The Great Dissolving

DOUG GEORGE

DROP A DIRTY PENNY into a glass of Coke. If you examine the penny after a week, Abraham Lincoln's head will be gleaming. The carbonic acid in the cola has dissolved the organic grime on the copper-plated coin. It's a science-class experiment many of us will remember from childhood. Now consider that the ocean is becoming corrosive, like Coke.

The phenomenon is called ocean acidification, and, like climate change, it is a result of increasing carbon dioxide (CO_2) emissions. The oceans have absorbed about one third of the CO_2 released into the atmosphere by humans over the past 200 years, and that is changing the waters' chemistry. The oceans are not fizzing like that glass of Coke—the chemical change is not that extreme—but they are becoming more acidic, with ominous consequences. A shift in the pH balance of seawater is under way, and it threatens shell-building creatures, corals, fisheries such as salmon, oysters, mussels, and sea urchins, and entire marine ecosystems.

The chemical reactions involved in acidification are well understood. There is also no controversy over the fact that acidification is happening on a global scale. And what can be done to slow it down is simple from a scientific view: eliminate all sources of human CO_2 emissions, immediately. Even if it were possible for this to occur, however, the harm will likely continue. Enough CO_2 may have already entered the ocean to cause hundreds of years of damage to millions of years' worth of evolutionary progression.

Acidity is measured on a pH scale, which ranges from 0 (strong acid) to 14 (strong base), with pure water a neutral 7. Like the seismic scale for earthquakes, the pH scale is logarithmic, so each additional 0.1 is in fact an increase of 30 percent. Depending on the marine habitat and depth, seawater can range in pH from 7.5 to 8.4, so it's slightly basic. When CO_2 dissolves in seawater, it forms carbonic acid. A few chemical reactions later, extra hydrogen ions are released; it is those ions that lower the pH level, making the water more acidic.

Ken Caldeira, an ocean acidification researcher at the Carnegie Institution for Science, recently described a demonstration experiment simple

Sea whips and feather stars, Redang Marine Park, Malaysia

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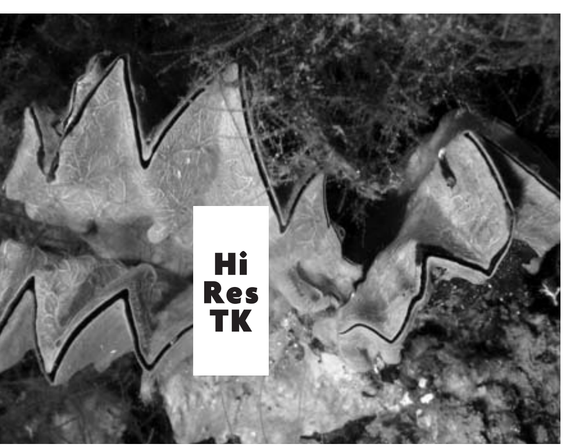
enough for a middle-school science fair. First, place a beaker of water inside an airtight bell jar and start pumping CO_2 into the jar. The water begins to absorb the gas as the bell jar fills. A few dips of litmus paper into the water over a short amount of time will give pH readings. “You can test the pH of the water and watch it shift,” Caldeira said.

Unlike pure water, seawater contains many dissolved ions that help maintain a stable pH, including carbonate ions. The more CO_2 is forced into the water, the more carbonate ions are needed to keep the system balanced. If seawater were used in Caldeira’s experiment, it would take longer to see the pH change because of the carbonate ions—at first. Once those carbonate ions run out, however, the pH would plummet and the water would acidify. In the oceans, whatever carbonate ions are used to equilibrate the seawater chemistry are no longer available for corals and other animals to build their protective shells.



Top: An Indian sea star *(Fromia indica)* spawning

Center: The pteropod *Creseis acicula* has a fragile shell.

Bottom: Cock's comb oyster *(Lopha cristagalli)*, Great Barrier Reef, Australia

A Dissolving Food Web

Researchers estimate that the oceans have absorbed about 33 percent of the CO_2 produced by human activities since 1750. During that same time, the average surface ocean pH has dropped 0.1 units, translating to a 30 percent increase in acidity. That humans could change the chemistry of 329 million cubic miles of water is a mind-boggling thought. “People are astounded,” said Victoria Fabry, a biological oceanographer at California State University, San Marcos.

Fabry’s research on the effects of ocean acidification brings in a group of zooplankton called pteropods, which can constitute up to 45 percent of the diet of Pacific salmon species. “Pteropod” in Latin means “winged foot,” but these planktonic snails are more playfully called sea butterflies because of how they flit through the water column. Pteropods need carbonate ions to build their aragonite (a form of calcium carbonate) shells, and Fabry and her colleagues observed in laboratory experiments that the shells start to dissolve in more acidic seawater: the sea butterflies were alive and swimming even as their protective calcium carbonate shells started to dissolve. “The juveniles secreting calcium carbonate may be particularly vulnerable,” said Fabry. If fewer youngsters survive to adulthood, large changes may radiate through food webs. A 10 percent decrease in pteropod numbers could lead to a 20 percent drop in mature salmon body weight, according to preliminary research done by some of Fabry’s colleagues.

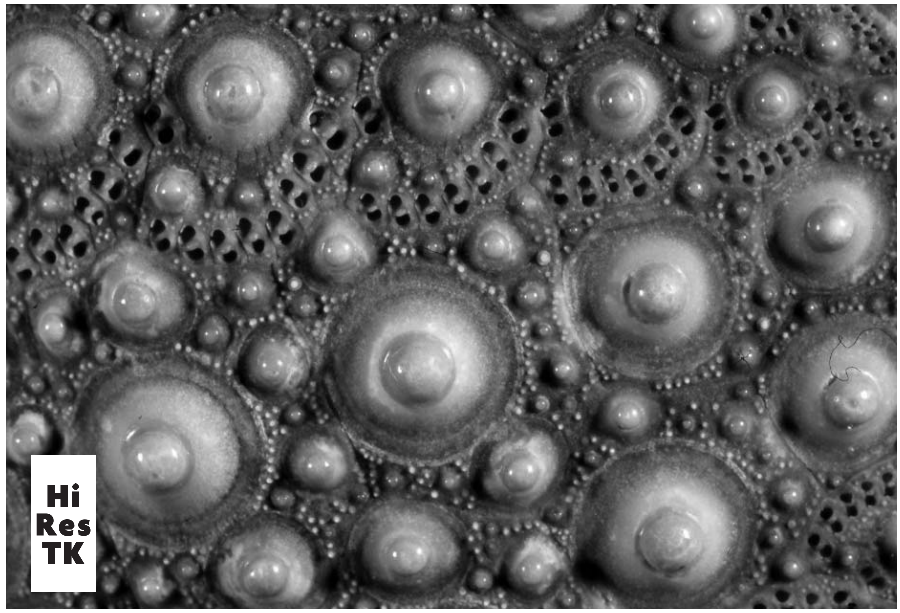
Other researchers look at another foundational group of organisms, called coccolithophores. Like microscopic baseballs made from hubcap-shaped calcium carbonate disks, these single-cell algae are at the base of the food web. In laboratory experiments that mimic the predicted pH of the ocean in 2100, one species, *Emiliania huxleyi,* showed an 18 percent drop in shell-building. But a cousin, *Gephyrocapsa oceanica*, was even worse off, with a 45 percent decrease. This could have serious consequences for food webs in some of the ocean’s most productive regions—especially in upwelling zones, like the California Current ecosystem.

Late in spring on the West Coast of North America, the dominant winds shift from blowing onshore to heading south. The constant blowing peels the surface layers of the ocean to the west and draws deep, cold, and nutrient-rich waters upward. The sudden supply of nutrients allows fantastic growth of phytoplankton, which builds the complicated food web that reaches up through fish, birds, and marine mammals, such as sea lions and the California gray whale.

Last year, researchers discovered that the upwelled water also carried an unwelcome amount of CO_2; moreover, it was more corrosive than they expected. Richard Feely, a chemical oceanographer at the National Oceanic and Atmospheric Administration's (NOAA) Pacific Marine Environmental Laboratory in Seattle, and his collaborators sampled seawater from Canada to Baja California to analyze water chemistry during May. Upwelled water typically has high amounts of CO_2 and low amounts of oxygen due to the natural respiratory processes of marine life and because the water has not been exposed to fresh air at the sea surface for decades. The water Feely sampled probably last saw daylight 50 years ago, when atmospheric CO_2 concentrations were less than today. Even so, the scientists found higher amounts of CO_2, low levels of carbonate ion concentration, and an undersaturation of aragonite; chemical reactions from the increased CO_2 resulted in the lowered carbonate ion concentration, which in turn caused the aragonite undersaturation. Aragonite shells will dissolve in seawater with such corrosive characteristics.

In the northeastern Pacific, the aragonite undersaturation started only 100–300 meters below the ocean surface, which happens to be exactly where upwelled water originates. "These corrosive waters are on our continental shelf right now," said Feely at a joint U.S. Geological Survey and U.S. Fish and Wildlife conference in San Francisco in January 2009, adding that climate change models did not predict these levels of aragonite until the end of this century. "This is a serious problem for our region and its ecosystems," Feely said.

Researchers from the University of Chicago published a study in 2008 that found ocean acidification was occurring ten times faster than predicted. The large difference could be related to how the climate change models were first designed. Most of the ocean chemistry data that forms the backbone of the models was collected from the open ocean, not the coastal zones. The models are appropriate to use thousands of miles from the California coast, but new ones are needed that incorporate the complex circulation patterns in upwelling areas along the coast.



The calcareous test (skeleton) of a purple sea urchin *(Strongylocentrotus purpuratus)*

Fisheries at Risk

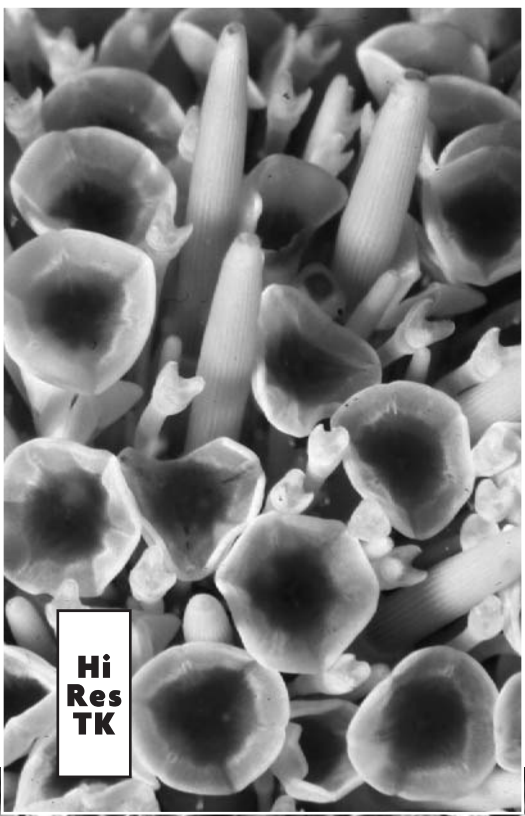
The upwelled corrosive water gives a sneak peek at what some West Coast marine organisms will be facing in the coming decades. For levels of atmospheric CO_2 that the Intergovernmental Panel on Climate Change predicts by the end of the century, mussels show a 25 percent decrease in shell formation, and oysters 10 percent. Less shell could mean higher mortality rates because the animals are weakly defended against the harsh living conditions of the ocean and coastline. Besides being what Feely calls "ecosystem engineers"—critters that form the physical structure and biological basis of a local ecosystem—mussels and oysters are part of a $2 billion at-risk fishing industry that also includes shrimp, crabs, lobsters, and sea urchins.

Sea urchins are spiny globe-like creatures about the size of a human fist. Anyone who's visited an aquarium would instantly recognize an urchin, with its spindly rigid spines that look like a frozen fireworks explosion. In their natural habitat, urchins feed busily on algae as they slowly tip-toe across the seabed and rocks. They construct their spines by calcification, using available carbonate ions in the water to build calcium carbonate crystals. As with pteropods, the sea urchins' ability to build those vital crystals decreases with declines in seawater pH and availability of carbonate ions. Researchers at the University of California, Santa Barbara, found that in more acidic waters the animals grow "short and stumpy skeletons" and are more easily killed by temperature increases. For the Channel Islands region of southern California, deformed and disappearing sea urchins evoke a nightmare scenario.

The Channel Islands are outcrops continuing the Santa Monica Mountain Range west into the Pacific off the coast of Santa Barbara and Ventura Counties. The Santa Barbara Channel is a prime shipping route for the ports of Los Angeles and Long Beach, but it is also a crucial sea urchin fishing area. From 2003 to 2008, fishermen in the Santa Barbara–Ventura–Oxnard region landed 3.1 billion pounds of red and purple sea urchins, according to records from the California Department of Fish and Game. Urchins are sold for sushi, with the Channel Islands region contributing the bulk of California's supply.

Below: Flower urchin *(Toxopneustes pileolus)*, Belau, Micronesia

Bottom: Pencil urchin *(Cidaroida)* on coral, Réunion Island



"I like to say we should ban ocean acidification from the Channel Islands," joked Shiva Polefka, a marine conservation analyst at the nonprofit Environmental Defense Center (EDC) in Santa Barbara. In 2008, EDC published "Ocean Acidification and the Channel Islands National Marine Sanctuary: Cause, Effect, and Response," a report that looked at how the Sanctuary can plan for a future when some of its iconic species are dissolving. The Sanctuary encompasses about 1,470 square miles of water surrounding the five islands of Anacapa, Santa Cruz, Santa Rosa, San Miguel, and Santa Barbara. It was carved out of the Santa Barbara Channel in 1980 and given a special protected status. Oil and gas drilling are prohibited and fishing is restricted. Polefka said the EDC report suggests that the Sanctuary should take the lead in acting to slow ocean acidification by reducing its operational CO_2 emissions with increased use of biodiesel. The report also says many questions remain unanswered about whether the marine organisms of the Sanctuary will adapt to an increasingly acidic ocean, and how they might do so. "What's uncertain is the time scale of what will happen," said Polefka, adding that the Channel Islands Sanctuary could become an advocate for managing the 14 national marine sanctuaries in less carbon-intensive ways.

Upsetting the Balance

When an environment changes radically, some organisms suffer while others thrive. "Seagrasses represent a group of winners as ocean acidification is making it harder for calcifying organisms," said Richard Zimmerman, chair of the Department of Ocean, Earth and Atmospheric Sciences at Old Dominion University in Norfolk, Virginia. Larger fields of eelgrass would trap more suspended sediment and clear the water column—solving a widespread problem in polluted places such as Chesapeake Bay.

Zimmerman and a postdoctoral researcher conducted a year-long experiment on eelgrass in 2001–02, bubbling emissions from the natural-gas power plant at Moss Landing into tanks of sea grasses to test their reaction to a more acidic environment. They found that photosynthesis increased, as did the amount of flowering and the overall growth rate. "Seagrasses are the legacy from a different environment—they evolved in a high-CO_2 environment," Zimmerman said. The ocean he is describing is from 100 million years ago, when atmospheric CO_2 levels were higher than in recent times—until humans started burning fossil fuels at extraordinary rates, that is. "We're doing an uncontrolled experiment now [on our atmosphere]," he added.

As with most experiments, more questions will undoubtedly arise. A next step in ocean acidification research is to look beyond individual species and examine how ecosystems will respond. As part of his work on deep-sea ecology, James Barry, a senior scientist at the Monterey Bay Aquarium Research Institute (MBARI), studies scavengers that feed on the carcasses of animals that fall to the sea floor. "Deep-sea animals are less physiologically able to tolerate large perturbations to the environment," he said. Despite the constant rain of dead organisms from above, the sea bed is a food-poor place, and that predisposes its dwellers to vulnerability. The predicted large change in pH and the higher levels of CO_2 will hit the deep-sea animals with a "double-whammy," Barry said. For example, large amounts of CO_2 are known to act like a narcotic and lull larger fish to sleep.

Imagine an ocean filled with dozing tuna or halibut. While it may make for easy fishing, growth rates and reproduction could plummet, with only negative effects hypothesized for their populations. "We need to do coordinated ecosystems studies to see how changes in parts of the system will affect the whole thing," he added.

Adapting to a Different Ocean

Adaptation to those new ecosystems will be the future. As with global warming, there is no realistic solution to reverse acidification. The growing amount of CO_2 will stay in the atmosphere for thousands of years. Most of it will eventually be dissolved into the oceans, where it will take even longer for the extra hydrogen ions to fully impact the ecosystems. When asked if there are technological solutions, Caldeira suggested installing limestone blocks around coral reefs to mitigate corrosive waters, but said that would only work in a small bay or marine sanctuary.

"We have to look back 40 million years to see a similar ocean environment [to what is expected]," said Barry. Since then, over the millennia, corals, large predators, and kelp forests have evolved in an ocean that was less acidic. This proliferation of life built the complex food web that has sustained humans and other creatures.

Future ocean ecosystems will be simpler, Barry said. "We may lose [species] that are important to us, but it's not going to be the end of the world—just a different one."

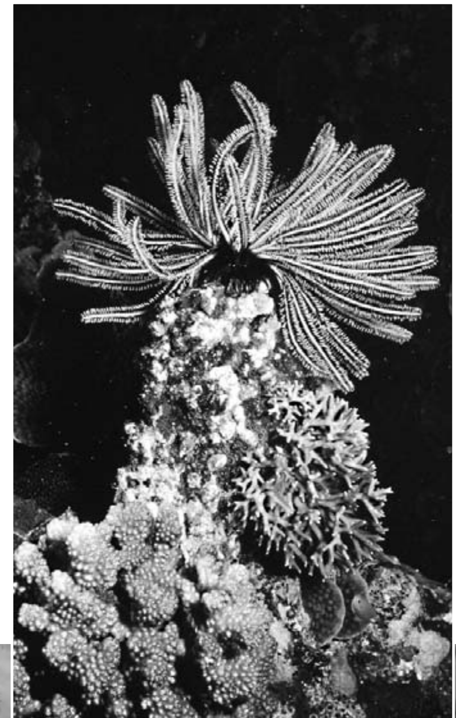
To survive in this new world, many current practices need to change, including those of the fishing industry. Acidification is damaging not only shellfish but other commercial stocks, such as English sole, a bottom-dweller that feeds on invertebrates. Phil Levin, a research fisheries biologist at the NOAA Pacific Marine Environmental Laboratory, works with computer models that predict a 50 percent decrease in the sole population with expected levels of ocean acidification by the end of the century. Without changing current fishing quotas, "we would overfish if we ignore ocean acidification," Levin said. The risk of overfishing in a more acidic ocean increases the need to understand the ecosystems. "Knowledge of indirect effects can promote sustainable fishing," he said.

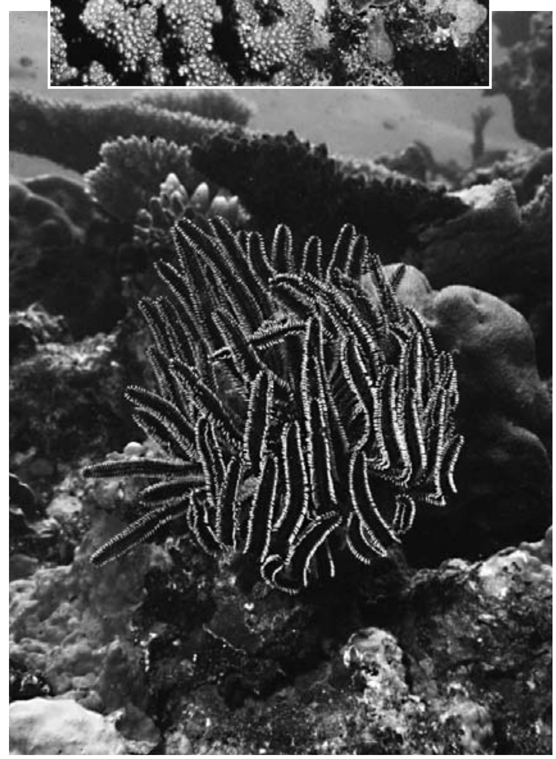
"Protect and control what you can," said Fabry when asked about adaptation strategies. She referred to a 2006 report titled simply "A Reef Manager's Guide to Coral Bleaching," published by the Great Barrier Reef Marine Park Authority in Australia, NOAA, and the World Conservation Union. The guide describes effective responses to a bleaching event and the steps to take to restore an affected reef. While reef bleaching is a much different problem caused by warming ocean temperatures, a search through the 178-page report did not find any reference to ocean acidification, which can potentially dissolve reefs entirely. Adaptation plans still have a ways to go.

The U.S. Congress intends to give those plans a strong boost. In January 2009, a bill was introduced in the House of Representatives called the Federal Ocean Acidification Research and Monitoring, or FOARAM, Act, with a nod to foraminifera, a group of calcareous protists threatened by falling pH. Over four years, from 2009 to 2013, the Act authorizes \$55 million to NOAA and \$41 million to the National Science Foundation to develop, among other things, adaptation plans to cope with the loss of marine species and ecosystems. The first adaptation plan is to be produced within the next four years, including a National Academies review of the strategy.

Ultimately, cutting CO_2 emissions is the only way to slow down ocean acidification. But the process has already begun, and the oceans may be unrecognizable by the end of the century. The geologic record shows that the ocean ecosystem took five million years to fully adjust to new levels of acidity. That vast time scale is intimidating and almost paralyzing. Hopefully, the creativity that led us to this brink will give us an opportunity to change our ways. ■

Doug George is an oceanographer and freelance science journalist based in the San Francisco Bay Area. He currently works for the Ocean Protection Council, and now avoids Coke to save his teeth.





Crinoids (probably *Oxycomantus bennetti*) at Davies Reef, Australia. Even these feathery echinoderms, related to sea stars, and gorgonians like sea whips, have calcareous skeletons that are threatened by ocean acidification.

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