THE SCIENCE AND CONSEQUENCES OF OCEAN ACIDIFICATION

SCIENCE BRIEF 3 AUGUST 2009

Since the Industrial Revolution, the acidity of the world's oceans has increased significantly. This change is entirely the result of human activities. About one third of all the carbon dioxide (CO_2) emitted by human activities has been absorbed by the oceans. The uptake of CO_2 by the oceans produces carbonic acid, altering the chemistry of the oceans and making seawater corrosive to some minerals. Without strong action to reduce CO_2 emissions, the oceans will deteriorate to conditions detrimental to shell-forming organisms, coral reefs, and the marine food chain, thus threatening fisheries and marine ecosystems generally. This brief describes the changes in the chemistry of the world's oceans and explores the potential implications for marine ecosystems and the global food supply.

Greenhouse gas (GHG) emissions from human activity, particularly CO_2 from the burning of fossil fuels, are increasing the heat-trapping capacity of the atmosphere.[1] However, not all of the CO_2 emitted by human activities remains in the atmosphere—about one third of manmade CO_2 emissions have been absorbed by the oceans (Sabine et al. 2004). Without this ocean "carbon sink," the atmospheric concentration of CO_2 would be even higher than it is today. Although the ocean carbon sink has delayed some of the impacts of climate change, the accumulation of carbon in the oceans is beginning to change the chemistry of seawater, which is likely to have detrimental impacts on marine ecosystems and cause the fraction of manmade CO_2 that the oceans can absorb to decrease in the coming decades.

Ocean acidification is happening now. Acidity is measured in pH units, with decreasing pH corresponding to more acidic conditions. Before humans began emitting large quantities of CO_2, the pH of the oceans was 8.1—8.2 (Caldeira and Wickett 2005). Since then, the pH of the oceans has declined by 0.1 unit (Figure 1; Orr et al. 2005; IPCC 2007a). This change might sound small, but it represents a 26 percent increase in acidity.[2] This change is fundamentally altering the seawater chemistry to which marine life has adapted over millions of years. In its Fourth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) estimates from its mid-range projection for future emissions that the pH of the oceans will decline by an additional 0.3 to 0.4 unit (or become 2 to 2.5 times more acidic than the pre-industrial oceans) by 2100 (IPCC 2007b, p. 793).

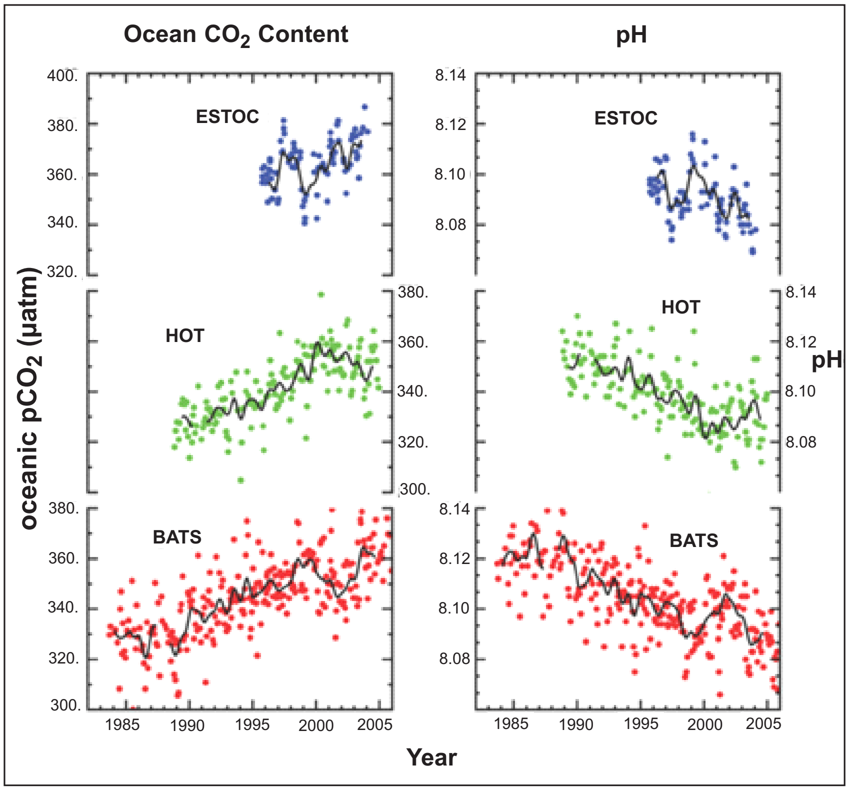

Figure 1: Changes in surface ocean CO_2 content (left) and pH (right) from three measurement stations. The upper data set was recorded in the Atlantic Ocean off the coast of West Africa, the middle data set was recorded near Hawaii, and the lower data set was recorded near Bermuda. Reproduced from Figure 5-9 of the IPCC AR4 WGI (IPCC 2007b, p.404).

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[1] See Pew's Science Brief 1, "The Causes of Global Climate Change".

[2] The pH scale is logarithmic, meaning that 1 pH unit represents a tenfold change in acidity.

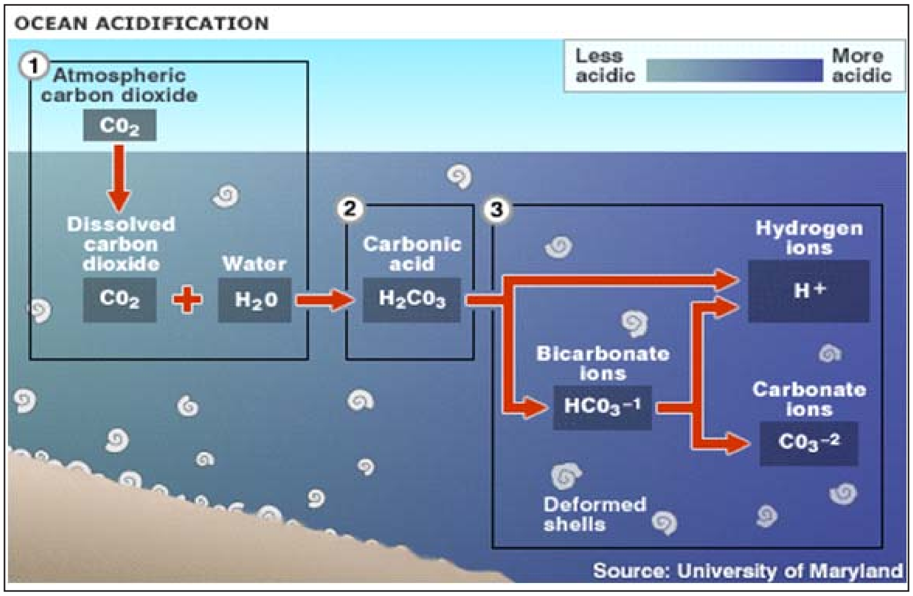
Other models suggest that continued emissions of fossil-fuel CO_2 could lead to a pH drop of 0.7 (which would be five times more acidic than the pre-industrial oceans) by the year 2300, a level not seen in the Earth's oceans in the last 300 million years. Since the oceans have not been so acidic in the last 300 million years, current marine life is not adapted to such conditions (Caldeira and Wickett 2003; Raven et al. 2005). How different organisms in different regions will react remains uncertain, but a pH drop as small as 0.2 unit could harm some that are important to human welfare (Zeebe et al. 2008).

In June 2009, 100 of the world's science academies, including the U.S. National Academy of Sciences, jointly issued a warning about the serious risks of ocean acidification and called for rapid and large reductions in global CO_2 emissions to address the problem[3]:

> *"The rapid increase in CO_2 emissions since the industrial revolution has increased the acidity of the world's oceans with potentially profound consequences for marine plants and animals especially those that require calcium carbonate to grow and survive, and other species that rely on these for food."*

How Does It Work? The Science of Ocean Acidification

Seawater has a unique chemistry. The **marine carbonate buffer system** controls the pH of the oceans by allowing them to absorb far more CO_2 than would be expected based on the solubility of CO_2 alone (Denman et al. 2007). The ultimate effect of adding more CO_2 to seawater is to produce an excess of positively charged hydrogen ions[4], which is the source of acidity (Figure 2). Acids are corrosive because hydrogen ions are extremely reactive. In seawater, hydrogen ions readily attach to carbonate ions (CO_3^{2-}) to form bicarbonate ions (HCO_3^-). Shell-forming marine organisms use carbonate ions to build shells and skeletons made of calcium carbonate ($CaCO_3$), a process called **calcification**. Today, the upper levels of the ocean largely contain enough carbonate ions to sustain marine life as we know it, but as acidity increases fewer carbonate ions will be available for sea organisms to calcify. At high enough concentrations, hydrogen ions can even react directly with calcium carbonate, dissolving existing shells of living organisms.



Source: University of Maryland

Figure 2: Ocean carbonate chemistry. As the oceans absorb CO_2, the dissolved CO_2 reacts with water (H_2O) to form carbonic acid (H_2CO_3). Carbonic acid is relatively unstable and breaks down into a bicarbonate ion (HCO_3^-) and a hydrogen ion (H^+). The conversion of CO_2 to bicarbonate removes a CO_2 molecule from the seawater, making room for another atmospheric CO_2 molecule to dissolve; this property of seawater allows it to absorb more CO_2 from the atmosphere than an equivalent volume of freshwater in a lake or a river. Hydrogen ions, the other product of the conversion process, make seawater more acidic; as the concentration of hydrogen ions increases, the pH decreases. Some of the free hydrogen ions react with carbonate ions to form more bicarbonate ions, shifting the balance to favor bicarbonate over carbonate and reducing the number of carbonate ions in the seawater. Credit BBC News website.

What Is Happening? Harm to Marine Life

Marine organisms have evolved gradually over millions of years, and many are extremely sensitive to changes in the chemical environment, particularly when those changes occur so quickly that the organisms may not be able to adapt to new and changing conditions. The marine ecosystems threatened by ocean acidification represent much of world's biodiversity, and they provide huge benefits to society, including coastal protec-

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[3] http://www.interacademies.net/Object.File/Master/9/075/Statement_RS1579_IAP_05.09final2.pdf

[4] An ion is a molecule or atom that has an overall positive or negative electrical charge. Ions readily react with oppositely charged ions to form neutral (non-charged) substances. This chemical reactivity is why acidification of seawater is important to the biology and carbon uptake capacity of the oceans.

tion, food supply, and aesthetic and economic value through recreation and tourism.

The chemical response of the oceans to increased atmospheric concentrations of CO_2 is well understood, and predictions of future ocean acidity levels under various emissions scenarios are well established. What is less certain is how marine animals and ecosystems will ultimately respond to increased acidity levels. The ability of marine animals (particularly mollusks, corals, and plankton) to make structures out of calcium carbonate is directly affected by changes in ocean carbonate chemistry. While much research remains to be done, ocean acidification and other human-induced stressors (such as coastal development, overfishing, marine pollution, and warmer ocean temperatures) provide "great potential for widespread changes to marine ecosystems" (Fabry et al. 2008).

The recent decline of the Pacific oyster population in the Pacific Northwest appears to be connected to ocean acidification. The decline began in 2005 in Washington State and continued in 2006, 2007, and 2008; two of the largest oyster hatcheries report an 80 percent decline in production rates (Miller et al. 2009). Scientists suspect that more acidic seawater is being pumped into the coastal areas by north winds, which force the surface waters away from the coast and encourage deep water to well up. The deeper waters naturally contain a great deal of CO_2, but human activity has increased the CO_2 load. In a 2007 upwelling event, surface waters in a region near the California-Oregon border reached an astonishingly low pH level of 7.75 (Feely et al. 2008). Because of this high CO_2 content and the corresponding acidity levels, the upwelling waters are corrosive to baby oysters. Ocean acidification will likely affect other shellfish and commercial fish species in coastal ecosystems (Miller et al. 2009).

Much more research is needed to understand how various marine organisms will respond to acidification in nature, but laboratory studies demonstrate that some commercially important species such as mussels and oysters are known to be sensitive to changes in ocean chemistry, and some species of snails and sea urchins have shown reduced shell weights under higher pH (Table 1). These classes of animals may be particularly vulnerable to ocean acidification during larval stages of development (Fabry et al. 2008).

Ocean acidification could even strike at the base of the marine food chain. Tiny floating organisms called plankton serve as a critical food source to shellfish and finfish and play a key role in regulating the carbon cycle by removing CO_2 from surface waters through their biological activities. After they die, the plankton sink to the ocean floor, transporting the carbon they removed from the atmosphere to deep ocean sediments where it is buried. Key shell-forming plankton called foraminifera are very abundant in the oceans and are responsible for much of the carbon removal. In the Southern Ocean, shell weights of foraminifera are currently 30—35 percent lower than the weights of shells that are thousands of years old found in sea sediments, suggesting they may already be affected by acidification (Moy et al. 2009).

Type	Species	pH	CO_2 level	Shell loss	Mortality	Effects
Mussel	*M. edulis*	7.1	740 ppm	Y	Y	25% decrease in calcification rate
Pacific Oyster	*C. gigas*		740 ppm			10% decrease in calcification rate
Giant scallop	*P. magellanicus*	<8.0				Decreased fertilization and embryo development
Clam	*M. mercenaria*	7.0-7.2		Y	Y	
Crab	*C. pagurus*					Reduced thermal tolerance
Crab	*N. puber*	7.98-6.04		Y		Disruption of internal chemistry
Sea Urchin	*S. purpuratus*	6.2-7.3		Y		Lack of pH regulation
Dogfish	*S. canicula*	7.7			Y	
Sea bass	D. labrax	7.25				Reduced feeding

Table 1: Results from laboratory experiments showing effects of ocean acidification on selected species. Adapted from Cooley and Doney (2009) and based on review by Fabry et al. (2008).

Coral Reefs as a Case Study

Coral reefs offer a compelling case of the risks associated with ocean acidification. These “rainforests of the seas” harbor a large fraction of the planet’s biodiversity. Reefs are unique ecosystems that provide important services to society, ranging from habitat for fisheries to coastal protection against tsunamis and storm surges. Reefs support many millions of people around the world who rely on them for subsistence food gathering, particularly in the developing world, and many more people are supported through industries such as tourism and fishing (Raven et al. 2005).

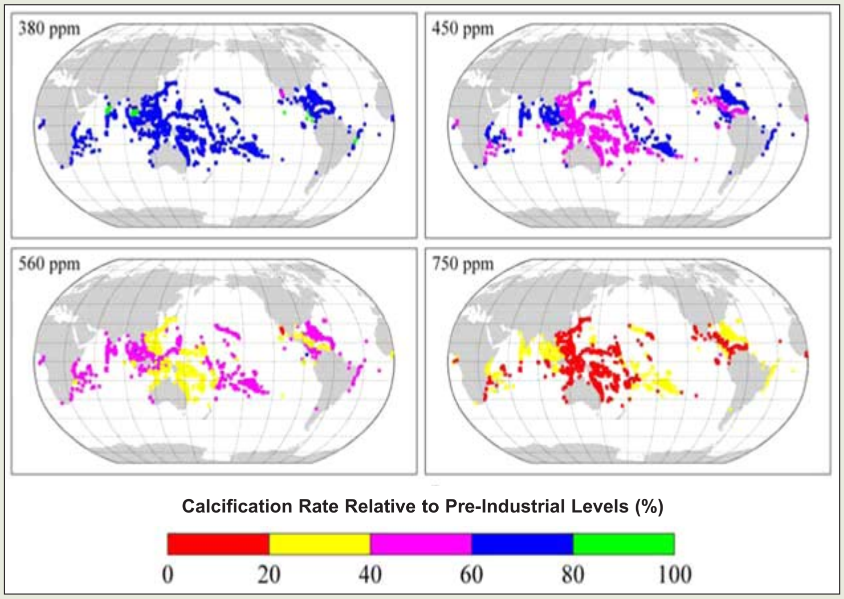

Figure 3: These world maps show the location and anticipated decline of the world’s coral reefs. Each map represents the ocean water pH for a given atmospheric CO_2 stabilization level. The colors indicate the rate of calcification of coral reefs relative to the pre-industrial rate, when the CO_2 concentration was about 280 ppm. Reproduced from Silverman et al. (2009).

Corals have adapted over millions of years to the chemistry and temperature of the oceans, and they are extremely vulnerable to changes in their physical environment. They are already experiencing damage due to ocean acidification. A study of 328 coral colonies from 69 reefs in Australia’s Great Barrier Reef demonstrated that these corals are under increasing stress from both ocean acidification and rising ocean temperatures. Calcification of corals throughout the Great Barrier Reef has declined 14.2 percent since 1990. Such a large and rapid decline is unprecedented in coral records dating back 400 years (De'ath, Lough, and Fabricius 2009).

The combination of rising ocean temperatures and increased acidity will likely cause major changes to coral reefs over the next few decades and beyond (Raven et al. 2005). Already, CO_2 concentrations have risen enough that calcification rates in corals will drop to 60-80 percent of their pre-industrial values (Figure 3). Existing reefs may even begin to dissolve at atmospheric CO_2 concentrations as low as 560 ppm, which could be reached by the middle of this century if emissions are not curbed (Silverman et al. 2009).

Reefs provide a variety of economic benefits, including recreational activities, tourism, coastal protection, habitat for commercial fisheries, and preservation of marine ecosystems. An analysis of potential impacts on coral reefs concluded that annual losses in 2100 could total $870 billion (Brander et al. 2009). That analysis considered only damages that could readily be monetized, such as tourism (including activities such as diving and snorkeling) and the harvesting of important commercial fish species that rely on reefs for habitat.

Coral reefs have other benefits to society that are not easily quantified and are generally excluded from economic analyses. For instance, reefs aid in coastal protection. A modeling study indicated that healthy reefs within a meter or two of the ocean surface help reduce tsunami run-up on land by around 50 percent (Kunkel, Hallberg, and Oppenheimer 2006). Anecdotal reports[5] following the 2004 Indian Ocean tsunami and scientific research appear to validate this finding (Fernando et al. 2005).

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[5] “On Asia’s Coasts, Progress destroys natural defenses,” *The Wall Street Journal* 12/31/04, reported by A. Brown, http://online.wsj.com/article/SB110443750029213098.html.

What Does the Future Hold? Projected Impacts on Marine Life

As discussed below, ocean acidification has the potential to negatively impact many forms of marine life. Some organisms, like oysters, may already be affected. Without significant reductions in CO_2 emissions, ocean conditions are expected to deteriorate further over this century, reaching acidity levels that could be detrimental to many vital species.

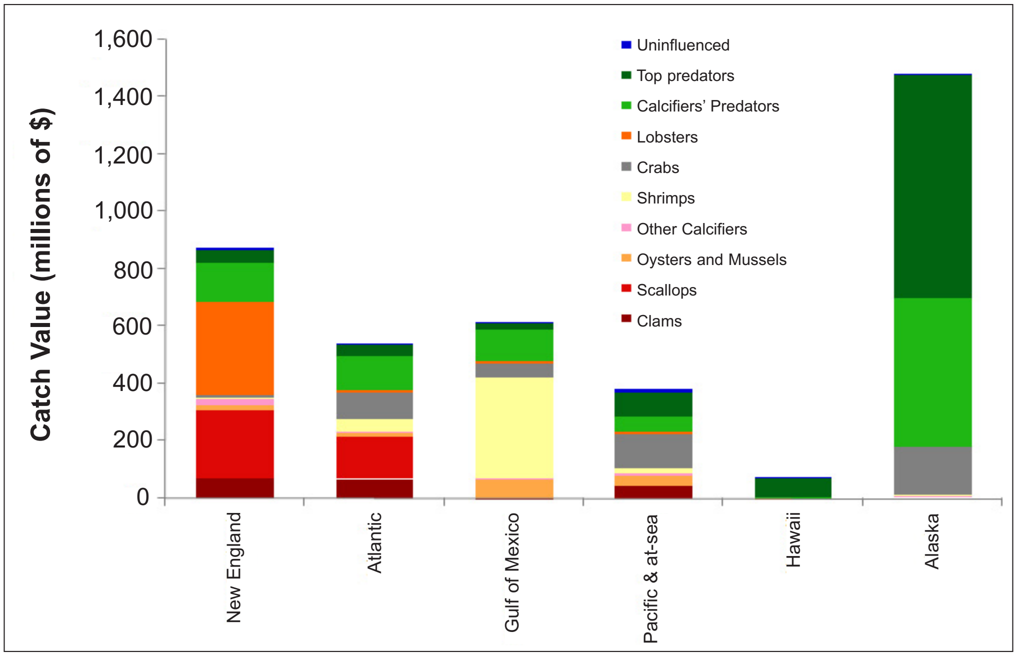

Figure 4: U.S. Commercial fishing revenue for 2007. Total for entire U.S. was $3.97 billion. Adapted from Cooley and Doney (2009).

Observations of marine ecosystems affected by natural underwater volcanic CO_2 vents provide clues into the long-term impacts of acidification. Although volcanic vents emit a tiny amount of CO_2 compared to human activities, they can drastically alter local marine environments, providing a natural laboratory for studying the effects of ocean acidification. A study of one vent site in the Mediterranean Sea found that the presence of one species of calcifying algae (which helps prevent coral reef erosion in the tropics) was reduced significantly at acidity levels expected by the end of the century and replaced by non-calcifying algal species more resilient to higher acidity (Hall-Spencer et al. 2008; Hoegh-Guldberg et al. 2007). This indicates that acidification may benefit highly invasive, non-native algal species. The potential for dramatic changes in marine environments illustrates the danger of ocean acidification, which "will probably bring about reductions in biodiversity and radically alter ecosystems" (Hall-Spencer et al. 2008).

Shellfish may be further negatively impacted by increasing acidity of surface ocean waters. Experiments on the edible mussel and the Pacific oyster show that these organisms exhibit a strong decrease in calcification rates as a function of increasing CO_2, decreasing pH, and decreasing carbonate concentrations (Table 2; Gazeau et al. 2007). These two species are important to coastal ecosystems and are a large portion of worldwide seafood production. The predicted decline in calcification of mussels and oysters will likely have negative impacts on coastal biodiversity and lead to economic losses.

Changes to the physical marine environment may also result in unanticipated consequences of ocean acidification. As the pH of the oceans decreases, low frequency sound absorption decreases; the anticipated decrease of 0.3 pH unit would decrease sound absorption by 40 percent. Increased noise from passing ships, due to critical environmental, economic, and military interests, may affect marine mammals, and it is unclear how they might adapt (Hester et al. 2008).

As discussed previously, certain species of calcifying plankton form the base of the marine food chain and also face detrimental conditions under increasing acidity levels. As these species decline or disappear, larger animals that feed on them may be affected, potentially leading to ripple effects throughout the ocean food chain (Fabry et al. 2008). The Southern Ocean, which surrounds Antarctica, already has the lowest amounts of carbonate because it is colder than the other oceans. As early as the 2030s, seawater there may be able to dissolve the shells of calcifying organisms in the wintertime (McNeil and Matear 2008). This could have potentially dramatic consequences for the marine food chain in this region, since important species of plankton go through larval developmental stages in winter.

Why Should We Care? Economic Implications of Ocean Acidification

The fundamental chemistry of the oceans is changing, and the impacts to marine life from these changes will impact human society. The socio-economic value of coral reefs, for example, has been highlighted (see *Coral Reefs as a Case Study*).

In addition to damaging coral reefs, ocean acidification will affect human society through its impact on fisheries, with the possibility of declining harvests and loss of fishery revenues from shellfish and their predators. According to the United Nations Food and Agriculture Organization,[6] global fisheries provide around 15 percent of the animal protein consumed by humans worldwide (much higher in Africa and Asia), provide direct and indirect employment for nearly 200 million people, and generate $85 billion annually. In 2007, the U.S. annual domestic commercial fisheries contributed $34 billion to the U.S. GNP (Cooley and Doney 2009). Mollusks, such as oysters and mussels, contributed 19 percent of the value of the commercial harvest for 2007, crustaceans about 30 percent, and some 24 percent of revenues came from fish that prey directly on calcifiers (see Figure 4). Ocean acidification could therefore lead to "substantial revenue declines, job losses, and indirect economic costs" (Cooley and Doney 2009).

Economic losses from decreased fishery harvests will be concentrated in specific regions that rely heavily on such income. New Bedford, MA is a prime example—the city has traditionally relied on fishing income and was the top U.S. port in terms of mollusk harvest in 2007. A 25 percent loss due to ocean acidification could lead to direct revenue losses of between $0.5 and $2.2 billion by 2060, and that estimate does not include indirect losses (Cooley and Doney 2009). That could be economically devastating to a city like New Bedford, which has already seen a 25 percent drop in seafood products employment from 1992—1999 and 20 percent of its residents falling below the poverty line in 1999.

What Can We Do About It? Solutions

The emission of CO_2 from human activities is driving fundamental changes in the chemistry of the oceans. These changes are essentially irreversible—it will likely take many thousands of years for natural processes to remove the excess CO_2 that has been absorbed by the oceans (Raven et al. 2005). Damage from ocean acidification could be permanent, and adaptation options for managing the expected changes are still being developed.

Federal Action on Ocean Acidification

Congress has signaled an interest in studying ocean acidification. The Federal Ocean Acidification Research and Monitoring Act of 2009, signed by President Obama on March 30, 2009, requires federal agencies to coordinate research and monitoring of the acidification of the world's oceans and to develop a strategic plan to assess impacts and recommend solutions. The Act also establishes a research program on ocean acidification at the National Oceanic and Atmospheric Administration (NOAA).

In response to a petition from the Center for Biological Diversity, the Environmental Protection Agency has agreed to consider how ocean acidification could be addressed under the Clean Water Act.[7] If the EPA agrees to change the standards for the pH of seawater—which has not been updated since 1976—in light of the predicted impacts of ocean acidification, regulation of CO_2 emissions under the EPA's current authority to regulate water quality could be one mechanism to mandate a reduction in domestic CO_2 emissions.

Climate engineering approaches that do not address the amount of CO_2 in the atmosphere would not alleviate ocean acidification. One idea is injecting tiny particles into the upper atmosphere to reflect incoming sunlight and cool the Earth's surface, but if emissions continue unabated, ocean acidification would also continue. One way of capturing carbon from power plants (one of the biggest sources of GHG emissions) and keep it from being released into the atmosphere is to pump CO_2 directly into the deep oceans, but this runs the risk of worsening chemical changes to the oceans (Raven et al. 2005). Adding limestone to the oceans to counteract the increased acidity levels would not completely reverse the effect and may also cause severe local environmental degradation, in addition to being cost prohibitive and energy intensive on a global scale (Raven et al. 2005). **The only reliable method for reducing the impacts of ocean acidification is to reduce and ultimately stop CO_2 emissions from human activity** (Raven et al. 2005).

The impacts of ocean acidification on coral reefs in particular are further exacerbated by other stressors, including coastal development, marine pollution, and overfishing. To help reefs survive acidification, these stressors, also caused by human activities, must be reduced in combination with policies to reduce future CO_2 emissions.

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[6] "The State of the World's Fisheries and Aquaculture" (2008), available at http://www.fao.org/docrep/011/i0250e/i0250e00.HTM

[7] http://www.epa.gov/waterscience/criteria/aqlife/marine-ph.html

Summary

Ocean acidification has already been observed and will continue to worsen as CO_2 emissions from human activity continue. The IPCC notes that “ocean acidification is not a direct consequence of climate change but a consequence of fossil fuel CO_2 emissions, which are [also] the main driver of the anticipated climate change” (Denman et al. 2007). Changes in ocean chemistry are likely to negatively impact marine organisms that make shells from calcium carbonate, and many could die off under the extreme conditions projected for 2100. Such fundamental changes would harm biodiversity of marine ecosystems, reduce tourism and recreational activities, interrupt the ocean’s natural food chain, disrupt the Earth’s carbon cycle, and contribute to the decline of fisheries, thus threatening the world’s food supply.

Expanded efforts are now underway to better understand the relationship between CO_2 emissions and ocean acidification, as well as its impact on marine organisms and society. The risks of ocean acidification are just now beginning to become an important new part of the policy dialogue about potential responses to our continued reliance on coal, oil, and natural gas.

> ***“Ocean acidification will impact the millions of people that depend on seafood and other ocean resources for their livelihoods. Losses of crustaceans, bivalves, their predators, and their habitat—in the case of reef-associated fish communities—would particularly injure societies that depend heavily on consumption and export of marine resources.”***
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> Scott Doney, Woods Hole Oceanographic Institution[8]

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[8] http://www.sciencedaily.com/releases/2009/06/090601111948.htm

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