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How Acidification Threatens Oceans from the Inside Out

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 | Monday, August 9, 2010 | 23 comments

"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 CO_2 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 CO_2 mitigates some climate effects of the gas. The atmospheric CO_2 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 CO_2 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 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 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 simulate acidification by pumping extra CO 2 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 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 *Hemicentrotus 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 micronutrient 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 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.

Alarmingly, 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 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 CO_2 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.