



John Carey is a freelance writer and former senior correspondent for *BusinessWeek*, where he covered science, technology, medicine and the environment.

ENVIRONMENT

GLOBAL WARMING:

Faster Than Expected?

Loss of ice, melting of permafrost and other climate effects are occurring at an alarming pace

By John Carey

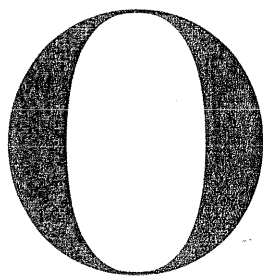
IN BRIEF

Scientists thought that if planetary warming could be kept below two degrees Celsius, perils such as catastrophic sea-level rise could be avoided.

Ongoing data, however, indicate that three global feedback mechanisms may be pushing the earth into a period of rapid climate change even before the two de-

gree C "limit" is reached: meltwater altering ocean circulation; melting permafrost releasing carbon dioxide and methane; and ice disappearing worldwide.

The feedbacks could accelerate warming, alter weather by changing the jet stream, magnify insect infestations and spawn more and larger wildfires.



VER THE PAST DECADE SCIENTISTS THOUGHT THEY HAD FIGURED OUT HOW TO PROTECT humanity from the worst dangers of climate change. Keeping planetary warming below two degrees Celsius (3.6 degrees Fahrenheit) would, it was thought, avoid such perils as catastrophic sea-level rise and searing droughts. Staying below two degrees C would require limiting the level of heat-trapping carbon dioxide in the atmosphere to 450 parts per million (ppm), up from today's 395 ppm and the preindustrial era's 280 ppm.

Now it appears that the assessment was too optimistic. The latest data from across the globe show that the planet is changing faster than expected. More sea ice around the Arctic Ocean is disappearing than had been forecast. Regions of permafrost across Alaska and Siberia are spewing out more methane, the potent greenhouse gas, than models had predicted. Ice shelves in West Antarctica are breaking up more quickly than once thought possible, and the glaciers they held back on adjacent land are sliding faster into the sea. Extreme weather events, such as floods and the heat wave that gripped much of the U.S. in the summer of 2012 are on the rise, too. The conclusion? "As scientists, we cannot say that if we stay below two degrees of warming everything will be fine," says Stefan Rahmstorf, a professor of physics of the oceans at the University of Potsdam in Germany.

The X factors that may be pushing the earth into an era of rapid climate change are long-hypothesized feedback loops that may be starting to kick in. Less sea ice, for example, allows the sun to warm the ocean water more, which melts even more sea ice. Greater permafrost melting puts more CO₂ and methane into the atmosphere, which in turn causes further permafrost melting, and so on.

The potential for faster feedbacks has turned some scientists into vocal Cassandras. Those experts are saying that even if nations do suddenly get serious about reducing greenhouse gas emissions enough to stay under the 450-ppm limit, which seems increasingly unlikely, that could be too little, too late. Unless the world slashes CO₂ levels back to 350 ppm, "we will have started a process that is out of humanity's control," warns James E. Hansen, director of the NASA Goddard Institute for

Space Studies. Sea levels might climb as much as five meters this century, he says. That would submerge coastal cities from Miami to Bangkok. Meanwhile increased heat and drought could bring massive famines. "The consequences are almost unthinkable," Hansen continues. We could be on the verge of a rapid, irreversible leap to a much warmer world.

Alarmist? Some scientists say yes. "I don't think that in the near term, catastrophic climate change is in the cards," says Ed Dlugokencky of NOAA, based on his assessment of methane levels. Glaciologist W. Tad Pfeffer of the University of Colorado at Boulder has examined ice loss around the planet and concludes that the maximum conceivable ocean rise this century is less than two meters, not five. Yet he shares Hansen's sense of urgency because even smaller changes can threaten a civilization that has known nothing but a remarkably stable climate. "The public and policy makers should understand how serious a sea-level rise of even 60 to 70 centimeters would be," Pfeffer warns. "These creeping disasters could really wipe us out."

Although scientists may not agree on the pace of climate change, the realization that specific feedback loops may be amplifying the change is causing a profound unease about the planet's future. "We have to start thinking more about the known unknowns and the unknown unknowns," explains Eelco Rohling, a professor of ocean and climate change at the University of Southampton in England. "We might not know exactly what all possible feedbacks are, but past changes demonstrate that they exist." By the time researchers do pin down the unknowns, it may be too late, worries Martin Manning, an atmospheric scientist at Victoria University of Wellington in New Zealand and a key player in the 2007 round of the Intergovern-

mental Panel on Climate Change (IPCC) reports: "The rate of change this century will be such that we can't wait for the science."

HOT PAST SUGGESTS HOT FUTURE

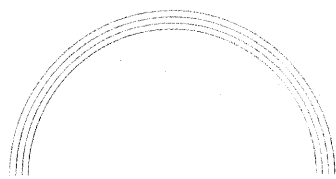
ONE BIG REASON scientists are becoming increasingly concerned about rapid climate change is improved understanding of our distant past. In the 1980s they were stunned to learn from the record written in ice cores that the planet had repeatedly experienced sudden and dramatic swings in temperature. Since then, they have put together a detailed picture of the past 800,000 years. As Hansen describes in a new analysis, there are remarkably tight correlations among temperature, CO₂ levels and sea levels: they all rise and fall together, almost in lockstep. The correlations do not prove that greenhouse gases caused the warming. New research by Jeremy Shakun of Harvard University and his colleagues, however, points in that direction, showing that the CO₂ jump preceded the temperature jump at the end of the last ice age. They conclude in a recent *Nature* paper that "warming driven by increasing CO₂ concentrations is an explanation for much of the temperature change." (*Scientific American* is part of Nature Publishing Group.)

Some changes in the past were incredibly rapid. Work on Red Sea sediments by Rohling shows that during the last warm period between ice ages—about 125,000 years ago—sea levels rose and fell by up to two meters within 100 years. "That's ridiculously fast," Rohling says. His analysis indicates that sea levels appear to have been more than six meters higher than they are today—in a climate much like our own. "That doesn't tell you what the future holds, but man, it gets your attention," says Richard Alley, a professor of geosciences at Pennsylvania State University.

Also surprising is how little extra energy, or "forcing," was required to trigger past swings. For instance, 55 million years ago the Arctic was a subtropical paradise, with a balmy average temperature of 23 degrees C (73 degrees F) and crocodiles lurking off Greenland. The tropics may have been too hot for most life. This warm period, dubbed the Paleocene-Eocene Thermal Maximum (PETM), apparently was sparked by a preceding bump of about two degrees C in the planet's temperature, which was already warmer than today. That warming may have caused a rapid release of methane and carbon dioxide, which led to more warming and more emissions of greenhouse gases, amplifying further warming. The eventual result: millions of years of a hothouse earth [see "The Last Great Global Warming," by Lee R. Kump; *SCIENTIFIC AMERICAN*, July 2011].

In the past 100 years humans have caused a warming blip of more than 0.8 degree C (1.4 degree F). And we are pouring greenhouse gases into the atmosphere 10 times faster than what occurred in the run-up to the PETM, giving the climate a mighty push. "If we spend the next 100 years burning carbon, we are going to take the same kind of leap," says Matthew Huber, a professor of earth and atmospheric sciences at Purdue University.

We are also shoving the climate harder than the known



**The feedback
scientists fear
most is loss of
ice, uncovering
darker land
and seas that
absorb solar
heat, melting
even more ice,
amplifying
global warming.**

causes of various ice ages did. As Serbian astronomer Milutin Milanković noted nearly 100 years ago, the waxing and waning of ice ages can be linked to small variations in the orbit and tilt of the earth. Over tens of thousands of years the earth's orbit changes shape, from nearly circular to mildly eccentric, because of varying pulls from other planets. These variations alter the solar energy hitting the planet's surface by an average of about 0.25 watt per square meter, Hansen says. That amount is pretty small. To cause the observed swings in climate, this forcing must have been amplified by feedbacks such as changes in sea ice and greenhouse gas emissions. In past warmings, "feedback just follows feedback, follows feedback," says Euan Nisbet, a professor of earth sciences at the Royal Holloway, University of London.

The climate forcing from human emissions of greenhouse gases is much higher—three watts per square meter and climbing. Will the climate thus leap 12 times faster? Not necessarily. "We can't relate the response from the past to the future," Rohling explains. "What we learn are the mechanisms that are in play, how they are triggered and how bad they can get."

TROUBLING FEEDBACKS

THE MOST RAPID of these feedback mechanisms, scientists have figured out, involves ocean currents that carry heat around the globe. If a massive amount of freshwater is dumped into the northern seas—from say, collapsing glaciers or increased precipitation—warm currents can slow or stop, disrupting the engine that drives global ocean currents. That change could turn Greenland from cool to warm within a decade. "Greenland ice-core records show that shifts can occur very, very quickly, even in 10 years," says Pieter Tans, a senior scientist at the NOAA Earth System Research Laboratory.

When the freshwater mechanism became clear by the early 2000s, "a lot of us were really nervous," Alley recalls. Yet more detailed modeling showed that although "adding freshwater is a scary thing, we're not adding it nearly fast enough" to fundamentally alter the planet's climate, he says.

A more immediately worrisome feedback that is beginning to bubble up—literally—involves permafrost. Scientists once thought that organic matter in the tundra extended only a meter deep into the frozen soil—and that it would take a long time for warming to start melting substantial amounts of it deep down. That assessment was wrong, according to new research. "Pretty much everything we've documented has been a surprise," says biologist Ted Schuur of the University of Florida.

The first surprise was that organic carbon exists up to three meters deep—so there is more of it. Plus, Siberia is dotted with giant hills of organic-rich permafrost called yedoma, formed by windblown material from China and Mongolia. Those carbon stores add up to hundreds of billions of metric tons—"roughly double the amount in the atmosphere now," Schuur says. Or as methane hunter Joe von Fischer of Colorado State University

puts it: "That carbon is one of the ticking time bombs." More thawing allows more microbes to dine on the organic carbon and turn it into CO₂ and methane, raising temperatures and prompting more thawing.

The ticking may be speeding up. Meltwater on the permafrost surface often forms shallow lakes. Katey Walter Anthony of the University of Alaska Fairbanks has found methane bubbling up from the lake bottoms. Many researchers have also found that permafrost can crack open into mini canyons called thermokarsts, which expose much greater surface area to the air, speeding melting and the release of greenhouse gases. And recent expeditions off Spitsbergen, Norway, and Siberia have detected plumes of methane rising from the ocean floor in shallow waters.

If you extrapolate from these burps of gas to wider regions, the numbers can get big enough to jolt the climate. Yet global measurements of methane do not necessarily show a recent increase. One reason is that hotspots "are still pretty local," says the University of Alaska Fairbanks's Vladimir E. Romanovsky, who charts permafrost temperatures. Another may be that scientists have just gotten better at finding hotspots that have always existed. That is why Dlugokencky says, "I am not concerned about a rapid climate change brought about by a change in methane."

Others are not so sure, especially because there is another potentially major source of methane—tropical wetlands. If rainfall increases in the tropics, which is likely as the atmosphere warms, the wetlands will expand and become more productive, creating more anaerobic decomposition that produces methane. Expanded wetlands could release as much, or more, additional methane as that from Arctic warming. How worried should we be? "We don't know, but we'd better keep looking," Nisbet says.

THE ICE EFFECT

THE FEEDBACK that scares many climate scientists the most is a planetary loss of ice. The dramatic shrinking of sea ice in the Arctic Ocean in recent summers, for instance, was not predicted by many climate models. "It is the big failure in modeling," Nisbet says. Ice on Greenland and along Antarctica is disappearing, too.

To figure out what is going on, scientists have been charting glaciers in Greenland by satellite and ground measurement and have been sending probes under the Antarctic ice shelves, "seeing things never seen before," says Jerry Meehl, a senior scientist at the National Center for Atmospheric Research.

On Greenland, glaciologist Sarah Das of the Woods Hole Oceanographic Institution watched as a lake of meltwater suddenly drained through a crack in the 900-meter-thick (3,000-foot-thick) ice. The torrent was powerful enough to lift the massive glacier off the underlying bedrock and increase the speed at which it was sliding into the ocean. In Alaska, Pfeffer has data showing that the huge Columbia Glacier's slide into the sea has accelerated from one meter a day to 15 to 20 meters a day.

In Antarctica and Greenland, large ice shelves that float on ocean water along the coast are collapsing—a wake-up call about how unstable they are. Warmer ocean waters are eating away at the ice shelves from below while warmer air is opening cracks from above. The ice shelves act as buttresses, holding back ice that is grounded on the ocean bottom and adjacent glaciers on land from slinking into the sea under gravity's relentless pull. Although the loss of floating ice does not raise sea levels, the submerging glaciers do. "We're now working hard to find out whether sea-



RAPID CHANGE: Feedback mechanisms could be speeding up global warming: thawing permafrost, like that in central Iceland (*left*); retreating glaciers such as Trift in the Swiss Alps (*center*), which has receded three kilometers; and melting ice that spills into the sea, seen in Spitsbergen, Norway (*right*).

level rise could be remarkably faster than expected," Alley says.

Ice loss is feared not just because of sea-level rise but also because it kicks off a powerful feedback mechanism. Ice reflects sunlight back to space. Take it away, and the much darker land and seas absorb more solar heat, melting more ice. This change in the albedo (reflectivity) of the earth's surface can explain how small forcings in the paleoclimate record could be amplified, Hansen says, "and the same will occur today."

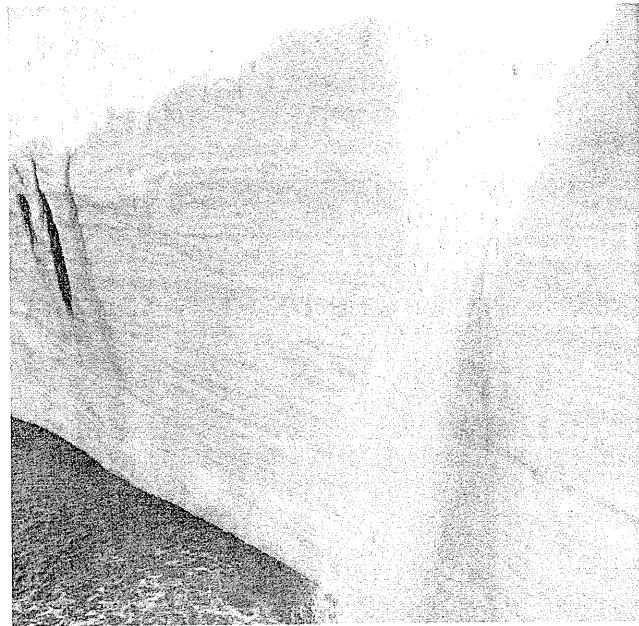
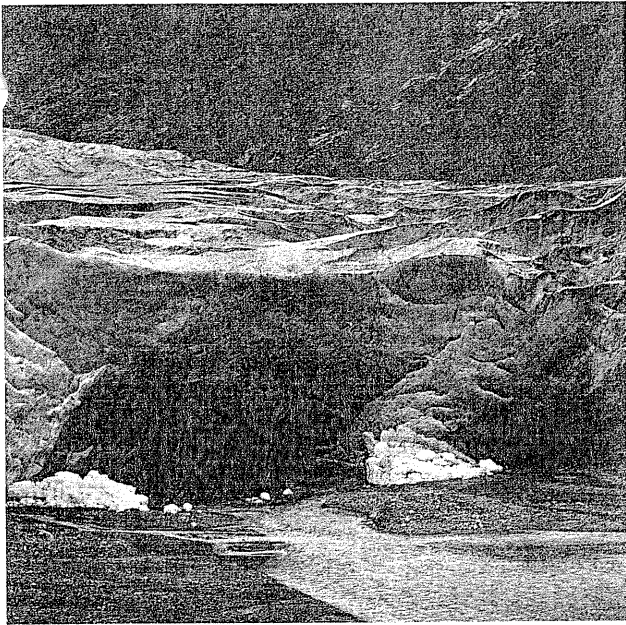
So far only a few scientists are willing to go as far as Hansen in predicting that the oceans could rise by as much as five meters by 2100. "But we don't really know," Alley says. "I'm still guessing that the odds are in my favor [in expecting a smaller rise], but I would hate for anyone to buy coastal property based on anything I said."

FOREST FOR THE TREES

THE FLUCTUATIONS in the earth's past climate make it clear that feedbacks will dramatically transform the planet now if we push hard enough. "If we burn all the carbon we have access to, we're pretty much guaranteed of having a PETM-like warming," Huber says. Good for Arctic crocodiles, perhaps, but not for humans or most ecosystems.

Yet what really keeps scientists up at night is the possibility that even if these particular feedbacks do not bring near-term threats to humanity, they could drive other mechanisms that do. A prime candidate is the planet's water, or hydrological, cycle. Each year brings additional evidence that climate change is causing more extreme weather events such as floods and droughts while fundamentally altering regional climates.

A recent analysis by Rahmstorf shows that heat waves like the one that devastated Russia in 2010 are five times more likely because of the warming that has already occurred—"a massive



factor," he says. And new work pins the record-breaking warm 2011–2012 U.S. winter (and record-breaking cold spell in Europe that same season) on the loss of Arctic sea ice. One suggested mechanism: with less sea ice, more Arctic water warms. The ocean releases that extensive heat in the autumn, altering pressure gradients in the atmosphere, which creates bigger bends in the jet stream that can get stuck in place for longer periods. Those bends can bask the U.S. Northeast in winter warmth while locking eastern Europe in a deep freeze.

Making this story even more complex is the potential for ecological feedbacks. Warmer temperatures in the western U.S. and Canada, for instance, have helped unleash an epidemic of mountain pine beetles. The insects have killed hundreds of thousands of hectares of trees, threatening to turn forests from carbon sinks (healthy trees absorbing CO₂) into carbon sources (dead trees decomposing). A hot spell in 2007 set the stage for the first fire on the North Slope's tundra in 7,000 years, accelerating permafrost melting and its carbon emissions in that area. Warming in Siberia is starting to transform vast forests of larches into spruce and fir woodlands. Larches drop their needlelike leaves in winter, thereby allowing the sun's heat to reflect off the snow cover and return to space. Spruces and firs keep their needles, absorbing the solar heat before it can reach the snow, explains ecologist Hank Shugart of the University of Virginia. Feedbacks from vegetation changes alone could give the planet a 1.5 degree C kick, he estimates: "We're playing with a loaded gun here."

Nisbet's own "nightmare scenario" starts with a blip in methane emissions and a very warm summer that leads to massive fires, pouring carbon into the atmosphere. The smoke and smog blanket Central Asia and weaken the monsoons, causing widespread crop failures in China and India. Meanwhile a large El Niño pattern of unusually warm water in the tropical Pacific brings drought to the Amazon and Indonesia. The tropical forests and peatlands also catch fire, injecting even more CO₂ into the atmosphere and putting the climate on the fast track to rapid warming. "It's a feasible scenario," Nisbet

observes. "We may be more fragile than we think we are."

But just how powerful could the various feedback loops become? Climate models, which are good at explaining the past and present, stumble when it comes to predicting the future. "People can conceptualize these abrupt changes better than the models do," Schuur says. Even if the planet is in a tipping point now, he adds, we may not recognize it.

The unsettling conclusion for climate policy is that science does not have definitive answers. "We know the direction but not the rate," Manning says. Yet the uncertainties do not justify inaction, scientists insist. On the contrary, the uncertainties bolster the case for an immediate worldwide effort to reduce greenhouse gas emissions because they reveal how substantial the risks of rapid change really are. "What we're doing at the moment is an experiment comparable on a geological scale to the big events of the past, so we would expect the inputs to have consequences similar to those in the past," Nisbet says.

That is why Hansen cannot look at his grandchildren and not become an activist on their behalf. "It would be immoral," he says, "to leave these young people with a climate system spiraling out of control." ■

MORE TO EXPLORE

Abrupt Climate Change. U.S. Climate Change Science Program and the Subcommittee on Global Change Research. U.S. Geological Survey, December 2008. <http://downloads.climate-science.gov/sap/sap3-4/sap3-4-final-report-all.pdf>

Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2012. http://ipcc-wg2.gov/SREX/images/uploads/SREX-All_FINAL.pdf

Paleoclimate Implications for Human-Made Climate Change. James E. Hansen and Makiko Sato in *Climate Change: Inferences from Paleoclimate and Regional Aspects*. Edited by André Berger et al. Springer, 2012.

Video by Katey Walter Anthony of the University of Alaska Fairbanks of methane—from melting permafrost—catching fire: www.youtube.com/watch?v=YegdEOSQotE

For a slide show of images showing climate feedbacks and the ecological feedback mechanisms they can cause, visit ScientificAmerican.com/nov2012/climate-change