NOVA Next

Oceans of Acid: How Fossil Fuels Could Destroy Marine Ecosystems

By Scott Doney on Wed, 12 Feb 2014

In 2005, hatchery-grown oyster larvae in the Pacific Northwest began mysteriously dying by the millions. Then it happened again in 2006. And again in 2007 and 2008. Oceanographers and fisheries scientists raced to understand what was behind the catastrophe. Was it bacterial infections? Or something more sinister?

By 2008, after billions of shellfish larvae had died, they had their answer. The waters of the Pacific Ocean had turned corrosively acidic. The changes were too subtle to be noticed by swimmers and boaters, but to oysters, they were lethal. Many oyster larvae never made it to adulthood. Those that did suffered from deformed shells or were undersized. A $110 million industry was on the brink of collapse.

The oyster industry in the Pacific Northwest, worth over $110 million, is threatened by ocean acidification.

The problem is with the water, of course—its pH had dropped too much—but the root cause is in the winds that blow above the Pacific Ocean. A shift in wind patterns had pushed surface waters aside, allowing acidic water from the deep to well up onto the shore. Even a few decades ago, such upwelling events weren't as acidic and probably wouldn't have been cause for concern. But the oceans absorb massive amounts of CO_2—about one quarter of our excess emissions—and as we pump more of the greenhouse gas into the atmosphere, we are driving the pH of ocean water lower and lower. Today, ocean waters are up to 30% more acidic than in preindustrial times.

In some ways, the problem of the Pacific oyster farms has been a success story. Working with scientists, hatchery operators quickly identified seawater chemistry as the primary culprit and took remedial steps, including placing sentinel buoys offshore that can warn of inflowing acidic water.

Still, the fishery isn't the same. One hatchery even decided to relocate to Hawaii where ocean chemistry remains more conducive to oyster larval growth. They ship the shellfish back to Washington State when they're hardy enough to survive the acidic waters. But not everyone expects that arrangement to last forever. Larger drops in ocean pH are projected in coming decades as fossil fuel use expands, particularly in rapidly developing countries like China and India.

Many people are familiar with the link between using fossil fuels as an energy source and climate change. Less appreciated is how burning fossil fuels changes ocean chemistry. Marine plants, animals, and microbes are bathed in seawater, and somewhat surprisingly, even relatively small alterations in seawater chemistry can have big effects. Oysters are the canary in the coal mine.

A Watery Laboratory

The basic principles of seawater carbon dioxide chemistry were well understood even as far back as the late 1950s when David Keeling started his now famous time-series of atmospheric carbon dioxide measurements (http://www.esrl.noaa.gov/gmd/ccgg/trends/) in Hawaii. Then, levels were at 315 parts per million. Now, a little more than a half-century later, carbon dioxide levels are approaching 400 ppm and continuing to rise as we burn more fossil fuels.

The potential for serious biological ramifications, however, only began to come to light in the late 1990s and early 2000s. Like other gases, carbon dioxide dissolves in water; but in contrast to other major atmospheric constituents —oxygen, nitrogen, argon—carbon dioxide (CO_2) reacts with the water (H_2O) to form bicarbonate (HCO_3^-) and hydrogen (H^+) ions. The process is often called ocean acidification to reflect the increase in acidity—more H^+ ions— and thus lower pH. The other part of the story has to do with the composition of salty seawater. Over geological time scales, weathering of rocks on land adds dissolved ions, or salts, to the ocean, including calcium (Ca^+) and carbonate (CO_3^{2-}) from limestone. Seawater is on the basic end of pH—which greatly increases the amount of carbon dioxide that can dissolve in seawater.

Oyster larvae are particularly susceptible to the effects of ocean acidification.

Oysters are just one of many organisms that are dependent on ocean water plentiful with carbonate ions, a building block that many marine plants and animals use to build hard calcium carbonate ($CaCO_3$) shells. These include corals, shellfish, and some important types of plankton, the small floating organisms that form the base of the marine food web.

Today, there are major research programs around the world that are tracking changes in seawater chemistry and testing how those shifts affect marine organisms and ecosystems. Early experiments involved growing these organisms in the laboratory where seawater chemistry can be easily manipulated. Many of the species tested under acidified conditions had a more difficult time building shell or skeleton material, sometimes even producing malformed shells. Together these factors could slow growth and lower survival of these species in the wild.

The laboratory isn't perfect, though. Unlike most lab settings, in the real ocean, organisms live in a community with many different species and a complex web of interactions. Some species are competitors for space and food; others are potential prey, predators, or even parasites.

Acid Future

We can get a glimpse of what a future acid ocean might look like by traveling to volcanic vents on the ocean floor, where carbon dioxide bubbles into shallow waters. These sites are ready-made laboratories for studying acidification effects on entire biological communities. And surveys of these regions largely validate the results from laboratory experiments. In the highly acidified water, corals, mollusks, and many crustacean species are absent, replaced with thick mats of photosynthetic algae.

Scientists are also moving forward with the engineering equivalent of volcanic vents: deployable systems that can be used to deliberately acidify a small patch of coral reef or volume of the upper ocean. These purposeful manipulation experiments are important tools for moving research out of artificial lab conditions into the ocean.

Volcanic vents in the ocean floor, like this white smoker, provide scientists with ready-made natural laboratories to study acidic waters.

Preliminary results from ocean acidification experiments seemed rather dire. Some predicted that coral reefs would disappear and shellfish supplies would be decimated. But as with many new findings in science, reality may turn out to be more complex, more nuanced, and more interesting. For example, the sensitivity of shell and skeleton formation to carbon dioxide appears to vary widely across groups of biological species and even, in some cases, within closely related strains of the same species.

Volcanic vents give us a glimpse of what a future acid ocean might look like.

Carbon dioxide and pH play a central role in biochemistry and physiology, and further research has shown that acidification may have a much wider range of possible biological impacts beyond simply decreasing shell and skeleton formation. In some plankton and seaweeds, elevated carbon dioxide speeds photosynthesis, the process used to convert carbon dioxide and light energy into organic matter and food.

Acidification also affects the functioning of some small microbes that govern many aspects of ocean and atmosphere chemistry, including the transformation of nitrogen gas into valuable nutrients used by plankton while inhibiting the conversion of other inorganic forms of nitrogen, potentially unbalancing a key ecosystem process. Seawater chemistry of dissolved trace metals could also be upended, for better or worse—some of those metals are essential for life while others are toxic. Still other experiments have even shown changes in fish behavior and their ability to smell approaching predators. Their olfactory nerve cells are stymied by subtle changes in the acid-base chemistry inside their bodies.

Coping with Acidification

So why the range of reactions? One possible explanation is that over evolutionary time-scale species have developed different strategies for coping with life in the ocean, for example differing in the way they form calcium carbonate minerals. In many organisms, biomineralization occurs inside special internal pockets that are not directly exposed to the surrounding ambient seawater. Crustaceans such as crabs and lobsters appear better able to control their internal fluid chemistry, and thus may fare better in acid ocean water than mollusks, such as clams and oysters.

Organisms can often compensate to an external stress such as acidification, at least up to a point. But this requires them to expend extra energy and resources. As a result, larvae and juveniles are often more vulnerable than adults. That’s what happened to oysters in the Pacific Northwest. It’s not that their calcium carbonate shells dissolved in the acidic waters, it’s that they expended too much energy trying to coax enough carbonate out of the water. Essentially they died of exhaustion.

The Pacific Northwest is among the first regions to experience the effects of ocean acidification, but it likely won't be the last.

Another reason why some organisms have escaped is because seawater pH and carbonate ion concentrations vary geographically and temporally across the surface ocean. Productive coastal waters and estuaries can have both much higher and much lower pH levels than open-ocean waters, and water chemistry at specific coastal location can change rapidly over only a few hours to days. Therefore, some coastal species already may be adapted, through natural selection, to more acidic or more variable seawater conditions.

In contrast, open-ocean species may be more sensitive because they are accustomed to a more stable environment. Small, fast growing species with short generation times may be able to evolve to a changing world. As with many environmental shifts, acidification may threaten some species while being relatively inconsequential or even beneficial to others. If acidification were the only threat to marine life, perhaps I wouldn't be so worried about our oceans. But there are many other environmental stresses that stack on top of it, including climate change, pollution, overfishing, and the destruction of valuable coastal wetlands.

Coral reefs are at particular risk from rising atmospheric carbon dioxide's two faces—acidification and global warming. Tropical corals are sensitive to even relatively small increases in summer temperatures. High temperatures can cause coral bleaching, when the coral animals expel the colorful symbiotic algae that usually live inside each coral polyp. Extended heat spells leave the coral vulnerable to disease and, if severe enough, death. Acidification exacerbates coral bleaching. Coral reefs could be greatly diminished once atmospheric carbon dioxide reaches levels expected by the middle of this century, some researchers say.

Acidic waters can cause coral to expel their symbiotic algae, a phenomenon known as bleaching.

Nutrient pollution is another threat. Runoff into coastal waters can be rich in nutrients from fertilizers used in agriculture and landscaping. These excess nutrients cause large plankton blooms that can't sustain themselves. When they eventually collapse, their decaying bodies use up dissolved oxygen and release carbon dioxide into seawater. Low oxygen stresses many marine organisms, and it's made only worse by lower pH. Nutrient pollution causes localized pockets of acidified waters that added to ocean acidification from global fossil fuel emissions of carbon dioxide. Poor water quality and land-based nutrient inputs are contributing to the Pacific Northwest oyster hatchery problem and may currently be the dominant acidification factor in many estuaries and enclosed bays.

Rising atmospheric carbon dioxide is ratcheting up its pressure on marine life. From ice cores, we know that the present-day rate of atmospheric carbon dioxide rise is unprecedented over at least the past 800,000 years. One needs to look back tens of millions of years or more in the geological record for a few time periods with possibly comparable rapid acidification.

While imperfect analogues of today, those geological events were often marked by large-scale extinction of marine species. Combined with what we're seeing in the laboratory and at natural volcanic vents, there is good reason to be concerned that ocean acidification will affect marine life in the decades to come. We still aren't sure exactly how, when, or where. But we can bet it will happen.

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Questions

1. What is an acid? Give the definition of an acid based on your notes.
2. What is pH? What is the range for an acid on the pH scale?
3. What is causing the ocean to become more acidic?
4. What is “ocean acidification”?
5. What are some effects that are being seen because of ocean acidification?