NEWS

Ocean Acidification Unprecedented, Unsettling

Humans are caught up in a grand planetary experiment of lowering the ocean's pH, with a potentially devastating toll on marine life

ASIDE FROM THE DINOSAUR-KILLING asteroid impact, the world has probably never seen the likes of what's brewing in today's oceans. By spewing carbon dioxide from smokestacks and tailpipes at a gigatons-per-year pace, humans are conducting a grand geophysical experiment, not just on climate but on the oceans as well.

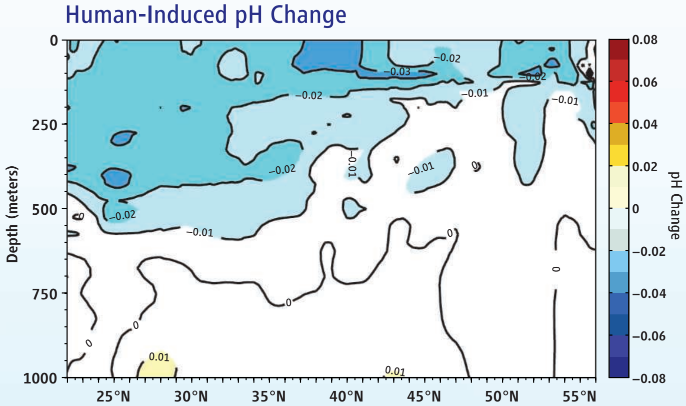
Over the past 4 years, there's been a crescendo of concern that the ocean experiment may be scarier than its climate counterpart (http://news.sciencemag.org/sciencenow/2006/07/05-01.html). Now the geochemists are weighing in, and they are not mincing words: The physics and chemistry of adding an acid to the ocean are so well understood, so inexorable, that there cannot be an iota of doubt—gigatons of acid are lowering the pH of the world ocean, humans are totally responsible, and the more carbon dioxide we emit, the worse it's going to get. Unconstrained emissions growth is likely to leave the current era of human planetary dominance "as one of the most notable, if not cataclysmic, events in the history of our planet," geochemist Lee Kump of Pennsylvania State University, University Park, and colleagues wrote last December in a special issue of *Oceanography*. The geochemical disruption will reverberate for tens of thousands of years.

It's less clear how marine life will fare. "We can detect these changes [in ocean acidity], but we still don't have a good idea of how ecosystems would change," says marine biologist Victoria Fabry of California State University, San Marcos. With nothing in the geologic record as severe as the ongoing plunge in ocean pH, paleontologists can't say for sure how organisms that build carbonate shells or skeletons will react. In the laboratory, corals always do poorly. The lab responses of other organisms are mixed (http://news.sciencemag.org/sciencenow/2009/12/01-01.html). In the field, researchers see signs that coral growth does slow, oyster larvae suffer, and plankton with calcareous skeletons lose mass. There are enough alarming signs that global oceanic acidification "is an experiment we would not choose to do," says Fabry.

Nothing like it

Strictly speaking, the ocean, now at a pH of 8.1, will not turn into an acid, as its pH will not drop below 7.0. But on dissolving into the ocean, carbon dioxide instantly forms bicarbonate ions (HCO_3^-) and hydrogen ions—the H^+ of pH. The "acidification" resulting from the current carbon dioxide emissions is massive and rapid, a combination that is "almost certainly unprecedented in Earth history," says earth systems modeler Andrew Ridgwell of the University of Bristol, United Kingdom.

The closest analog in the geologic record to the present acidification appears to be the Paleocene-Eocene Thermal Maximum (PETM) 55.8 million years ago. At its start, anywhere from 2000 to 7000 gigatons of carbon were released as methane and carbon dioxide, the methane quickly oxidizing to carbon dioxide. Where it all came from—volcanoes, icy sea-floor methane hydrates, marshy peat, or a combination—no one is sure, but almost all of it would eventually have gone into the ocean. PETM's carbon gush was on a par with what burning the 2180 gigatons of carbon in the world's fossil fuel reserves would produce, notes Kump and his colleagues.



Blue, blue, blue. Measurements to 1000 meters deep across the North Pacific revealed that in 15 years carbon dioxide emissions drove down pH (blues) in all surface waters and as deeply as 550 meters.

The difference this time around is speed. Today, "you could argue the rate of release is 10 times faster [than at the PETM], if not faster," says paleoceanographer James Zachos of the University of California, Santa Cruz. Whereas nature took a few thousand years to spout out thousands of gigatons of carbon, he notes, humans could be doing it in a few centuries.

And speed makes a big difference. It takes the ocean about 1000 years to flush carbon dioxide added to surface waters into the deep sea where sediments can eventu-

First victims? Corals appear to be particularly vulnerable to falling pH caused by rising carbon dioxide.

CREDITS (TOP TO BOTTOM): R. H. BYRNE *ET AL.*, *GEOPHYSICAL RESEARCH LETTERS* 37 © 2010 AMERICAN GEOPHYSICAL UNION; PHOTOS.COM ally neutralize the added acid. The PETM release appears to have been slow enough that no biological catastrophe struck in the upper ocean, only an extinction among tiny shell-forming organisms living on the deep sea floor. But today's emissions are so rapid that they are piling up in surface waters.

And the acid flows

The latest evidence of raging acidification of surface waters comes in the first direct, basinwide observation of plunging pH. Marine chemist Robert Byrne of the University of South Florida in St. Petersburg and colleagues reported 20 January in *Geophysical Research Letters* that the pH of surface waters along a line running 3200 kilometers north from near the island of Hawaii fell between 1991 and 2006 (see figure, p. 1500). The pH decline attributable to human activities over the 15 years was 0.026 pH unit, a drop Byrne calls "startling" in its rapidity. Overall, researchers estimate there has been a 0.1-pH-unit decline for the global ocean since industrialization began a couple of centuries ago. In logarithmic pH units, the change may seem tiny, but in absolute terms, that translates into a 30% increase in surface-ocean acidity.

Now ocean pH is lower than it's been for 20 million years, and it's going to get lower, says marine chemist Richard Feely of the National Oceanic and Atmospheric Administration's (NOAA's) Marine Environmental Laboratory in Seattle, Washington. He and his colleagues have modeled future pH based on what he calls the irrefutable chemistry of acidification. The model assumes a business-as-usual growth in carbon dioxide emissions. As they report in the same *Oceanography* issue, the modeling predicts a drop from a pre-industrial pH of 8.2 to about 7.8 by the end of this century. That would increase the surface ocean's acidity by about 150% on average.

Living with acid

The future of marine life in an acidifying ocean is far less clear than the chemistry of acidification but nonetheless looks bleak for many organisms. Falling pH has two effects on species that build shells or skeletons of calcium carbonate. These organisms include tropical corals, echinoderms, mollusks, microscopic foraminifera floating in surface waters, and certain algae. When the hydrogen ion concentration of seawater gets high enough, the calcium carbonate in these organisms begins to dissolve.

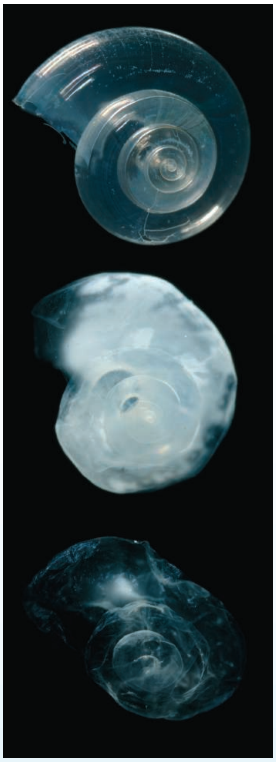
Colder waters with a greater capacity for carbon dioxide will be affected first. Feely's modeling projects that by midcentury, all Arctic waters will corrode the most vulnerable crystal form of calcium carbonate, called aragonite. By the end of the century, all of the Southern Ocean and parts of the North Pacific will be corrosive to sea snails called pteropods and other aragonitic organisms.

The other effect of falling pH is already at work. As hydrogen ion concentrations go up, more and more of the ocean's carbonate ions—the building block of all carbonate shells and skeletons—combine with hydrogen ions to form bicarbonate, driving down the concentration of the essential carbonate. Organisms have a harder time extracting the carbonate they need from the surrounding water.

In a compilation of controlled acidification studies, marine chemist Scott Doney of the Woods Hole Oceanographic Institution in Massachusetts and his colleagues found that all 11 species of tropical coral studied under falling pH slowed their aragonite production. Among noncoral calcifiers, most also slowed their carbonate building, though a few, such as certain coralline red algae and echinoderms, increased it.

So far, field observations tend to support the deleterious effects of falling pH. In the 2 January 2009 issue of *Science* (p. 116), marine scientists Glenn De'ath, Janice Lough, and Katharina Fabricius of the Australian Institute of Marine Science in Townsville reported on their broad survey of coral across the Great Barrier Reef of Australia. Reading the rate of growth recorded in coral skeletons, the group found that calcification across the Great Barrier Reef had declined 14.2% since 1990. And they found no sign that such a "severe and sudden decline" had occurred in the past 400 years. Although the group could not pin down what caused the slower growth, they pointed to a rise in ocean temperatures combined with declining pH.

Planktonic foraminifera also seem to be suffering in this lower pH environment. Paleoceanographer Andrew Moy and his colleagues at the Antarctic Climate and Ecosystems Cooperative Research Centre in Hobart, Australia, found that the shells of one type of foram growing in today's Southern Ocean are 30% lighter than those of the same species from the past few thousand years. In a paper published online 8 March 2009 in *Nature Geoscience*, they point to acidification as the cause because they find a correlation between higher atmospheric carbon dioxide and lower shell weight in a 50,000-year-long Southern Ocean sediment record.



Going, going, … In seawater of the pH that may prevail by the century's end, the shell of a pteropod dissolves in a matter of weeks (*top to bottom*).

Curtailed shell growth may be fatal for some organisms. Water naturally low in pH wells up along the coast of Oregon and sometimes floods into Netarts Bay, from which the Whiskey Creek Shellfish Hatchery in Tillamook draws its water. Alan Barton, now of Bear Creek Shellfish Hatchery in North Carolina; Sue Cudd of Whiskey Creek Shellfish Hatchery in Tillamook, Oregon; and chemical oceanographer Burke Hales of Oregon State University, Corvallis, found a strong correlation between corrosively high concentrations of carbon dioxide in hatchery water and mass mortality of oyster larvae forming their first partially aragonitic shells. "We're getting a window into the future of what the open ocean will be like in 100 years," says Hales.

In April, the National Research Council (NRC) pointed out in a report that getting a clearer view through that window will take more time and money, which governments are starting to spend. For the European Project on Ocean Acidification, a 27-institute research consortium is expanding the monitoring of ongoing acidification and examining biological effects. The 2009 Federal Ocean Acidification Research and Monitoring Act got interagency coordination going in the United States, and $5.5 million in NOAA's fiscal year 2010 budget has boosted research in that agency. But the NRC report also concluded that "development of a National Ocean Acidification Program will be a complex undertaking." They got that right. **–RICHARD A. KERR**

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