

Carbon dioxide emissions are making the oceans more acidic, imperiling the growth and reproduction of species from plankton to squid

BY MARAH J. HARDT AND CARL SAFINA

Threatening Ocean Life



PHOTOGRAPH BY JAMIE CHUNG



from the Inside Out

KEY CONCEPTS

- The pH of seawater worldwide is dropping (acidifying) as oceans absorb ever more carbon dioxide from the atmosphere.
- Experiments show that the struggle by copepods, snails, sea urchins and brittlestars to balance the changing pH inside their bodies impairs their ability to reproduce and grow. Many species are unlikely to genetically adapt to ocean acidification, because the change is occurring too quickly.
 - As species wither, the marine food chain could be disrupted; human action is needed to curtail further acidification.

—The Editors

SLOW SPERM ... now that's a problem," said Jonathan Havenhand, his British accent compounding the gravity of the message. "That means fewer fertilized eggs, fewer babies and smaller populations." We were sharing a hilly cab ride along the glistening northern coast of Spain to attend an international symposium about the effects of climate change and excess atmospheric carbon dioxide on the world's oceans. As researchers, we were concerned about the underappreciated effects of changing ocean chemistry on the cells, tissues and organs of marine species. In laboratory experiments at the University of Gothenburg in Sweden, Havenhand had demonstrated that such changes could seriously impede the most fundamental strategy of survival: sex.

Ocean acidification—a result of too much carbon dioxide reacting with seawater to form carbonic acid—has been dubbed "the other CO₂ problem." As the water becomes more acidic, corals and animals such as clams and mussels have trouble building their skeletons and shells. But even more sinister, the acidity can interfere with basic bodily functions for all marine animals, shelled or not. By disrupting processes as fundamental as growth and reproduction,

ocean acidification threatens the animals' health and even the survival of species. Time is running out to limit acidification before it irreparably harms the food chain on which the world's oceans—and people—depend.

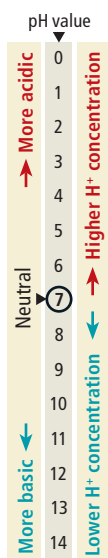
RAPID SEA CHANGE

THE OCEAN'S INTERACTION with CO₂ mitigates some climate effects of the gas. The atmospheric CO₂ concentration is almost 390 parts per million (ppm), but it would be even higher if the oceans didn't soak up 30 million tons of the gas every day. The world's seas have absorbed roughly one third of all CO₂ released by human activities. This "sink" reduces global warming—but at the expense of acidifying the sea. Robert H. Byrne of the University of South Florida has shown that in just the past 15 years, acidity has increased 6 percent in the upper 100 meters of the Pacific Ocean from Hawaii to Alaska. Across the planet, the average pH of the ocean's surface layer has declined 0.12 unit, to approximately 8.1, since the beginning of the industrial revolution.

That change may not sound like much, but because the pH scale is logarithmic, it equates to a 30 percent increase in acidity. Values of pH

pH PRIMER

The pH of a solution is determined by the concentration of hydrogen ions (H⁺) in it. A value of 7.0 is neutral; lower is acidic; higher is basic. "Acidification" means a drop in value, anywhere along the scale.



[BASICS]

ACID IN THE OCEAN

The ocean consists of relatively stable layers created by particular combinations of salinity and temperature (*left*). Sunlight at the top energizes phytoplankton—the base of the food chain—which ultimately nourish all marine life, including copepods that migrate between layers, feeding animals in the deeper water (*center, left*). As CO₂ in the atmosphere rises, though, it increases the acidity of the water (*center, right*)—a phenomenon already being observed (*far right*). Experiments indicate such acidity will harm sea life at various depths.

LAYERS

Atmospheric CO₂ lowers pH in the surface (sunlight) layer directly, and mixing between layers gradually reduces pH farther down, to lesser degrees. Animals in deeper layers are more vulnerable to smaller changes, however.

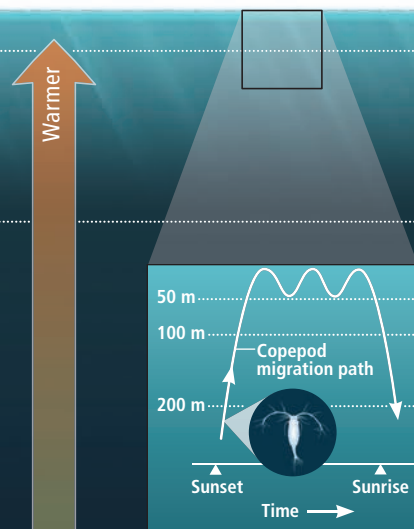
SUNLIGHT ZONE
200 m*

TWILIGHT ZONE
1,000 m

MIDNIGHT ZONE

4,000 m
THE ABYSS

*Depths are approximate and vary worldwide



FOOD CHAIN

Every night a squadron of tiny crustaceans called copepods migrate up and within the surface layer to feed on even tinier zooplankton. They descend by daybreak, serving as food for deeper species. Changing pH could affect their survival, disrupting the food chain.

GEORGE RETSECK (main illustration)

measure hydrogen ions (H^+) in solution. A value of 7.0 is neutral; lower values are increasingly acidic, and higher values are basic. Although 8.1 is mildly basic, the declining trend constitutes acidification. Marine life has not experienced such a rapid shift in millions of years. And paleontology studies show that comparable changes in the past were linked to widespread loss of sea life. It appears that massive volcanic eruptions and methane releases around 250 million years ago may have as much as doubled atmospheric CO_2 , leading to the largest mass extinction ever. More than 90 percent of all marine species vanished. A completely different ocean persisted for four million to five million years, which contained relatively few species.

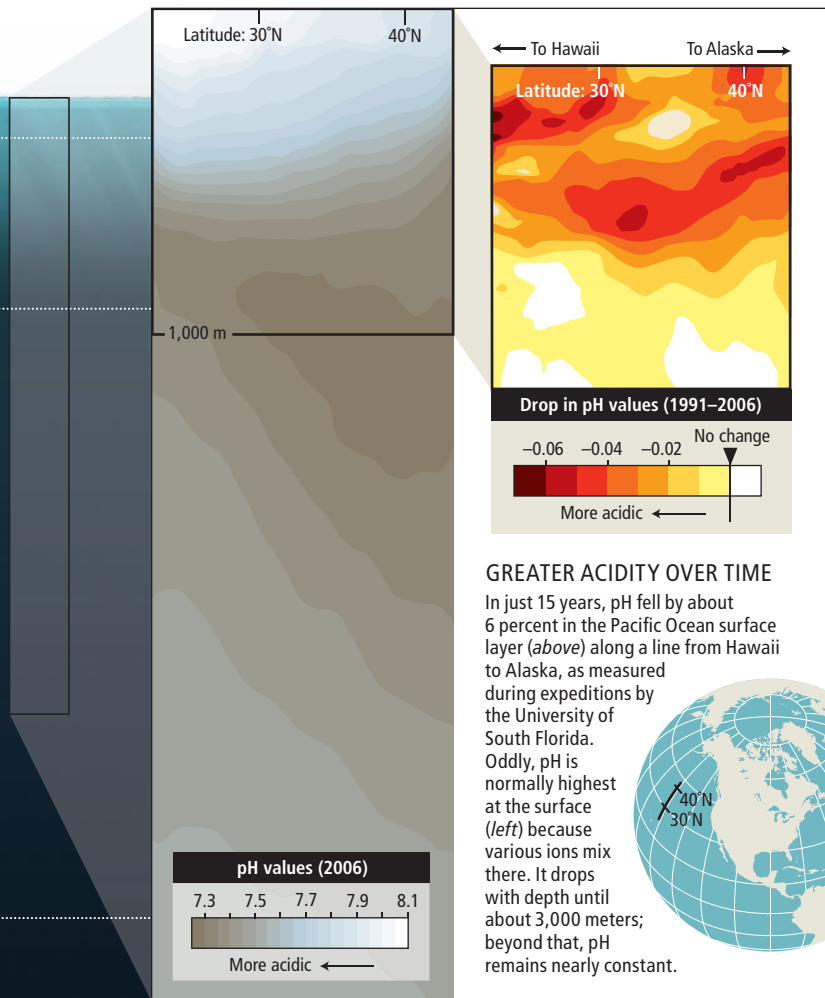
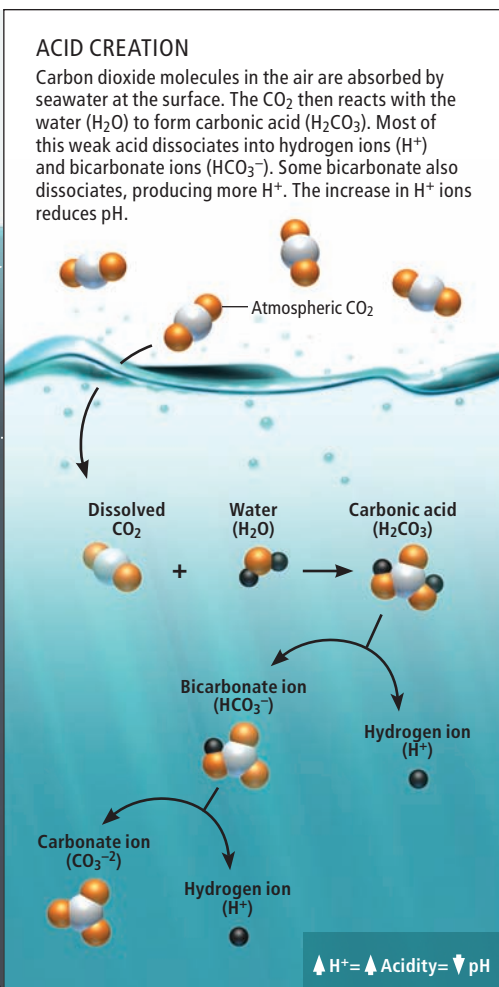
If we continue to emit greenhouse gases at current rates, scientists estimate that atmospheric CO_2 will reach 500 ppm by 2050 and 800 ppm by 2100. The pH of the upper ocean

could drop to 7.8 or 7.7—as much as a 150 percent increase in acidity compared with preindustrial times.

Most people envision the ocean as a giant pool of water. But the ocean is more like a layer cake, with each layer created by unique combinations of salinity and temperature. The warmest and freshest (least salty) floats from the surface down 50 to 200 meters, sometimes deeper. Plentiful oxygen and sunlight support the blooming base of the food chain: single-celled phytoplankton that, like plants, use sunlight to create sugar. The phytoplankton nourish zooplankton—small animals ranging from minuscule shrimplike crustaceans to the larvae of giant fish. Zooplankton are eaten by small fish, which feed bigger animals, and so on.

Winds help to mix the surface and deeper layers, sending oxygen down and bringing nutrients up. But the flux of nutrients between surface and seafloor also occurs through the movement of animals, alive and dead. An extensive class of tiny crustaceans called copepods migrate every night, under the cover of darkness, from middle

Geologic records show that comparable pH changes in the past wiped out almost all sea life.



GREATER ACIDITY OVER TIME

In just 15 years, pH fell by about 6 percent in the Pacific Ocean surface layer (above) along a line from Hawaii to Alaska, as measured during expeditions by the University of South Florida. Oddly, pH is normally highest at the surface (left) because various ions mix there. It drops with depth until about 3,000 meters; beyond that, pH remains nearly constant.

Emissions targets should limit pH declines to no more than 0.1 over the next century, given the consequences.

and even deep layers to the surface to dine on the banquet created by the day's rays. Many fish and squid follow their movements, while deep dwellers wait for that bountiful food to rain down, in the form of sinking remains. As organisms rise and fall, they pass through waters with different pH values. But as acidification changes this pH profile, it could harm the organisms.

THE INSIDE ANGLE

AT THE SCALE of individual marine animals, acidification can force creatures to spend more energy on restoring and maintaining their internal pH balance, diverting energy away from important processes such as growth and reproduction.

Even small increases in seawater CO₂ concentration can cause rapid diffusion into the bodies of water-breathing animals. Once inside, CO₂ reacts with internal fluids, creating hydrogen ions, making the bodily fluids or tissue more acidic. Species employ various mechanisms to balance their internal pH. These actions include producing negative ions such as bicarbonate that soak up, or buffer, the extra hydrogen ions; pumping ions in and out of cells and intercellular spaces; and reducing metabolism to absorb fewer ions and “wait out” the period of high H⁺ concentration. But none of these mechanisms is meant to handle a sustained drop in pH. As an organism struggles to regain an acid-base balance, it sacrifices energy. Basic life functions such as synthesizing protein and maintaining a strong immune system can also become compromised.

Most species possess at least some buffer molecules. Fish and other active species stockpile them to reduce temporary pH declines that result from extended swimming bursts. Just like in a runner, muscles shift to anaerobic (nonoxygen based) metabolism during sprints, which uses up ATP (the main fuel molecule) more quickly, causing extra H⁺ ions to accumulate. But few species can stockpile enough buffering to last across extended timescales. If small pH changes occurred gradually over tens of thousands of years, a species might evolve adaptations, for example, by retaining chance genetic mutations that result in greater production of buffer molecules. But species generally cannot adapt to changes occurring over mere hundreds of years or less. Similar changes produced in the lab over days to weeks are lethal.

In past eras when CO₂ concentrations rose, species with less well-buffered systems fared poorly. Declines in pH may especially harm deep-sea species, whose stable environment leaves them ill equipped to adapt to change. (For this reason, proposed strategies to combat climate change by pumping large quantities of CO₂ into the deep sea are worrisome; they could destabilize the habitats of a wide array of creatures.)

POOR GROWTH AND REPRODUCTION

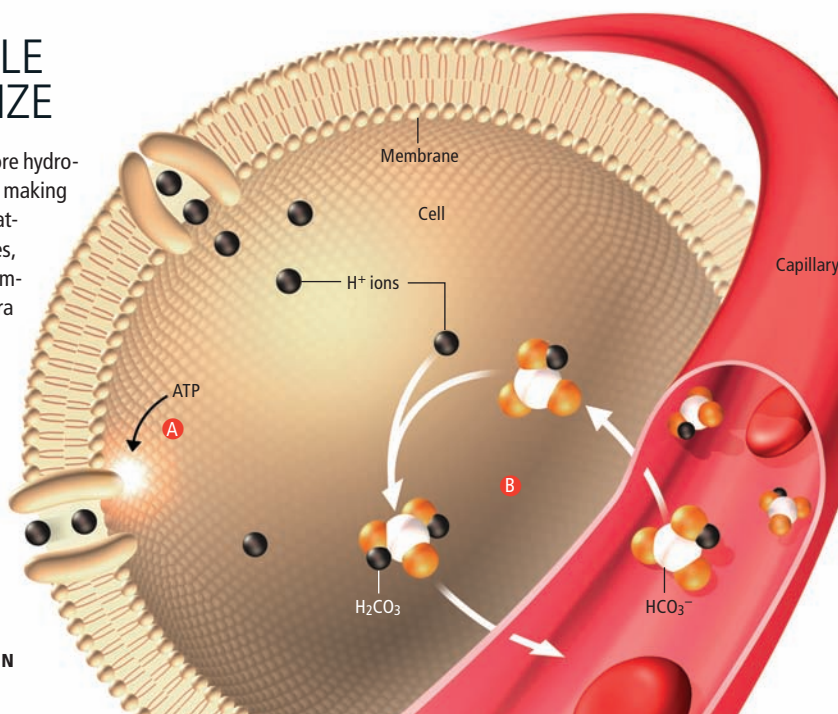
THE INTERNAL EFFECTS of ocean acidification vary across different developmental stages of life. A small but growing body of research points to a variety of potential trouble.

Indeed, the very first spark of life—fertilization—can be affected. In the lab, scientists sim-

[DEFENSE MECHANISMS]

THE STRUGGLE TO NEUTRALIZE

More CO₂ in seawater sends more hydrogen ions inside animals' bodies, making tissue more acidic. Species can attempt different countermeasures, but all sap energy. Cells, for example, can try to pump out the extra H⁺ ions: energy from an ATP molecule pushes the ions through a one-way channel in the cell membrane (a). Or the body can produce more buffer molecules such as carbonate (HCO₃⁻) that bind to the H⁺ ions and carry them away (b).



► CRIPPLED CRITTERS

Laboratory experiments show that the development and fertility of ocean animals suffer in more acidic waters. After being raised for eight days in 8.1 pH water, typical of today's oceans, the larvae of brittlestars were mature and symmetric (left, top), but larvae raised at 7.7 pH were deformed (left, bottom), and none reached full development. Snail eggs fertilized and raised at 8.05 pH all had embryos, which had grown shells after 18 days (right, top), but in 7.6 pH water (right, bottom) some eggs were empty, and embryos had still not developed shells.

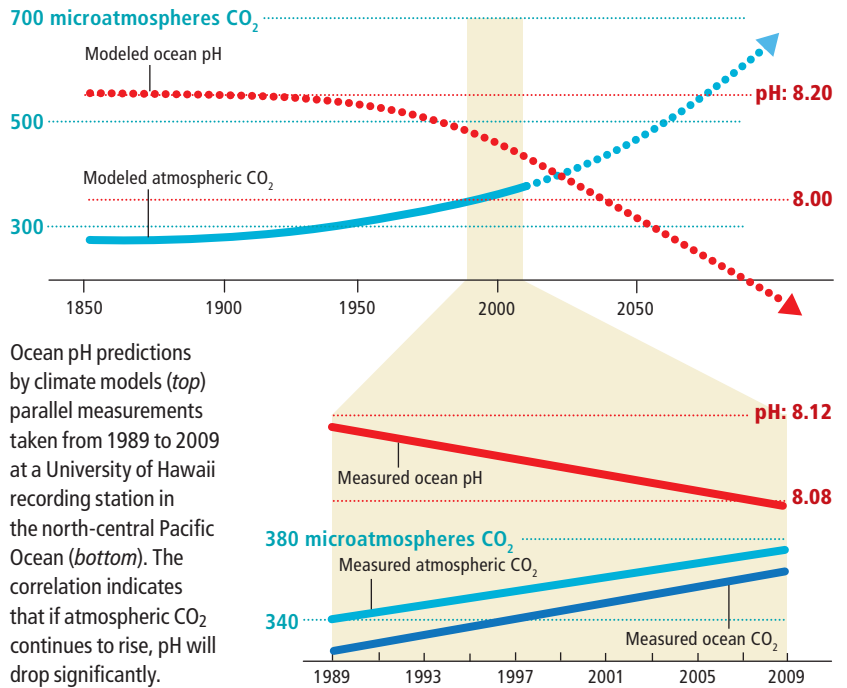
JEN CHRISTIANSEN (graphs); SOURCES: "DIRECT EFFECTS OF CO₂ CONCENTRATION ON GROWTH AND ISOTOPIC COMPOSITION OF MARINE PLANKTON," BY DIETER A. WOLF-GLADROW ET AL., IN *TELLUS SERIES B-CHEMICAL AND PHYSICAL METEOROLOGY*, VOL. 51, NO. 2, 2002, AND "PHYSICAL AND BIOGEOCHEMICAL MODULATION OF OCEAN ACIDIFICATION IN THE CENTRAL NORTH PACIFIC," BY JOHN E. DORE ET AL., IN *PMAS*, VOL. 106, NO. 30, JULY 28, 2009

ulate acidification by pumping extra CO₂ bubbles through seawater tanks. As Havenhand had explained during our cab ride, sperm of the Australian sea urchin *Heliocidaris erythrogramma* moved 16 percent less and swam 12 percent slower when experimenters lowered seawater pH by 0.4 (within the range predicted by 2100). Fertilization success dropped by 25 percent. In the wild, a 25 percent reduction could lead to significantly diminished adult populations over time. Although individual sea urchins release millions of sperm and eggs, the sperm do not remain viable for very long; they have to find and fertilize an egg within a few minutes. In a big, turbulent ocean, sluggish sperm may never reach their destination at all.

Acidification also thwarts early larval stages of several species. Samuel Dupont, down the hall from Havenhand at Gothenburg, exposed larvae of a temperate brittlestar—a relative of the common sea star—to pH reduced by 0.2 to 0.4 unit. Many showed abnormal development, and fewer than 0.1 percent survived more than eight days. In another study, fewer embryos of the snail *Littorina obtusata* hatched when exposed to lower pH waters, and those that did hatch moved less frequently and more slowly than normal.

A change of 0.2 to 0.4 pH all at once is more dramatic than species in the wild are experiencing, and some species might be able to adapt to gradual change. But for others, the effects of even slight acidification come on strong and fast. Scientists suspect ocean acidification explains recent mortality in larval oysters along

MODELS VS. MEASUREMENTS IN THE PACIFIC



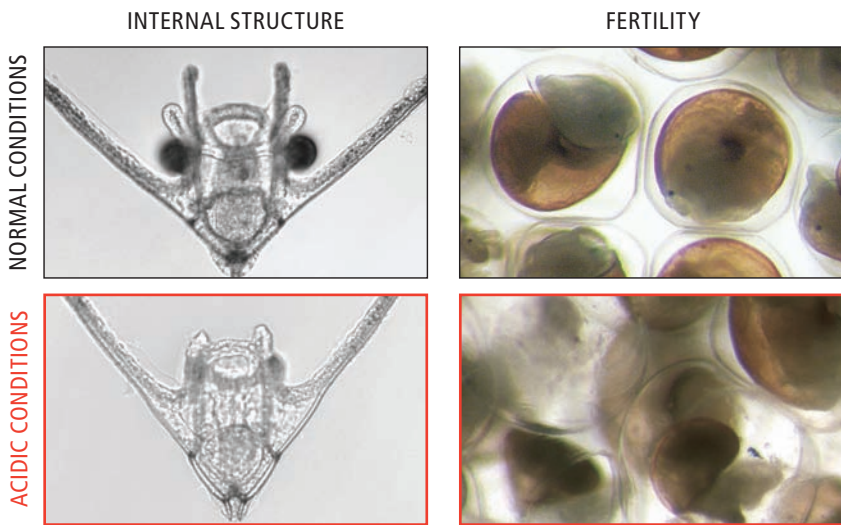
Ocean pH predictions by climate models (*top*) parallel measurements taken from 1989 to 2009 at a University of Hawaii recording station in the north-central Pacific Ocean (*bottom*). The correlation indicates that if atmospheric CO₂ continues to rise, pH will drop significantly.

the coast of Oregon, for example, sending some oyster growers scrambling to find enough babies to stay in business.

Adult animals suffer as well, especially when it comes to growth. Sea urchins and snails move slowly, but *growing* slowly is problematic. In 2005 researchers at Kyoto University in Japan determined that a CO₂ concentration 200 ppm higher than today's value, pumped into seawater for six months, reduced growth rates for the sea urchin species *Hemacentrotus pulcherrimus* and *Echinometra mathaei* and for the strawberry conch *Strombus luhuanu*. The 200-ppm increase is equal to that predicted over the next four to five decades. Slowed growth leaves individuals smaller for longer, making them more susceptible to predators and potentially reducing their reproductive output.

Acidification also makes it harder for some phytoplankton species to absorb iron, a micro-nutrient critical for growth. Researchers at Princeton University indicate that a 0.3 pH decline could reduce phytoplankton iron uptake by 10 to 20 percent. In addition to being an important link in the food chain, phytoplankton produce vast amounts of oxygen that we breathe.

In other experiments, the sediment-dwelling brittlestar *Amphiura filiformis* grew arms at greater rates under lower pH but lost significant muscle mass. Strong muscles are required for



[THE AUTHORS]



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feeding, building burrows and escaping predators. A pH decline of 0.3 to 0.5 suppressed the immune system response of the common blue mussel within one month. Reduced strength, growth, immune function or reproduction can cause long-term population declines—bad news for the victims, as well as for the many other species (including humans) that rely on them for food and even habitat. Grazing by sea urchins, for example, helps to keep coral reefs and kelp forests healthy, and the mixing of sediments by the brittlestars' movements is critical to making the sediments livable for many other species.

For some creatures, ocean acidification can simply mean the end. When a sample of copepod species common off the California coast (*Paraeuchaeta elongata*) was exposed to water that was 0.2 pH below normal, half of the organisms died within a week. The fish we prefer to eat, from tuna to salmon or striped bass, depend on an abundance of specific copepods to support the prey that supports them.

Several species of fish, such as the spotted wolffish (*Anarhichas minor*), have shown remarkable tolerance in the lab, because they maintain a relatively large stockpile of buffers and store extra oxygen in their tissue, which is handy because H⁺ ions interfere with the blood's ability to absorb oxygen from the water. Even very adaptable fish, however, may struggle if their food supply dwindles. Other species are not so well prepared. Highly active squid, for example, have no oxygen stores—they use all they have all the time. Less oxygen in their blood would limit their ability to hunt, avoid predators and find mates. For the commercially important squid *Illex illecebrosus*, a pH drop of just 0.15 could cause significant harm.

The message of lab studies as well as the geologic record is that ocean acidification forces animals to struggle harder, which today they are already doing because of other human-induced stressors such as warming waters, pollution and overfishing.

ACID ADAPTATION?

LAB EXPERIMENTS PERSIST for weeks to months. Climate change occurs over decades and centuries. Some species could adapt, especially if they have a short reproductive cycle. Each time an animal reproduces, genetic mutations can arise in the offspring that might help the next generation adjust to new circumstances. Ninety years—the predicted time frame for pH to decline by 0.3 to 0.5 unit—is extremely short, however, for

genetic adaptation by species that reproduce at relatively slow rates and that may already be stressed by the 30 percent pH decrease. Species extinctions often result from slow declines over centuries or more; a decline of just 1 percent of individuals per generation could cause extinction in less than a century.

Alarming, the pH drop observed so far and the predicted trajectory under current emissions trends are 100 times faster than any changes in prior millennia. Left unchecked, CO₂ levels will create a very different ocean, one never experienced by modern species.

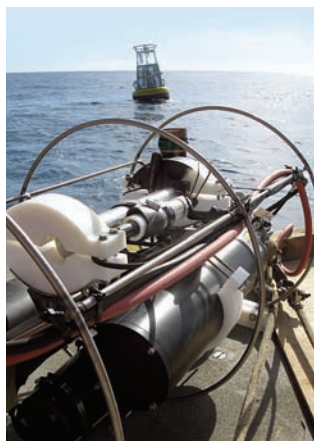
Adaptation is even more unlikely because the effects of acidification, and the other struggles creatures face, interact. For example, increased CO₂ levels can narrow the temperature range in which an individual can survive. We already see such constraints on corals and some algae, which become heat-stressed at lower temperatures than normal if exposed to higher CO₂.

OPTIONS FOR THE FUTURE

SCIENTISTS HAVE CONSISTENTLY underestimated rates of climate change, from Arctic ice melt to sea-level rise. Increasingly, experts recommend limiting atmospheric CO₂ to prevent dangerous levels of global warming. But the targets should be set with ocean acidification in mind as well. Unabated acidification could completely restructure marine ecosystems, with cascading effects across the food chain. Some species might thrive on a new combination of plankton while others suffer, but there is no telling if the species that we depend on most (or like the best) will be the winners. The changes could also hurt tourism and erase potential pharmaceutical and biomedical resources.

Ocean acidification also changes the rules for the planet's entire carbon cycle. Although the oceans now absorb a vast quantity of human emissions, the absorption rate slows as the seawater CO₂ concentration increases, and CO₂ “backs up” at the sea surface. As a result, atmospheric CO₂ concentration will rise even faster, accelerating global weather changes.

Such consequences warrant emissions targets that limit pH declines to no more than 0.1 over the next century. More and more, reducing the atmospheric CO₂ level to 350 ppm seems like the rational target. Stabilizing at 450 ppm by 2100, as some have suggested, could perhaps keep an additional pH decline to 0.1. But even that number could doom coral reefs and make it impossible for some animals to build shells, especially



FUTURE DATA

Carbon dioxide and pH sensors were deployed on buoys in the Pacific Ocean in December 2009 by the Scripps Institution of Oceanography, which provides data to California Current Ecosystem research projects. Such information will improve forecasts of ocean acidification trends.

THE NEW LSD

Increasingly acidic ocean water interferes with the internal body chemistry of many species. Researchers are also finding that acidification may be altering survival in other unusual ways.

For example, many marine species use subtle olfactory cues to seek prey, mates or suitable habitat. Certain clownfish differentiate between attractive and repulsive smells to decide which reef and anemone to settle on for the rest of their days. In laboratory studies, clownfish larvae raised in seawater with a pH 0.2 to 0.4 lower than today's ocean average swim toward negative cues and do not respond to positive ones. Their nasal organs look normal, but scientists think the acidification may disrupt the way chemical signals travel through the neurological system. It's a new kind of LSD: lost smell disorder. More studies are needed to determine if and how LSD may affect fish communities worldwide.

Complex, pH-regulated interactions between molecules in seawater also increase or decrease sound reception. Ocean acidification pumps up the volume; if pH declines by another 0.3 unit (within the scope predicted by 2100), oceans could be 40 percent louder. Although no studies have directly linked increased noise caused by acidification with changes in animal survival, the findings raise a warning flag, because marine wildlife, especially marine mammals, depend on sound for navigation, communication, hunting and courtship. —*M.J.H. and C.S.*



CLOWNFISH

in the Southern Ocean, which encircles Antarctica. Because of its cold temperatures and unique circulation patterns, the Southern Ocean will start dissolving shell and skeletal structures sooner than other oceans. It is far easier to prevent further acidification than to reverse changes once they occur; natural buffering systems would need hundreds to thousands of years to restore pH to preindustrial levels.

What can be done? For a start, the Obama administration should enact a National Ocean Policy—the first ever for the U.S.—because it could effectively coordinate action to combat these multiple threats. The U.S. Environmental Protection Agency should move forward with including CO₂ as a pollutant under the Clean Water Act, giving states authority to enforce CO₂ emissions limits. Establishing marine protected areas would allow species to recover from overexploitation; higher numbers would give their populations and gene pools more resilience in responding to climate changes. Adjusting fishery catch limits so they meet scientific recommendations rather than political desires would help. And signing the United Nations Convention on the Law of the Sea, which the U.S. has put off for decades, would make the nation a leader in marine stewardship.

More science is needed, too. Funding to support research initiatives by the European Project on Ocean Acidification and to implement the

Federal Ocean Acidification Research and Monitoring Act will deepen understanding of acidification's effects. But a dramatically scaled-up monitoring network to detect acidification is also required. An international team, led by Richard Feely of the Pacific Marine Environmental Laboratory in Seattle and Victoria J. Fabry of California State University, San Marcos, has created a blueprint for integrating acidification monitoring into existing ocean tracking programs, such as OceanSITES, and the recommendations should be followed as soon as possible. In addition, expanding efforts to combine field data with laboratory experiments, such as the California Current Ecosystem Interdisciplinary Biogeochemical Moorings project, will ensure that scientists' experiments simulate realistic conditions.

Ultimately, the solution to ocean acidification lies in a new energy economy. In light of recent lethal coal mine and offshore drilling explosions and the catastrophic Gulf of Mexico oil spill, the U.S. has more reason than ever to forge a safer energy strategy for the planet. Only a dramatic reduction in fossil fuel use can prevent further CO₂ emissions from contaminating the seas. An explicit plan to shift from finite, dangerous energy sources to renewable, clean energy sources offers nations a more secure path forward. And it offers the planet, especially the oceans, a chance for a healthy future. ■

MORE TO EXPLORE

The Dangers of Ocean Acidification. Scott C. Doney in *Scientific American*, Vol. 294, No. 3, pages 58–65; March 2006.

Impacts of Ocean Acidification on Marine Fauna and Ecosystem Processes. Victoria J. Fabry et al. in *ICES Journal of Marine Science*, Vol. 65, No. 3, pages 414–432; April 2008.

European Project on Ocean Acidification: www.epoca-project.eu

For more research and policy considerations, see the Ocean Acidification Network (www.oceanacidification.net), notably the Monaco Declaration, and the Research Priorities Report of the Ocean in a High CO₂ World II Symposium.

U.S. Ocean Carbon and Biogeochemistry program FAQ: www.whoi.edu/OCB-OA/FAQs

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