The Darkening Sea

Elizabeth Kolbert
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Pteropods are tiny marine organisms that belong to the very broad class known as zooplankton. Related to snails, they swim by means of a pair of winglike gelatinous flaps and feed by entrapping even tinier marine creatures in a bubble of mucus. Many pteropod species—there are nearly a hundred in all—produce shells, apparently for protection; some of their predators, meanwhile, have evolved specialized tentacles that they employ much as diners use forks to spear escargot. Pteropods are first male, but as they grow older they become female.

Victoria Fabry, an oceanographer at California State University at San Marcos, is one of the world's leading experts on pteropods. She is slight and soft-spoken, with wavy black hair and blue-green eyes. Fabry fell in love with the ocean as a teen-ager after visiting the Outer Banks, off North Carolina, and took up pteropods when she was in graduate school, in the early nineteen-eighties. At that point, most basic questions about the animals had yet to be answered, and, for her dissertation, Fabry decided to study their shell growth. Her plan was to raise pteropods in tanks, but she ran into trouble immediately. When disturbed, pteropods tend not to produce the mucus bubbles, and slowly starve. Fabry tried using bigger tanks for her pteropods, but the only correlation, she recalled recently, was that the more time she spent improving the tanks "the quicker they died." After a while, she resigned herself to constantly collecting new specimens. This, in turn, meant going out on just about any research ship that would have her.

Fabry developed a simple, if brutal, protocol that could be completed at sea. She would catch some pteropods, either by trawling with a net or by scuba diving, and place them in one-litre bottles filled with seawater, to which she had added a small amount of radioactive calcium 45. Forty-eight hours later, she would remove the pteropods from the bottles, dunk them in warm ethanol, and pull their bodies out with a pair of tweezers. Back on land, she would measure how much calcium 45 their shells had taken up during their two days of captivity.

In the summer of 1985, Fabry got a berth on a research vessel sailing from Honolulu to Kodiak Island. Late in the trip, near a spot in the Gulf of Alaska known as Station Papa, she came upon a profusion of *Clio pyramidata*, a half-inch-long pteropod with a shell the shape of an unfurled umbrella. In her enthusiasm, Fabry collected too many specimens; instead of putting two or three in a bottle, she had to cram in a dozen. The next day, she noticed that something had gone wrong. "Normally, their shells are transparent," she said. "They look like little gems, little jewels. They're just beautiful. But I could see that, along the edge, they were becoming opaque, chalky."

Like other animals, pteropods take in oxygen and give off carbon dioxide as a waste product. In the open sea, the CO_2 they produce has no effect. Seal them in a small container, however, and the CO_2 starts to build up, changing the water's chemistry. By overcrowding her *Clio pyramidata*, Fabry had demonstrated that the organisms were highly sensitive to such changes. Instead of growing, their shells were dissolving. It stood to reason that other kinds of pteropods—and, indeed, perhaps any number of shell-building species—were similarly vulnerable. This should have represented a major discovery, and a cause for alarm. But, as is so often the case with inadvertent breakthroughs, it went unremarked upon. No one on the boat, including Fabry, appreciated what the pteropods were telling them, because no one, at that point, could imagine the chemistry of an entire ocean changing.

MORE IN DREAMS THAN IN THE FLESH

No wind. No storm.
Just the trees heaving in their own sorrow.
The girl next door who went missing a week ago
Has come back; the faces of her parents stare
Like bare, wounded hills beyond the river.
Often a dream makes one afraid
Of the things one might do. It frightens one
That despair seems to have no boundaries.
The laments for a death are over while death
Is warm and safe and drifts into sleep
In a child's dream.

Some time back I had stumbled
On the decomposing bodies of a young couple
On the hill slope behind the temple. The girl
Couldn't have been more than sixteen years old.
I had made a great effort to defend myself.
Her half-open eyes now wander through
My subdued Sunday mornings as though testing
The courage it took to be a man.

No wind. No storm.
Just the vague light of daybreak
Coming down from the hilltops.
An unknown darkening is in my breath.
And I knew death is born to us in the same way
As when we cast our nets into the night
And draw in the shapes of day.

—*Jayanta Mahapatra*

Since the start of the industrial revolution, humans have burned enough coal, oil, and natural gas to produce some two hundred and fifty billion metric tons of carbon. The result, as is well known, has been a transformation of the earth's atmosphere. The concentration of CO_2 in the air today—three hundred and eighty parts per million—is higher than it has been at any point in the past six hundred and fifty thousand years, and probably much longer. At the current rate of emissions growth, CO_2 concentration will top five hundred parts per million—roughly double pre-industrial levels—by the middle of this century. It is expected that such an increase will produce an eventual global temperature rise of between three and a half and seven degrees Fahrenheit, and that this, in turn, will prompt a string of disasters, including fiercer hurricanes, more deadly droughts, the disappearance of most remaining glaciers, the melting of the Arctic ice cap, and the inundation of many of the world's major coastal cities. But this is only half the story.

Ocean covers seventy per cent of the earth's surface, and everywhere that water and air come into contact there is an exchange. Gases from the atmosphere get absorbed by the ocean and gases dissolved in the water are released into the atmosphere. When the two are in equilibrium, roughly the same quantities are being dissolved as are getting released. But change the composition of the atmosphere, as we have done, and the exchange becomes lopsided: more CO_2 from the air enters the water than comes back out. In the nineteen-nineties, researchers from seven countries conducted nearly a hundred cruises, and collected more than seventy thousand seawater samples from different depths and locations. The analysis of these samples, which was completed in 2004, showed that nearly half of all the carbon dioxide that humans have emitted since the start of the nineteenth century has been absorbed by the sea.

When CO_2 dissolves, it produces carbonic acid, which has the chemical formula H_2CO_3. As acids go, H_2CO_3 is relatively innocuous—we drink it all the time in Coke and other carbonated beverages—but in sufficient quantities it can change the water's pH. Already, humans have pumped enough carbon into the oceans—some hundred and twenty billion tons—to produce a .1 decline in surface pH. Since pH, like the Richter scale, is a logarithmic measure, a .1 drop represents a rise in acidity of about thirty per cent. The process is generally referred to as "ocean acidification," though it might more accurately be described as a decline in ocean alkalinity. This year alone, the seas will absorb an additional two billion tons of carbon, and next year it is expected that they will absorb another two billion tons. Every day, every American, in effect, adds forty pounds of carbon dioxide to the oceans.

Because of the slow pace of deep-ocean circulation and the long life of carbon dioxide in the atmosphere, it is impossible to reverse the acidification that has already taken place. Nor is it possible to prevent still more from occurring. Even if there were some way to halt the emission of CO_2 tomorrow, the oceans would continue to take up carbon until they reached a new equilibrium with the air. As Britain's Royal Society noted in a recent report, it will take "tens of thousands of years for ocean chemistry to return to a condition similar to that occurring at pre-industrial times."

Humans have, in this way, set in motion change on a geologic scale. The question that remains is how marine life will respond. Though oceanographers are just beginning to address the question, their discoveries, at this early stage, are disturbing. A few years ago, Fabry finally pulled her cloudy shells out of storage to examine them with a scanning electron microscope. She found that their surfaces were riddled with pits. In some cases, the pits had grown into gashes, and the upper layer had started to pull away, exposing the layer underneath.

The term "ocean acidification" was coined in 2003 by two climate scientists, Ken Caldeira and Michael Wickett, who were working at the Lawrence Livermore National Laboratory, in Northern California. Caldeira has since moved to the Carnegie Institution, on the campus of Stanford University, and during the summer I went to visit him at his office, which is housed in a "green" building that looks like a barn that has been taken apart and reassembled at odd angles. The building has no air-conditioning; temperature control is provided by a shower of mist that rains down into a tiled chamber in the lobby. At the time of my visit, California was in the midst of a record-breaking heat wave; the system worked well enough that Caldeira's office, if not exactly cool, was at least moderately comfortable.

Caldeira is a trim man with wiry brown hair and a boyish sort of smile. In the nineteen-eighties, he worked as a software developer on Wall Street, and one of his clients was the New York Stock Exchange, for whom he designed computer programs to help detect insider trading. The programs functioned as they were supposed to, but after a while Caldeira came to the conclusion that the N.Y.S.E. wasn't actually interested in catching insider traders, and he decided to switch professions. He went back to school, at N.Y.U., and ended up becoming a climate modeller.

Unlike most modellers, who focus on one particular aspect of the climate system, Caldeira is, at any given moment, working on four or five disparate projects. He particularly likes computations of a provocative or surprising nature; for example, not long ago he calculated that cutting down all the world's forests and replacing them with grasslands would have a slight cooling effect. (Grasslands, which are lighter in color than forests, absorb less sunlight.) Other recent calculations that Caldeira has made show that to keep pace with the present rate of temperature change plants and animals would have to migrate poleward by thirty feet a day, and that a molecule of CO_2 generated by burning fossil fuels will, in the course of its lifetime in the atmosphere, trap a hundred thousand times more heat than was released in producing it.

Caldeira began to model the effects of carbon dioxide on the oceans in 1999, when he did some work for the Department of Energy. The department wanted to know what the environmental consequences would be of capturing CO_2 from smokestacks and injecting it deep into the sea. Caldeira set about calculating how the ocean's pH would change as a result of deep-sea injection, and then compared that result with the current practice of pouring carbon dioxide into the atmosphere and allowing it to be taken up by surface waters. In 2003, he submitted his work to *Nature*. The journal's editors advised him to drop the discussion of deep-ocean injection, he recalled, because the calculations concerning the effects of ordinary atmospheric release were so startling. Caldeira published the first part of his paper under the subheading "The coming centuries may see more ocean acidification than the past 300 million years."

Caldeira told me that he had chosen the term "ocean acidification" quite deliberately, for its shock value. Seawater is naturally alkaline, with a pH ranging from 7.8 to 8.5—a pH of 7 is neutral—which means that, for now, at least, the oceans are still a long way from actually turning acidic. Meanwhile, from the perspective of marine life, the drop in pH matters less than the string of chemical reactions that follow.

The main building block of shells is calcium carbonate—$CaCO_3$. (The White Cliffs of Dover are a huge $CaCO_3$ deposit, the remains of countless tiny sea creatures that piled up during the Cretaceous—or "chalky"—period.) Calcium carbonate produced by marine organisms comes in two principal forms, aragonite and calcite, which have slightly different crystal structures. How, exactly, different organisms form calcium carbonate remains something of a mystery. Ordinarily in seawater, $CaCO_3$ does not precipitate out as a solid. To build their shells, calcifying organisms must, in effect, assemble it. Adding carbonic acid to the water complicates their efforts, because it reduces the number of carbonate ions in circulation. In scientific terms, this is referred to as "lowering the water's saturation state with respect to calcium carbonate." Practically, it means shrinking the supply of material available for shell formation. (Imagine trying to build a house when someone keeps stealing your bricks.) Once the carbonate concentration gets pushed low enough, even existing shells, like those of Fabry's pteropods, begin to dissolve.

To illustrate, in mathematical terms, what the seas of the future will look like, Caldeira pulled out a set of graphs. Plotted on one axis was aragonite saturation levels; on the other, latitude. (Ocean latitude is significant because saturation levels tend naturally to decline toward the poles.) Different colors of lines represented different emissions scenarios. Some scenarios project that the world's economy will continue to grow rapidly and that this growth will be fuelled mostly by oil and coal. Others assume that the economy will grow more slowly,

"I've been researching a little furniture company I'd like to rearrange."

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and still others that the energy mix will shift away from fossil fuels. Caldeira considered four much studied scenarios, ranging from one of the most optimistic, known by the shorthand B1, to one of the most pessimistic, A2. The original point of the graphs was to show that each scenario would produce a different ocean. But they turned out to be more similar than Caldeira had expected.

Under all four scenarios, by the end of this century the waters around Antarctica will become undersaturated with respect to aragonite—the form of calcium carbonate produced by pteropods and corals. (When water becomes undersaturated, it is corrosive to shells.) Meanwhile, surface pH will drop by another .2, bringing acidity to roughly double what it was in pre-industrial times. To look still further out into the future, Caldeira modelled what would happen if humans burned through all the world's remaining fossil-fuel resources, a process that would release some eighteen thousand gigatons of carbon dioxide. He found that by 2300 the oceans would become undersaturated from the poles to the equator. Then he modelled what would happen if we pushed still further and burned through unconventional fuels, like low-grade shales. In that case, we would drive the pH down so low that the seas would come very close to being acidic.

"I used to think of B1 as a good scenario, and I used to think of A2 as a terrible scenario," Caldeira told me. "Now I look at them as different flavors of bad scenarios."

He went on, "I think there's a whole category of organisms that have been around for hundreds of millions of years which are at risk of extinction—namely, things that build calcium-carbonate shells or skeletons. To a first approximation, if we cut our emissions in half it will take us twice as long to create the damage. But we'll get to more or less the same place. We really need an order-of-magnitude reduction in order to avoid it."

Caldeira said that he had recently gone to Washington to brief some members of Congress. "I was asked, 'What is the appropriate stabilization target for atmospheric CO_2?' " he recalled. "And I said, 'Well, I think it's inappropriate to think in terms of stabilization targets. I think we should think in terms of emissions targets.' And they said, 'O.K., what's the appropriate emissions target?' And I said, 'Zero.'

"If you're talking about mugging little old ladies, you don't say, 'What's our target for the rate of mugging little old ladies?' You say, 'Mugging little old ladies is bad, and we're going to try to eliminate it.' You recognize you might not be a hundred per cent successful, but your goal is to eliminate the mugging of little old ladies. And I think we need to eventually come around to looking at carbon-dioxide emissions the same way."

Coral reefs grow in a great swath that stretches like a belt around the belly of the earth, from thirty degrees north to thirty degrees south latitude. The world's largest reef is the Great Barrier, off the coast of northeastern Australia, and the second largest is off the coast of Belize. There are extensive coral reefs in the tropical Pacific, in the Indian Ocean, and in the Red Sea, and many smaller ones in the Caribbean. These reefs, home to an estimated twenty-five per cent of all marine fish species, represent some of the most diverse ecosystems on the planet.

Much of what is known about coral reefs and ocean acidification was originally discovered, improbably enough, in Arizona, in the self-enclosed, supposedly self-sufficient world known as Biosphere 2. A three-acre glassed-in structure shaped like a ziggurat, Biosphere 2 was built in the late nineteen-eighties by a private group—a majority of the funding came from the billionaire Edward Bass—and was intended to demonstrate how life on earth (Biosphere 1) could be re-created on, say, Mars. The building contained an artificial "ocean," a "rain forest," a "desert," and an "agricultural zone." The first group of Biosphereans—four men and four women—managed to remain, sealed inside, for two years. They produced all their own food and, for a long stretch, breathed only recycled air, but the project was widely considered a failure. The Biosphereans spent much of the time hungry, and, even more ominously, they lost control of their artificial atmosphere. In the various "ecosystems," decomposition, which takes up oxygen and gives off CO_2, was supposed to be balanced by photosynthesis, which does the reverse. But, for reasons mainly having to do with the richness of the soil that had been used in the "agricultural zone," decomposition won out. Oxygen levels inside the building kept falling, and the Biosphereans developed what amounted to altitude sickness. Carbon-dioxide levels soared, at one point reaching three thousand parts per million, or roughly eight times the levels outside.

When Biosphere 2 officially collapsed, in 1995, Columbia University took over the management of the building. The university's plan was to transform it into a teaching and research facility, and it fell to a scientist named Chris Langdon to figure out something pedagogically useful to do with the "ocean," a tank the size of an Olympic swimming pool. Langdon's specialty was measuring photosynthesis, and he had recently finished a project, financed by the Navy, that involved trying to figure out whether blooms of bioluminescent algae could be used to track enemy submarines. (The answer was no.) Langdon was looking for a new project, but he wasn't sure what the "ocean" was good for. He began by testing various properties of the water. As would be expected in such a high-CO_2 environment, he found that the pH was low.

"The very first thing I did was try to establish normal chemistry," he recalled recently. "So I added chemicals—essentially baking soda and baking powder—to the water to bring the pH back up." Within a week, the alkalinity had dropped again, and he had to add more chemicals. The same thing happened. "Every single time I did it, it went back down, and the rate at which it went down was proportional to the concentration. So, if I added more, it went down faster. So I started thinking, What's going on here? And then it dawned on me."

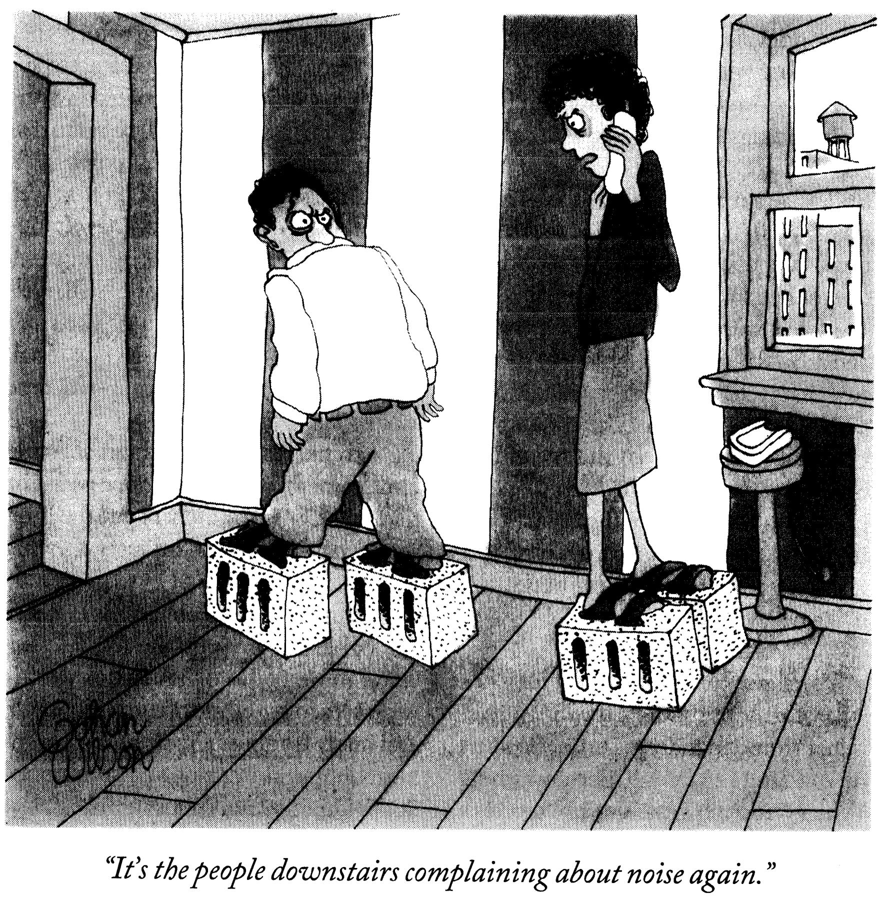
Langdon left Columbia in 2004 and now works at the Rosenstiel School of Marine and Atmospheric Science, at the University of Miami. He is fifty-two, with a high forehead, deep-set blue eyes, and a square chin. When I went to visit him, not long ago, he took me to see his coral samples, which were growing in a sort of aquatic nursery across the street from his office. On the way, we had to pass through a room filled with tanks of purple sea slugs, which were being raised for medical research. In the front row, the youngest sea slugs, about half an inch long, were floating gracefully, as if suspended in gelatine. Toward the back were slugs that had been fed for several months on a lavish experimental diet. These were the size of my forearm and seemed barely able to lift their knobby, purplish heads.

Langdon's corals were attached to tiles arranged at the bottom of long, sinklike tanks. There were hundreds of them, grouped by species: *Acropora cervicornis*, a type of staghorn coral that grows in a classic antler shape; *Montastrea cavernosa*, a coral that looks like a seafaring cactus; and *Porites divaricata*, a branching coral made up of lumpy, putty-colored protuberances. Water was streaming into the tanks, but when Langdon put his hand in front of the faucet to stop the flow, I could see that every lobe of *Porites divaricata* was covered with tiny pink arms and that every arm ended in soft, fingerlike tentacles. The arms were waving in what looked to be a frenzy either of joy or of supplication.

Langdon explained that the arms belonged to separate coral polyps, and that a reef consisted of thousands upon thousands of polyps spread, like a coating of plaster, over a dead calcareous skeleton. Each coral polyp is a distinct individual, with its own tentacles and its own digestive system, and houses its own collection of symbiotic algae, known as zooxanthellae, which provide it with most of its nutrition. At the same time, each polyp is joined to its neighbors through a thin layer of connecting tissue, and all are attached to the colony's collective skeleton. Individual polyps constantly add to the group skeleton by combining calcium and carbonate ions in a medium known as the extracytoplasmic calcifying fluid. Meanwhile, other organisms, like parrot fish and sponges, are constantly eating away at the reef in search of food or protection. If a reef were ever to stop calcifying, it would start to shrink and eventually would disappear.

"It's just like a tree with bugs," Langdon explained. "It needs to grow pretty quickly just to stay even."

As Langdon struggled, unsuccessfully, to control the pH in the Biosphere "ocean," he started to wonder whether the corals in the tank might be to blame. The Biosphereans had raised twenty different species of coral, and while many of the other creatures, including nearly all the vertebrates selected for the project, had died out, the corals had survived. Langdon wondered whether the chemicals he was adding to raise the pH were, by increasing the saturation state, stimulating their growth. At the time, it



"It's the people downstairs complaining about noise again."

seemed an unlikely hypothesis, because the prevailing view among marine biologists was that corals weren't sensitive to changes in saturation. (In many textbooks, the formula for coral calcification is still given incorrectly, which helps explain the prevalence of this view.) Just about everyone, including Langdon's own postdoc, a young woman named Francesca Marubini, thought that his theory was wrong. "It was a total pain in the ass," Langdon recalled.

To test his hypothesis, Langdon employed a straightforward but time-consuming procedure. Conditions in the "ocean" would be systematically varied, and the growth of the coral monitored. The experiment took more than three years to complete, produced more than a thousand measurements, and, in the end, confirmed Langdon's hypothesis. It revealed a more or less linear relationship between how fast the coral grew and how highly saturated the water was. By proving that increased saturation spurs coral growth, Langdon also, of course, demonstrated the reverse: when saturation drops, coral growth slows. In the artificial world of Biosphere 2, the implications of this discovery were interesting; in the real world they were rather more grim. Any drop in the ocean's saturation levels, it seemed, would make coral more vulnerable.

Langdon and Marubini published their findings in the journal *Global Biogeochemical Cycles* in the summer of 2000. Still, many marine biologists remained skeptical, in no small part, it seems, because of the study's association with the discredited Biosphere project. In 2001, Langdon sold his house in New York and moved to Arizona. He spent another two years redoing the experiments, with even stricter controls. The results were essentially identical. In the meantime, other researchers launched similar experiments on different coral species. Their findings were also the same, which, as Langdon put it to me, "is the best way to make believers out of people."

Coral reefs are under threat for a host of reasons: bottom trawling, dynamite fishing, coastal erosion, agricultural runoff, and, nowadays, global warming. When water temperatures rise too high, corals lose—or perhaps expel, no one is quite sure—the algae that nourish them. (The process is called "bleaching," because without their zooxanthellae corals appear white.) For a particular reef, any one of these threats could potentially be fatal. Ocean acidification poses a different kind of threat, one that could preclude the very possibility of a reef.

Saturation levels are determined using a complicated formula that involves multiplying the calcium and carbonate ion concentrations, and then dividing the result by a figure called the stoichiometric solubility product. Prior to the industrial revolution, the world's major reefs were all growing in water whose aragonite saturation level stood between 4 and 5. Today, there is not a single remaining region in the oceans where the saturation level is above 4.5, and there are only a handful of spots—off the northeastern coast of Australia, in the Philippine Sea, and near the Maldives—where it is above 4. Since the takeup of CO_2 by the oceans is a highly predictable physical process, it is possible to map the saturation levels of the future with great precision. Assuming that current emissions trends continue, by 2060 there will be no regions left with a level above 3.5. By 2100, none will remain above 3.

As saturation levels decline, the rate at which reefs add aragonite through calcification and the rate at which they lose it through bioerosion will start to approach each other. At a certain point, the two will cross, and reefs will begin to disappear. Precisely where that point lies is difficult to say, because erosion may well accelerate as ocean pH declines. Langdon estimates that the crossing point will be reached when atmospheric CO_2 levels exceed six hundred and fifty parts per million, which, under a "business as usual" emissions scenario, will occur sometime around 2075.

"I think that this is just an absolute limit, something they can't cope with," he told me. Other researchers put the limit somewhat higher, and others somewhat lower.

Meanwhile, as global temperatures climb, bleaching events are likely to become more common. A major worldwide bleaching event occurred in 1998, and many Caribbean reefs suffered from bleaching again during the summer of 2005. Current conditions in the equatorial Pacific suggest that 2007 is apt to be another bleaching year. Taken together, acidification and rising ocean temperatures represent a kind of double bind for reefs: regions that remain hospitable in terms of temperature are becoming increasingly inhospitable in terms of saturation, and vice versa.

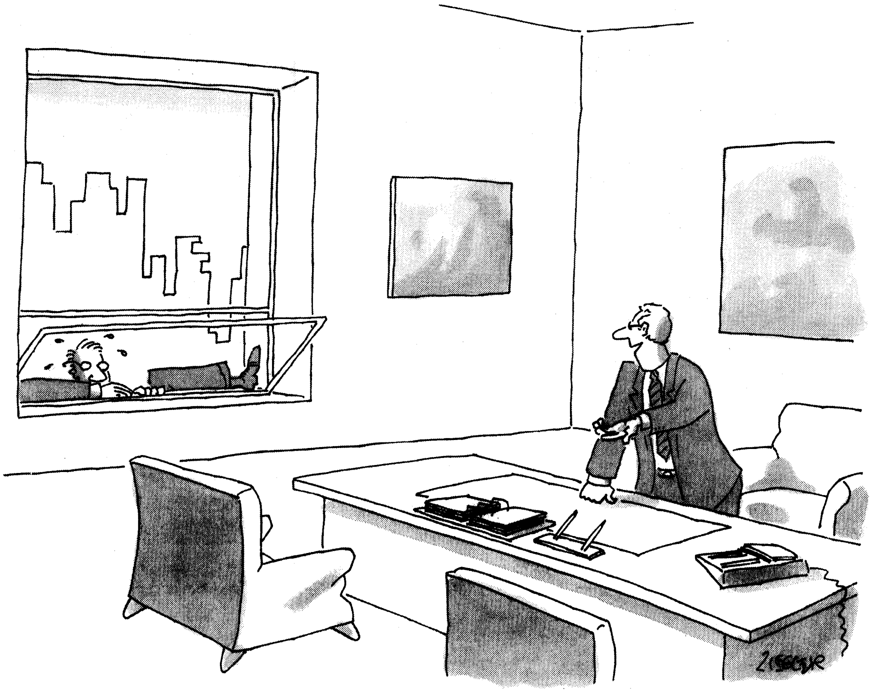
"While one, bleaching, is an acute stress that's killing them off, the other, acidification, is a chronic stress that's preventing them from recovering," Joanie Kleypas, a reef scientist at the National Center for Atmospheric Research, in Boulder, Colorado, told me. Kleypas said she thought that some corals would be able to migrate to higher latitudes as the oceans warm, but that, because of the lower saturation levels, as well as the difference in light regimes, the size of these migrants would be severely limited. "There's a point where you're going to have coral but no reefs," she said.

The tropical oceans are, as a rule, nutrient-poor; they are sometimes called liquid deserts. Reefs are so dense with life that they are often compared to rain forests. This rain-forest-in-the-desert effect is believed to be a function of a highly efficient recycling system, through which nutrients are, in effect, passed from one reef-dwelling organism to another. It is estimated that at least a million, and perhaps as many as nine million, distinct species live on or near reefs.

"Being conservative, let's say it's a million species that live in and around coral," Ove Hoegh-Guldberg, an expert on coral reefs at the University of Queensland, in Australia, told me. "Some of these species that hang around coral reefs can sometimes be found living without coral. But most species are completely dependent on coral—they literally live in, eat, and breed around coral. And, when we see coral get destroyed during bleaching events, those species disappear. The key question is how vulnerable all these various species are. That's a very important question, but at the moment you'd have to say that a million different species are under threat."

He went on, "This is a matter of the utmost importance. I can't really stress it in words strong enough. It's a do-or-die situation."

Around the same time that Langdon was performing his coral experiments at the Biosphere, a German marine biologist named Ulf Riebesell decided to look into the behavior of a class



"I don't see you pencilled in on my calendar, Armstrong. But, as long as you're up here, come on in and have a seat."

of phytoplankton known as coccolithophores. Coccolithophores build plates of calcite—coccoliths—that they arrange around themselves, like armor, in structures known as coccospheres. (Viewed under an electron microscope, they look like balls that have been covered with buttons.) Coccolithophores are very tiny—only a few microns in diameter—and also very common. One of the species that Riebesell studied, *Emiliani huxleyi*, produces blooms that can cover forty thousand square miles, turning vast sections of the ocean an eerie, milky blue.

In his experiments, Riebesell bubbled CO_2 into tanks of coccolithophores to mimic the effects of rising atmospheric concentrations. Both of the species he was studying—*Emiliani huxleyi* and *Gephyrocapsa oceanica*—showed a clear response to the variations. As CO_2 levels rose, not only did the organisms' rate of calcification slow; they also started to produce deformed coccoliths and ill-shaped coccospheres.

"To me, it says that we will have massive changes," Riebesell, who works at the Leibniz Institute of Marine Sciences, in Kiel, told me. "If a whole group of calcifiers drops out, are there other organisms taking their place? What is the rate of evolution to fill those spaces? That's awfully difficult to address in experimental work. These organisms have never, ever seen this in their entire evolutionary history. And if they've never seen it they probably will find it difficult to deal with."

Calcifying organisms come in a fantastic array of shapes, sizes, and taxonomic groups. Echinoderms like starfish are calcifiers. So are mollusks like clams and oysters, and crustaceans like barnacles, and many species of bryozoans, or sea mats, and tiny protists known as foraminifera—the list goes on and on. Without experimental data, it's impossible to know which species will prove to be particularly vulnerable to declining pH and which will not. In the natural world, the pH of the water changes by season, and even time of day, and many species may be able to adapt to new conditions, at least within certain bounds. Obviously, though, it's impractical to run experiments on tens of thousands of different species. (Only a few dozen have been tested so far.) Meanwhile, as the example of coral reefs makes clear, what's more important than how acidification will affect any particular organism is how it will affect entire marine ecosystems—a question that can't be answered by even the most ambitious experimental protocol. The recent report on acidification by Britain's Royal Society noted that it was "not possible to predict" how whole communities would respond, but went on to observe that "without significant action to reduce CO_2 emissions" there may be "no place in the future oceans for many of the species and ecosystems we know today."

Carol Turley is a senior scientist at Plymouth Marine Laboratory, in Plymouth, England, and one of the authors of the Royal Society report. She observed that pH is a critical variable not just in calcification but in other vital marine processes, like the cycling of nutrients.

"It looks like we'll be changing lots of levels in the food chain," Turley told me. "So we may be affecting the primary producers. We may be affecting larvae of zooplankton and so on. What I think might happen, and it's pure speculation, is that you may get a shortening of the food chain so that only one or two species comes out on top—for instance, we may see massive blooms of jellyfish and things like that, and that's a very short food chain."

Thomas Lovejoy, who coined the term "biological diversity" in 1980, compared the effects of ocean acidification to "running the course of evolution in reverse."

"For an organism that lives on land, the two most important factors are temperature and moisture," Lovejoy, who is now the president of the Heinz Center for Science, Economics, and the Environment, in Washington, D.C., told me. "And for an organism that lives in the water the two most important factors are temperature and acidity. So this is just a profound, profound change. It is going to send all kinds of ripples through marine ecosystems, because of the importance of calcium carbonate for so many organisms in the oceans, including those at the base of the food chain. If you back off and look at it, it's as if you or I went to our annual physical and the body chemistry came back and the doctor looked really, really worried. It's a systemic change. You could have food chains collapse, and fisheries ultimately with them, because most of the fish we get from the ocean are at the end of long food chains. You probably will see shifts in favor of invertebrates, or the reign of jellyfish."

Riebesell put it this way: "The risk is that at the end we will have the rise of slime."

Paleooceanographers study the oceans of the geologic past. For the most part, they rely on sediments pulled up from the bottom of the sea, which contain what might be thought of as a vast library written in code. By analyzing the oxygen isotopes of ancient shells, paleooceanographers can, for example, infer the temperature of the oceans going back at least a hundred million years, and also determine how much—or how little—of the planet was covered by ice. By analyzing mineral grains and deposits of "microfossils," they can map archaic currents and wind patterns, and by examining the remains of foraminifera they can re-create the history of ocean pH.

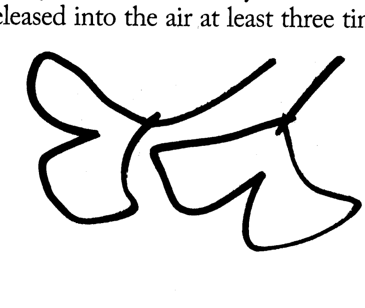
In September, two dozen paleooceanographers met with a roughly equal number of marine biologists at a conference hosted by Columbia University's Lamont-Doherty Earth Observatory. The point of the conference, which was titled "Ocean Acidification—Modern Observations and Past Experiences," was to use the methods of paleooceanography to look into the future. (The ocean-acidification community is still a relatively small one, and at the conference I ran into half the people I had spoken to about the subject, including Victoria Fabry, Ken Caldeira, and Chris Langdon.) Most of the meeting's first day was devoted to a discussion of an ecological crisis known as the Paleocene-Eocene Thermal Maximum, or P.E.T.M.

The P.E.T.M. took place fifty-five million years ago, at the border marking the end of the Paleocene epoch and the beginning of the Eocene, when there was a sudden, enormous release of carbon into the atmosphere. After the release, temperatures around the world soared; the Arctic, for instance, warmed by ten degrees Fahrenheit, and Antarctica became temperate. Presumably because of this, vertebrate evolution veered off in a new direction. Many of the so-called archaic mammals became extinct, and were replaced by entirely new orders: the ancestors of today's deer, horses, and primates all appeared right around the time of the P.E.T.M. The members of these new orders were curiously undersized—the earliest horse was no bigger than a poodle—a function, it is believed, of hot, dry conditions that favored smallness.

In the oceans, temperatures rose dramatically and, because of all the carbon, the water became increasingly acidic. Marine sediments show that many calcifying organisms vanished—more than fifty species of foraminifera, for example, died out—while others that were once rare became dominant. On the seafloor, the usual buildup of empty shells from dead calcifiers ceased. In ocean cores, the P.E.T.M. shows up vividly as a band of reddish clay sandwiched between thick layers of calcium carbonate.

No one is sure exactly where the carbon of the P.E.T.M. came from or what triggered its release. (Deposits of natural gas known as methane hydrates, which sit, frozen, underneath the ocean floor, are one possible source.) In all, the release amounted to about two trillion metric tons, or eight times as much carbon as humans have added to the atmosphere since industrialization began. This is obviously a significant difference in scale, but the consensus at the conference was that if there was any disparity between then and now it was that the impact of the P.E.T.M. was not drastic enough.

The seas have a built-in buffering capacity: if the water's pH starts to drop, shells and shell fragments that have been deposited on the ocean floor begin to dissolve, pushing the pH back up again. This buffering mechanism is highly effective, provided that acidification takes place on the same timescale as deep-ocean circulation. (One complete exchange of surface and bottom water takes thousands of years.) Paleooceanographers estimate that the release of carbon during the P.E.T.M. took between one and ten thousand years—the record is not detailed enough to be more exact—and thus occurred too rapidly to be completely buffered. Currently, CO_2 is being released into the air at least three times and perhaps as much as thirty times as quickly as during the P.E.T.M. This is so fast that buffering by ocean sediments is not even a factor.



"In our case, the surface layer is bearing all the burden," James Zachos, a paleooceanographer at the University of California at Santa Cruz, told me. "If anything, you can look at the P.E.T.M. as a best-case scenario." Ken Caldeira said that he thought a better analogy for the future would be the so-called K-T, or Cretaceous-Tertiary, boundary event, which occurred sixty-five million years ago, when an asteroid six miles wide hit the earth. In addition to dust storms, fires, and tidal waves, the impact is believed to have generated huge quantities of sulfuric acid.

"The K-T boundary event was more extreme but shorter-lived than what we could do in the coming centuries," Caldeira said. "But by the time we've burned conventional fossil-fuel resources what we've done will be comparable in extremeness, except that it will last millennia instead of years." More than a third of all marine genera disappeared at the K-T boundary. Half of all coral species became extinct, and it took the other half more than two million years to recover.

Ultimately, the seas will absorb most of the CO_2 that humans emit. (Over the very long term, the figure will approach ninety per cent.) From a certain vantage point, this is a lucky break. Were the oceans not providing a vast carbon sink, almost all of the CO_2 that humans have emitted would still be in the air. Atmospheric concentrations would now be nearing five hundred parts per million, and the disasters predicted for the end of the century would already be upon us. That there is still a chance to do something to avert the worst consequences of global warming is thanks largely to the oceans.

But this sort of accounting may be misleading. As the process of ocean acidification demonstrates, life on land and life in the seas can affect each other in unexpected ways. Actions that might appear utterly unrelated—say, driving a car down the New Jersey Turnpike and secreting a shell in the South Pacific—turn out to be connected. To alter the chemistry of the seas is to take a very large risk, and not just with the oceans. ♦