins again. Another patch of air rises over Brazil, and a third in central Africa, "so that in the tropics today, there are three fountains blowing air up, and everywhere else air is descending and it is not raining. The model suggests that by 2040 or 2050, there might be a coalescence of these three centers of precipitation in one enormous fountain of rising air somewhere near Indonesia, and drought everywhere else. The implications of this are devastating rainfall and floods in Indonesia, massive drought in Brazil, and destruction of the rainforests there and in Africa. What we'd be doing," he says, "is causing a climate disaster in the poorest countries in the world."

McElroy is describing what are sometimes called "climate switches," like the El Niño phenomenon. "There are currently two modes of wind and ocean interaction in the tropical Pacific," he explains. In one, trade winds blowing from the southeast and the northeast drive warm surface water across the Pacific and pile it up in Indonesia, so that the ocean's surface is actually several meters higher there than it is along the coast of South America. This exposes the cold, nutrient-rich waters off the coast of Peru, and the fisheries thrive. Once the elevation of the water gets high enough, though, it becomes unstable and collapses. "When that happens, you have a reverse flow of all this warm water back across the Pacific where it piles up against the coast of the Americas." The cycle repeats itself periodically like a pendulum. "When El Niño begins," McElroy says, "the warm water returning to the coast of South America caps off the colder water, nutrients don't get to the surface, the fish die, and it rains cats and dogs in Peru." Brazil and Indonesia suffer a drought.

What McElroy thinks is happening—and what the Hadley model also suggests—is that as the earth warms, "we are slowly increasing the amount of warm water that is stored in the surface levels of the Pacific Ocean, and could reach a point where the cold water is never exposed. Once you get to the point where you have enough warm water, then that's it," says McElroy: "a permanent El Niño. This is a serious issue that could give you a globally significant climate change in a matter of years."

Michael B. McElroy directs Harvard's Center for the Environment. An atmospheric scientist, he is concerned about the possibility of sudden, major disruptions to the global climate system.

Some evidence suggests this change is underway. One of McElroy's colleagues, professor of earth and planetary sciences Daniel P. Schrag, a geochemist, has developed ways of assessing the history of temperature in the Pacific Ocean by using the isotopic composition of coral as a proxy. "His analysis suggests there may be a real change in the last 25 years," says McElroy, who calls the work "incredibly important. If you can show that the rhythm of climate really is statistically different now, that is a big deal." Schrag's data show that the cold and warm periods regulated by El Niño were more evenly distributed in the past, whereas the last 25 years have brought more frequent warm spells.

An equally important regulator of climate is the North Atlantic circulation, sometimes referred to as "the global conveyor belt." In both the Northern and Southern hemispheres, westerly winds that carry Pacific Ocean moisture east are largely stripped of their

Photograph by Jim Harrison

water content before they reach the Atlantic by the line of mountains—the Rockies and the Andes—that runs from north to south along the continents. But near the equator, where trade winds blow in the opposite direction, from east to west, there is no barrier near the Panamanian isthmus, so winds there transfer moisture from the Atlantic to the Pacific. Likewise, westerly winds blowing from the Atlantic across the Eurasian continent encounter no particular barrier before reaching the Pacific. This net loss of fresh water makes the surface waters of the North Atlantic among the most saline in the world. Saltier water has a lower freezing point, so as it cools and reaches high density inside the Arctic Circle, some of it sinks, descending to the ocean floor and flowing south through the Atlantic at great depths to supply the oceans of the world. This sinking column of water draws the warm Gulf Stream north along the coast of Western Europe where it greatly tempers the climate all the way up into Northern Scandinavia, well inside the Arctic circle.

McElroy worries about what would happen if higher temperatures melt the land-based ice in Greenland. "You might add enough fresh water to the North Atlantic to remove the salinity contrast, in which case deep water will stop forming and the Gulf Stream might go straight across the Atlantic. It is much more complicated," he says, "than just talking about global temperature changes." The IPCC assigns a low probability to disruption of the North Atlantic circulation in this century, but an increasing probability after 2100.

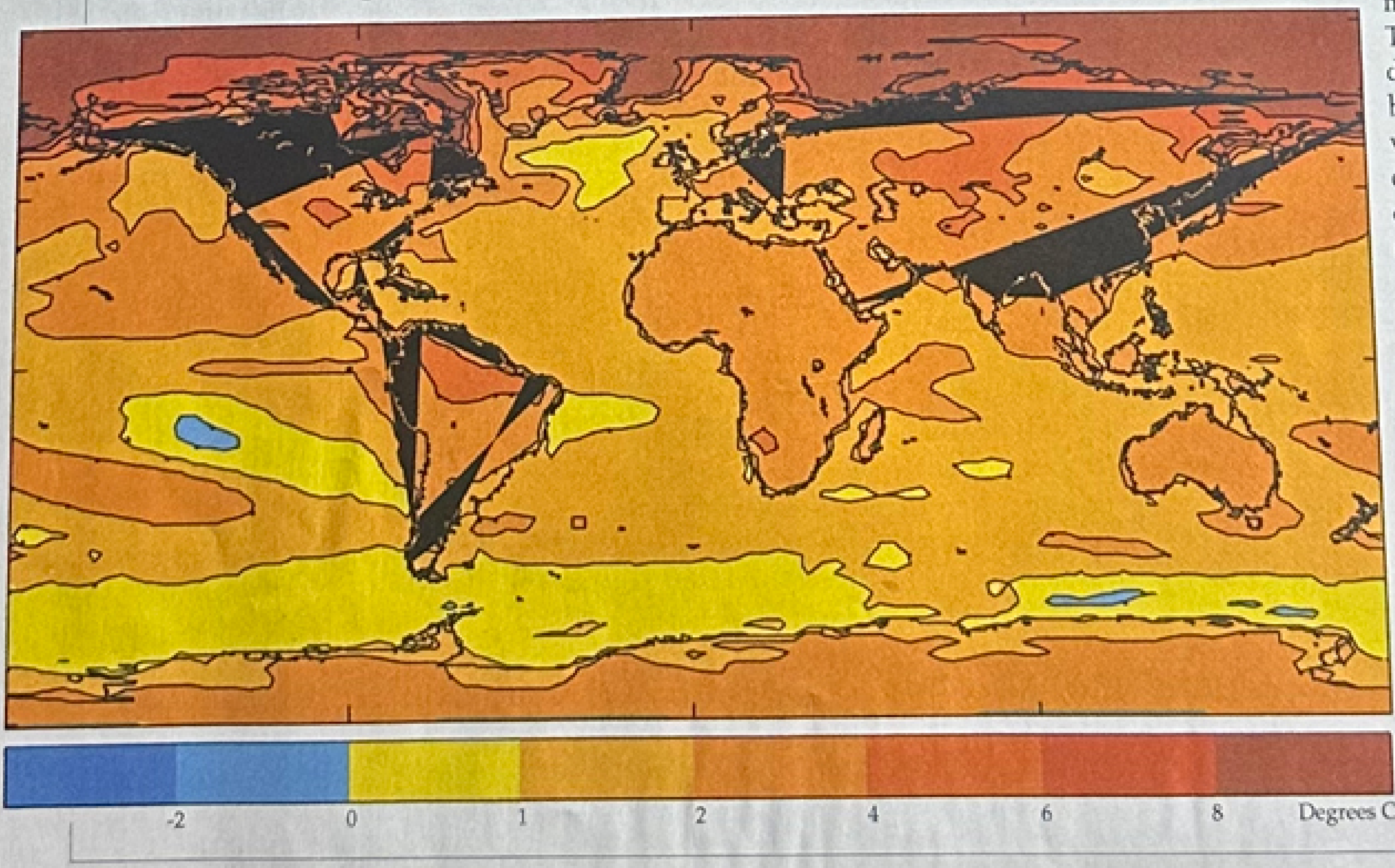
The Human Variable

How credible are these scenarios? One criticism of climate-change science is that its predictions seem so uncertain. The IPCC has created 35 different scenarios for changes in CO_2 emissions and the ensuing atmospheric concentrations over the next century, with a consequent rise in temperature ranging from 2.5 to 10.5 degrees Fahrenheit. One scenario assumes very rapid economic growth, a global population that peaks in mid-century and then declines, rapid introduction of new and more efficient technologies, and a convergence of developing- and developed-world standards of living. On this particular set of assumptions, there are three variant futures: one that is fossil-fuel intensive, a second that assumes a future emphasis on non-fossil-fuel energy sources, and a third that uses a balance among many sources of energy. "These last three variants represent the biggest uncertainty," says McCarthy. "What are we and our descendants going to do?" It is the future actions of humanity that will have the greatest impact on CO_2 concentrations and temperatures. Humans, rather than climate, are the biggest variable, the factor that introduces the biggest uncertainty into the models.

Assuming that humanity makes at least some attempt to rein in its use of fossil fuels, the IPCC forecasts that temperatures will rise in the northeastern United States on the order of 6 or 7 degrees over the coming century. The change will be greatest at night, and in the winter, McCarthy says, as lows fail to dip as low as they once did. Already, winters are warming more than summers, and nights are warming more than days. McCarthy calls these changes "the fingerprints of anthropogenic climate change." They are the result of the increased insulation in the atmosphere caused by greenhouse gases.

The consequences for nature seem profound. Because the rate of temperature increase is projected to be 2 to 10 times that of the last century, some species will be stressed or displaced beyond their limits for survival, the IPCC has concluded. Species unique to the Arctic and to heat-sensitive coral reefs—the tropical forests of the ocean world—are especially vulnerable.

For humanity, presumably a more adaptable species, one of the most startling conclusions of the IPCC report is that no proposed mitigation strategy will preclude some harm to natural and socioeconomic systems from the climate change already underway, so adaptation is not an option—it is inevitable. We can diminish the vulnerability of lives, livelihoods, and properties to anticipated climate change by planned adaptation, like changing agricultural practices and improving public health capabilities. But adaptive capacity is highly dependent upon the state of a nation's socioeconomic development. This country's highly developed food-distribution system, great wealth, and diversity of climate zones will confer relative advantages in adapting its agriculture. But because of extreme events—which are never included in economists' projec-



An unconventional prediction suggests significant warming and drying in the equatorial tropics as early as the 2050s. Brazil's rainforest could dry out and disappear. Source: Hadley Centre for Climate Prediction and Research.

tions of food production, says McCarthy—"the idea that climate change is going to be a win for some and a lose for others, rather than a lose for everybody, is very, very naive."

To the scientists who work with climate models, the risks of loss and the pressures to adapt point to action now, in spite of uncertainty. Of course, there are skeptics who question projections like the Hadley center's model of devastating drought and rainfall in the tropics by 2050, or who discount unusual events as part of natural variability. "It is fine to be skeptical," says McElroy. "But give me a sense of the probability that this particular, reasonable model is wrong. If there is just a 10 percent chance that the model is right, could we risk condemning people to disaster? The precautionary principle that operates here says that unless you are sure that you are not causing a serious problem, don't do it, or at least moderate your behavior."

McElroy's frustration with widespread American apathy is evident. "Shouldn't we react to the fact that we had an incredibly hot summer here in New England?" he asks. "Shouldn't we react to the fact that, for the last several years, the western part of the United States has been up in flames? Shouldn't people react to the fact that we had one of the warmest winters on record last year, and that Central Europe was devastated with unprecedented floods this summer? Is that a smoking gun?" he continues. "If somebody wants to be really skeptical, play roulette, and say we just happen to have spun a thirty-third consecutive red, I can accept that. And I will answer, given the evidence for the likelihood of significant changes in the rhythm of the climate system, that this is not untypical of what you might expect to see. So these events should add to your sense of unease."

"In the next few decades, when we go to atmospheric concentrations of CO_2 above 700 ppm," warns McElroy, "we will be going to a place where we have not been for perhaps the last 30 or 40 or 50 million years. This is a uniquely important disturbance of the carbon cycle."

Problems with the Protocol

THE KYOTO PROTOCOL is to date the only international agreement that calls for action to reduce emissions of CO_2. Yet the Harvard scientists and economists who study climate change express almost universal criticism of the accord, which they fault as economically inefficient, unobjective, inequitable, and—worst of all—ineffective. And they point out that the protocol fails to include the largest future sources of CO_2 emissions. China, for example, will pass the U.S. in annual emissions of CO_2 by 2013, according to Boas professor of international economics Richard N. Cooper. Another projection suggests that, by 2050, China's cumulative contributions of CO_2 to the atmosphere will exceed those of the United States.

The original agreement outlined in Kyoto committed individual countries to reduce their CO_2 emissions to below-1990 levels. But the choice of 1990 immediately introduced inequities into the ensuing political process to determine who should cut how much, says Butler professor of environmental science Michael B. McElroy. That particular date "gave the Europeans a massive advantage relative to other countries," he says, because "reunification of Germany led to the elimination (for economic reasons) of a lot of dirty, polluting industry in what was formerly East Germany." Similarly, in the United Kingdom, the discovery of natural gas in the North Sea facilitated Margaret Thatcher's phase-out of the coal industry, which had been a major source of fuel." That meant the European Union could apportion emissions not needed by Britain and Germany to big polluters (awarding large net increases in some cases), thereby obtaining flexibility that no individual country had. The United States, of course, had in the meantime experienced unprecedented economic growth.

By selecting a timescale that was almost immediate—a completion date of 2008—the Kyoto Protocol mandated economically inefficient measures to achieve its targets. "The economic lifetime of a power plant is maybe 30 years," says McElroy, "and the average automobile in the U.S. is on the road for 11 and a half or 12 years. If you try to change the energy economy too quickly, you are going to have to retire equipment that is still economically productive."

The protocol's target completion dates also effectively precluded the participation of developing countries that had experienced great economic growth, such as India and China. Cooper calls this a major flaw.

There are other problems with the agreement. Steven C. Wofsy, Rotch professor of atmospheric and environmental science, notes that it gives credit for planting forests to sequester carbon, but in a way that provides economic incentives to destroy wetlands, with concomitant releases of CO_2 in excess of what a forest might sequester. Cooper says that the protocol doesn't address the true problem, which is not emissions per se, but atmospheric concentrations of CO_2. The Kyoto Protocol doesn't even set a long-term goal for atmospheric concentrations of CO_2, so there is no objective reason for either the overall reductions or the particular reductions by individual nations that it proposes.

"The Kyoto Protocol may come into force even without U.S. participation," says Pratt professor of business and government Robert N. Stavins, "but the effects on climate change will be virtually nonexistent." (He calculates 2 to 3 percent emission reductions by 2050, well within the margin of error—and trivial compared to carbon sequestration by the marine and terrestrial biosphere.) "The scientific and economic consensus," he says, "points to the need for a credible mitigation strategy."

A (Scientific) Bias for Action

SO FAR, AMERICAN POLICYMAKERS don't seem to be listening to McElroy or his colleagues. It is as if the scientists and the policymakers speak a different language, and operate on a different clock. Perhaps nonscientists don't understand the nuanced differences of opinion over climate change that exist even among scientists.

Wofsy, for example, says that adding greenhouse gases to the atmosphere will indisputably warm the climate eventually, but that we can't know how much or how long it will take. He believes that anthropogenic forcing is likely to have played a significant role, but is not certain there is no other explanation. "The scientific paradigm that you learned here at Harvard or in high school is that you make a hypothesis and then do an experiment to test it," says Wofsy. "Imagine lining up 10 identical Earths and, because there is a lot of fluctuation, subjecting seven of them to greenhouse gases and leaving three as controls. I don't think we're going to be able to do that experi- *(please turn to page 87)*