Written Testimony of Sam Waterston
Subcommittee on Oversight and Subcommittee on Water and Wildlife of the Environment and Public Works Committee
Hearing on EPA's Role in Protecting Ocean Health

May 11, 2010

I. Introduction

Thank you for the opportunity to provide testimony on an issue that I care deeply about. I serve as a member of the Board of Directors of Oceana, a global ocean conservation organization based here in Washington, D.C. that works to protect and restore the world's oceans. Besides our headquarters in Washington DC, Oceana also has staff located in Alaska, California, New York, Oregon, and Massachusetts, as well as international offices in Brussels, Belgium; Madrid, Spain; Belize City, Belize; and Santiago, Chile. We have more than 300,000 members and supporters from all 50 states and from countries around the globe. Our mission is to protect our oceans and the fish and wildlife that depend on them.

Today, I will present testimony regarding the threat of ocean acidification to our oceans. Since the industrial revolution, humans have been burning fossil fuels and producing carbon dioxide at an alarming rate. While atmospheric carbon dioxide fluctuates in the short term, the most dramatic increase in the past 1000 years has occurred since the beginning of the Industrial Revolution, more than 250 years ago. The concentration of carbon dioxide in the atmosphere is currently 387 part per million (ppm), which is already almost 40% greater than the pre-industrial level of 280 ppm. The current level of carbon dioxide in the atmosphere is higher than any other time in the last 800,000 years.

Where does all of this carbon dioxide go? About 30% is absorbed by the oceans. [1] The oceans are the largest repository for anthropogenic carbon dioxide on Earth, having absorbed over 460 billion metric tons of carbon dioxide since the Industrial Revolution.[2] Currently, the world's oceans absorb about 30 million metric tons of carbon dioxide daily[3], nearly twice the amount of carbon dioxide that is emitted in the United States each day.[4]

There is no debate that carbon dioxide is changing our oceans. Ocean acidification is a result of a simple chemical reaction that occurs when carbon dioxide combines with seawater. When seawater reacts with carbon dioxide, it forms carbonic acid, making the water more acidic. The acidity of the oceans has increased by 30% since the Industrial Revolution[5], and if current emissions trends continue, it could rise by another 100% by the end of the century[6], making it higher than any other time in the past 20 million years.[7]

A tool used to measure the relative acidity of a liquid is the pH scale. The pH scale runs from 0 (a highly acidic solution) to 14 (a highly basic solution). For example, vinegar has a pH of 2, pure water has a pH of 7, and bleach has a pH of 13. The pH of the ocean surface has already fallen 0.1 units, representing a 30% increase in acidity.[8] The pH scale can be misleading because it is logarithmic, so while 0.1 units may sound insignificant, it actually represents a major change in acidity. If we continue to emit carbon dioxide at current levels, it could fall by another 0.3 units.[9] In the last 300 million years, the pH of the oceans has never fallen to more than 0.6 units below the level it was at the start of the Industrial Revolution.[10]

These chemical changes to seawater impact marine life. Large additions of carbon dioxide can reduce the availability of ions that are essential to animals that form calcified shells, such as corals, mollusks, crabs and lobsters, as well as organisms at the bottom of the food chain, like swimming sea snails, pteropods. Increased acidity reduces the availability of carbonate which is vital to sea life. In the future, the oceans could experience a reduction of carbonate so significant that calcium carbonate shells and skeletons could start to dissolve.

Ocean acidification is already having a negative impact on marine organisms, including decreased growth rates of some corals on the Great Barrier Reef [11] and massive die-offs of oyster larvae in commercial hatcheries on the West Coast. If current emissions trends continue, reefs will continue to degrade and could be pushed past a tipping point, which is likely to occur at an atmospheric carbon dioxide concentration of 450 ppm. Beyond this tipping point, reefs as we know them would be threatened with extinction.[12] Tropical coral reefs could be gone by the middle to end of this century.[13] Since coral reefs take decades or even centuries to form, once the damage is done, the impacts will be irreversible for generations.

The loss of coral reefs would mean a loss of habitat for many millions of species. Reefs provide homes, nurseries, feeding grounds and spawning sites to a diversity of life that is virtually unparalleled anywhere else in the world. Without reefs, severe consequences would result for as many as nine million different species (including four thousand species of fish) that rely on reefs for shelter and nourishment.[14] Coral reefs are often called the rain forests of the sea, I actually like to call rain forests the reefs of land because reefs are more diverse and hold more life than rain forests do.

Cold water, deep sea corals are especially at risk, particularly since acidification is occurring more rapidly in colder waters. Carbon dioxide is more soluble in cold water, accelerating the rate of ocean acidification in these areas. Not only are cold water deep sea corals at risk, but acidification also threatens the many marine species that rely on deep sea corals for their habitat. Since a large portion of the U.S. fishing industry relies on cold, deep waters ocean acidification would impact the industry and the people who rely on it for food and jobs.

Coral reef ecosystems provide food for millions, they protect coastal communities from storms and erosion, they provide habitat and feeding, nursery and spawning grounds for many commercially important fish species, and they provide jobs and income to local economies. An estimated half billion people worldwide rely on coral reefs for food, income, and protection, and provide a net global economic benefit of approximately $30 billion per year.[15]

Coastal economies rely on healthy oceans. Coastal tourism and recreation produce $70 billion in annual revenue in the United States.[16] In 2008, commercial fisheries contributed almost $70 billion in economic activity to the United States gross domestic product (GDP) and recreational fisheries contributed more than $31 billion to the GDP in 2006.[17,18] Coastal and marine waters support over 28 million jobs, and provide a tourism destination for 180 million Americans each year.[19]

The impact to commercial and recreational fisheries has the potential to be devastating. On the West Coast, an upwelling of acidified water occurred to an extent not expected to occur until 2050. At the same time, major die-offs occurred in oyster beds in the area. The oyster industry in the Pacific Northwest contributes more than 100 million to the economy each year, but in 2007 and 2008, one of the region's largest oyster hatcheries, the Whiskey Creek[20] Shellfish Hatchery at Netarts Bay, saw a 70-80% decrease in production.[21] Initially attributed to a bacterium, scientists eventually determined that the die-offs were in fact due to the acidity of the seawater. Similar experiences have been reported with clams in East Coast bays, and acidified water has been observed in the rich fishing grounds off Alaska, such as the Bering Sea.

Not only will marine calcifiers be impacted, but so will the animals that rely on them as a food source. In the cold waters of the polar and sub-polar regions, many species, including whales and salmon, rely on tiny marine organisms called pteropods, or swimming sea snails, as their major food source. Pteropods account for up to 45 percent of the diet of the Alaskan pink salmon.[22] Preliminary studies indicate that a 10 percent reduction in pteropod production could result in a 20 percent reduction in pink salmon body weight.[23] Because pteropods exist in cold water regions, they are particularly vulnerable to ocean acidification, and a disruption in pteropod production means a disruption at the base of marine food webs. Rising acidity could ultimately affect even the largest of top predators in the oceans, as well as many fisheries.

Action is needed and it is needed now. While research and monitoring are necessary to mitigate the damage due to ocean acidification, the only way to actually stop acidification is to reduce carbon dioxide emissions. Burning fossil fuels such as oil and coal makes ocean acidification worse and contributes to climate change. We must cap and reduce carbon emissions to stop the acidification of our oceans and promote U.S. innovation and investment in renewable carbon-free fuels.

II. A Clean Energy Future Without Offshore Drilling

Rather than perpetuating our addiction to fossil fuels, Congress should create an energy policy that increases investments in responsible renewable energy development consistent with the protection of wildlife and habitat, and that promotes energy efficiency and conservation, while creating jobs in new clean energy sectors, without putting our oceans and coasts and the economies they support at risk.

In the face of ocean acidification and climate change, the continued extraction and burning of offshore oil and gas reserves makes even less sense. Alternative offshore resources, such as wind, have the potential to contribute greatly to our energy needs, while drastically reducing carbon dioxide emissions. Offshore wind farms do not pollute the air, water, or coastal communities.

The recent tragic events in the Gulf of Mexico provide incentive and urgency to end new offshore drilling, including any exploratory wells. All new leasing should be permanently off the table. As of May 5th, about 4 million gallons have spilled into the Gulf of Mexico, and an estimated 200,000 gallons still freely flows into the surrounding waters each day. It is still unclear what the long term impact to the Gulf coast, fisheries, wildlife and economy from this tragedy will be. What is clear is that we can't let this happen again.

The oceans can and should be part of the solution. The United States has a great resource offshore that could power our economy cleanly, and create hundreds of thousands of jobs for generations to come. The U.S. offshore wind resource is arguably the best in the world. The Department of the Interior estimates offshore wind could provide more electricity than the current U.S. demand.[24] If we follow Europe's example and significantly develop this resource, it could create well over 300,000 jobs by 2030.

Europe is already realizing the potential of their offshore wind resource. More than two gigawatts of offshore wind farms are installed off European coasts[25] – or about as much as two nuclear power plants. The United Kingdom has the most offshore wind farms currently installed and by 2020, the UK plans to install enough offshore wind farms to power every household in the country.[26]

Europe's ambitious offshore wind plans will not only supply substantial amounts of clean energy, but will also support nearly 300,000 direct and indirect jobs annually by 2030.[27] These "Green Collar" jobs will slash carbon dioxide emissions by 200 million metric tons annually[28]- helping prevent the worst effects of climate change and ocean acidification. Even China recognizes the significance of offshore wind energy – that country just last month finished the installation of its first offshore wind farm near Shanghai.[29]

The United States has been a laggard when it comes to offshore wind. But, just two weeks ago, Secretary of the Interior, Ken Salazar approved the country's first ever offshore wind farm – the Cape Wind project off Massachusetts's coast. Cape Wind and other United States projects will benefit from the nearly 20 years of offshore wind experience gathered from operational European offshore wind farms. Offshore wind power is a reality, and we need to play catch-up with the rest of the world to develop this amazing resource.[30] The Senate should prioritize innovation and incentives for clean, renewable energy that will not put our oceans and coastal economies at risk. This is the future and as country that prides itself and benefits from being a leader technologically, the United States should be a leader here.

III. Cap and Reduce Carbon Dioxide Emissions

The only way to stop ocean acidification is to cap and reduce carbon dioxide emissions. Any climate legislation moving forward must reduce carbon dioxide to levels low enough to still allow for healthy, robust and productive oceans.

The International Panel on Climate Change (IPCC) concluded that in order to stabilize carbon dioxide in the atmosphere at 350 ppm, global carbon dioxide emissions would need to be cut 85 percent below 2000 levels by 2050.[31] There are several pieces of climate legislation under consideration by Congress this session, and it is vital that we remain focused on passing the strongest possible bill if we hope to halt ocean acidification as well. Obviously ocean acidification being simple chemistry lends force for immediate action on climate change and its effects.

Furthermore, the Environmental Protection Agency's authority to regulate greenhouse gases must be preserved. Any actions to the contrary undermines the finding announced on April 24, 2009 by the administrator of the EPA that greenhouse gas emissions are a threat to public health. This finding is consistent with the 2007 Supreme Court decision in *Massachusetts vs EPA* which ruled that under the Clean Air Act, the EPA is responsible for regulating greenhouse gas pollution as it endangers public health.

The Senate must be diligent in passing the strongest possible climate legislation. This means remaining focused on increasing investments in clean energy technology such as solar and wind; reducing harmful giveaways to fossil fuel industries such as coal and oil; and stopping any new offshore drilling, including any exploration, off our coasts. Ocean acidification is simple chemistry that is observable and preventable if we take action now to reduce the amount of carbon dioxide in the atmosphere. From the decreased growth rates of corals on the Great Barrier Reef to the massive die-offs of oyster larvae at the Whiskey Creek Oyster Hatchery in Oregon, acidification is already beginning to damage ecosystems and fisheries alike.

IV. Support Implementation of the FOARAM Act

Last year, Congress passed the Federal Ocean Acidification Research and Monitoring (FOARAM) Act, which represents a great first step in addressing ocean acidification. The FOARAM Act recognized the lack of funding and coordination of research, and called for the development of an interagency plan for ocean acidification research and monitoring. The bill authorized $55 million over four years for the National Oceanic and Atmospheric Administration (NOAA) and $41 million over four years for the National Science Foundation (NSF).

The FOARAM Act is a great starting point, and now that the funds have been authorized, it is time to appropriate those funds at their full levels. Acidification is a serious threat to our oceans, and the federal agencies need to seriously addressing it. Implementing and fully funding the FOARAM Act will allow for monitoring and research into the impacts of acidification and the development of strategies to assist marine organisms and ecosystems in adapting to the harsh new environment.

V. Conclusion

Ocean acidification poses a grave threat to marine wildlife, fisheries, and coastal economies. While the chemistry driving acidification is simple and broadly accepted, less is understood about the exact impacts that it will have on marine ecosystems. One thing we do know is that the impacts will be far-reaching and potentially catastrophic.

In order to stop further ocean acidification, we must cap and reduce carbon dioxide emissions now to turn the tide on ocean acidification. Carbon dioxide emissions are wreaking havoc on our air and our oceans, and we must act now to restore the health of our planet.

Our oceans are already under extreme stress from acidification, overfishing, warming and pollution. As illustrated by the recent disaster with the Deepwater Horizon rig in the Gulf of Mexico, offshore oil and gas drilling is a dangerous endeavor, and one where the risk far outweighs the reward. Ending all new offshore drilling, including exploratory wells, in U.S. waters including the Arctic will protect coastal communities, economies and marine life from further impacts of drilling.

Even with the strongest possible climate legislation, it will take time to reduce atmospheric carbon dioxide, and acidification will continue to impact our oceans. Funding for research and monitoring programs such as that authorized in the FOARAM Act must be appropriated so that work can begin to restore the health of our oceans. The programs outlined in the law must be implemented immediately in order to prevent further losses to our fisheries such as those suffered by the West Coast oystermen.

The House of Representatives introduced H. Res. 989 on ocean acidification in December. This resolution supports adopting national and international policies to prevent acidification and to research and address the impacts of ocean acidification on marine ecosystems and coastal communities. The Senate should introduce and pass a companion resolution.

For the health of marine wildlife, coastal tourism and recreation economies, and the vitality of our nation's fisheries, it is time to take action to stop destroying oceans.

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Photo: Dave Burdick

ACID TEST:

CAN WE SAVE OUR OCEANS FROM CO_2?

Ellycia Harrould-Kolieb
Jacqueline Savitz
Second Edition June 2009

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Photo: NOAA/James Walter

"Not only are the oceans warming and rising, but they are also becoming more acidic."

EXECUTIVE SUMMARY

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Introduction

Climate change is now widely recognized as the most significant environmental challenge of our time. This does not just mean that the environment or 'nature' is in danger. We too will suffer the consequences. We are inherently inseparable from the environment around us and are reliant upon the services it provides, from the air we breathe and the climates we inhabit, to the fertilized crops we consume. We are exquisitely adapted to the Earth as we know it. Unfortunately, our activities are now altering the balance of gases in the atmosphere—the very gases that help regulate the temperature and climate.

Our ever-growing greenhouse gas emissions, predominantly carbon dioxide, are trapping more heat in the atmosphere, causing the temperature of the Earth's surface to rise. The result? Melting ice caps, sea level rise, hotter average temperatures, shifting wildlife populations, changing disease patterns, and more severe droughts and storms.

The disrupted climate system will dramatically change the way people live on this planet. We can expect to see more heat-related sickness and death, and food supplies and food prices disrupted by more severe droughts. There will likely be widespread hunger in some countries and perhaps even famine. Rising sea levels will flood huge swaths of coastline. Within the coming centuries some of the world's largest and most important cities—including New York City, Bangkok and London—will be at risk of flooding and even total immersion. Entire countries such as Bangladesh and most small island nations will lose significant land area forcing millions of climate refugees to flee the rising seas.

Along with a disrupted climate system, our emissions of carbon dioxide are having a severe, but more insidious, impact on the oceans. The oceans absorb roughly 30 percent of global carbon emissions and 80 percent of the heat generated by increased levels of greenhouse gases, thereby mitigating some of the climate change that would otherwise occur.[1,2] However, this relief comes at a great cost. Not only are the oceans warming and rising, but they are also becoming more acidic.

The increasing amount of carbon dioxide in the oceans results in reactions that are changing the chemistry of the oceans, through a process known as ocean acidification. This threatens marine organisms like hard corals, clams and crabs that create calcium carbonate shells and skeletons. The acid created by excess carbon dioxide in the oceans takes the materials these organisms would otherwise use to create shells and skeletons, and makes it unavailable. This makes it increasingly difficult for corals and other marine animals to strengthen existing structures and build new ones. If ocean acidification continues, the very water that these organisms live in could become so corrosive that it would dissolve their shells and skeletons directly.

While the chemical processes making the oceans more acidic are well understood and accepted, we are just beginning to understand the wide-ranging effects acidification is likely to have on marine wildlife. Increased acidity may not directly kill non-calcifying organisms, but many are likely to be harmed in ways that reduce their overall fitness and ability to survive. These impacts could include decreased growth rate, reduced reproduction, disrupted respiratory and nervous system function and increased susceptibility to predators and disease, all of which could produce ripple effects through food webs and ecosystems. Ultimately, ocean acidification could transform the oceans, leaving them far less diverse and productive and making the lives and livelihoods of those who depend on them far more uncertain.

According to Stanford University oceanographer Ken Caldeira and his colleagues:

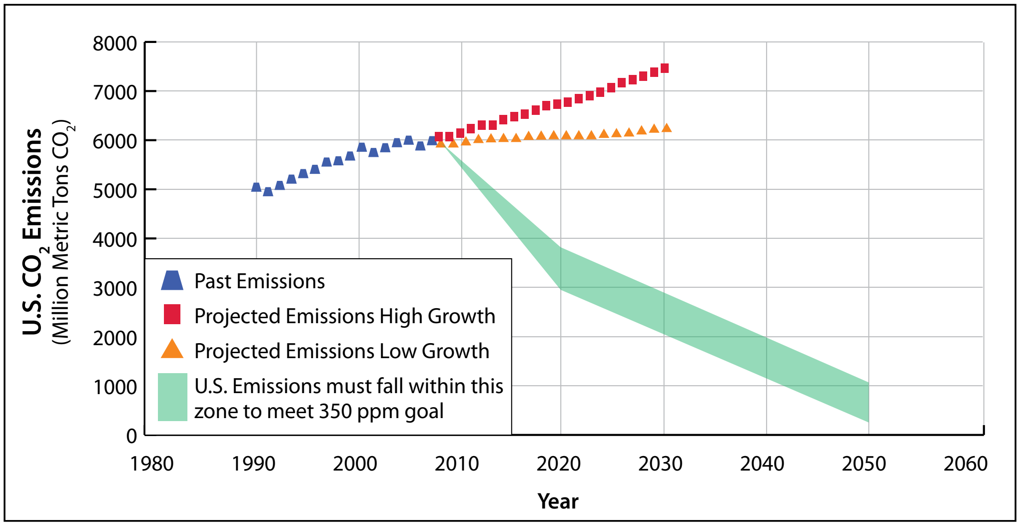
> *"[The] chemical effects of CO_2 on the marine environment may be as great a cause for concern as the radiative effects of CO_2 on Earth's climate."*[3]

"The longer we wait to act the more difficult averting catastrophe becomes"

Reaching the Limits

Current atmospheric carbon dioxide concentrations are already above safe levels. As a result, significant changes are already taking place throughout the oceans, from decreasing growth rates of corals on the Great Barrier Reef to massive coral bleaching events across the tropics. Coral reefs provide important habitat to a quarter of all marine species and are critical to the lives and livelihoods of many humans. Allowing coral reefs to disappear would result in intolerable changes throughout the oceans and to the lives of hundreds of millions of humans. What happens to coral reefs will foreshadow other catastrophic changes that are likely to take place around the world due to ocean acidification and climate change.

Projected U.S. CO_2 Emissions vs. Emissions Trajectory for 350 ppm



Source: Oceana, based on EIA (2008) and IPCC (2007)

To prevent the loss of coral reefs, and ultimately avert a climate crisis, we must reduce atmospheric carbon dioxide levels below 350 parts per million (ppm).[4] Unfortunately, carbon dioxide in the atmosphere has already reached 385 part per million and is still climbing.[5] This current level is also much higher than it has been at any time over the course of human civilization.[6]

In today's society carbon dioxide emissions are directly tied to our continually growing need for energy. Recent figures released by the U.S. Energy and Information Administration (EIA) suggest that staying on the current business-as-usual (BAU) path, where current laws and policies remain unchanged, will result in world energy consumption in 2030 that is 50 percent above 2005 levels.[7] This would result in an atmospheric carbon dioxide concentration of over 570 ppm.[8]

If we continue along our current emissions path reefs will continue to degrade and could be pushed passed a tipping point, which is likely to occur at an atmospheric carbon dioxide level of around 450 ppm. At this point, reefs as we know them would be threatened with extinction. Once we surpass this tipping point coral reefs will shrink rapidly,[9] and at least half of coral-associated wildlife will become rare or extinct. Shortly after that, coral reef ecosystems will likely be reduced to crumbling frameworks with few calcareous corals remaining.[10] Since coral reefs take decades or even centuries to form, once such damage is done, the impacts will be irreversible for generations.

To save coral reefs from ocean acidification, we must stabilize atmospheric carbon dioxide at or below a concentration of 350 ppm. By doing so, we will also prevent other climate-related catastrophes. Current atmospheric carbon dioxide levels already exceed this amount, and with a projected increase over the coming decades it is vital to get on the right trajectory within the next few years and to make sure that carbon emissions peak and begin to decline within a decade.

The Intergovernmental Panel on Climate Change (IPCC) concluded that in order to stabilize carbon dioxide in the atmosphere at 350 ppm, global carbon dioxide emissions would need to be cut 85 percent below 2000 levels by 2050,[11] and in order to achieve this Annex I countries (industrialized countries and countries with economies in transition, such as the Russian Federation) would need to reduce their carbon emissions by 25 to 40 percent below 1990 levels by 2020 and 80 to 95 percent by 2050. Because these are not easy goals to achieve, countries and the international community must take action now to meet them. Our ability to set and meet short-term goals over the coming years will determine how successful we will be at safely stabilizing the climate. The longer we wait to act the more difficult averting catastrophe becomes.

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Findings

This report highlights the following recent findings demonstrating that ocean acidification is already occurring and threatening the oceans. It also identifies the likely consequences of continued carbon dioxide emissions for oceans and marine ecosystems.

- Carbon dioxide in the atmosphere is higher than it has been for 800,000 years and probably for much longer.[12]
- The acidity of the ocean surface has increased 30 percent since before the Industrial Revolution.[13] If current trends continue, it could rise by another 100 percent by the end of this century[14], exceeding the levels of the past 20 million years.[15]
- The increased amount of carbon dioxide the oceans are absorbing alters the movement of nutrients and chemicals in the oceans and has wide-ranging effects on ecosystems and marine life.[16]
- The higher acidity will also affect growth, reproduction, disease resistance and other biological and physiological processes in many species.[21]
- Many species will be unable to adapt to the rapid changes in ocean acidity and carbonate concentrations, especially those that build calcium carbonate shells and skeletons. This may lead to population crashes in many species, including oysters, mussels, crabs and lobsters.[17,18,19, 20]
- Impacts on carbonate-dependent species like corals and pteropods could cause major ripple effects throughout ecosystems and food webs ultimately affecting even the largest animals in the oceans, as well as many commercial fisheries.[22]
- Nearly 30 percent of the world's tropical corals have vanished since 1980, mainly due to warming events. At the current rate of emission growth, tropical corals could be gone by the middle to the end of this century.[23,24]
- If current emission trends continue, cold-water corals will be severely stressed by 2040, and two-thirds of them could be in a corrosive environment by the century's end.[25]
- The disappearance of coral reefs would cost society billions of dollars annually due to losses in fishing, tourism and coastal protection services.[26]
- Over 100 million people depend on coral reefs economically,[27] and subsistence communities may experience health consequences and lack of food security due to the loss of protein associated with coral reefs.[28]
- Many commercial fisheries depend on reefs which provide food and shelter for fish.[29,30] The loss of reefs may further destabilize already depressed commercial fish populations.
- To protect coral reefs and the ecosystems that depend on them, we must stabilize carbon dioxide in the atmosphere at or below 350 ppm. To achieve this, global emissions must be reduced to 85 percent below 2000 levels by 2050, which will require industrialized nations to reduce their emissions 25 to 40 percent below 1990 levels by 2020 and 80 to 95 percent by 2050.[31,32,33]

Solutions

A variety of solutions will be needed to reduce levels of carbon dioxide in the atmosphere to 350 ppm. These include: (1) a shift away from our carbon-based energy economy, which can been done by building an infrastructure for energy alternatives such as solar, wind and hydrogen, and scaling back the use of coal unless carbon capture is effectively employed; (2) increasing energy efficiency in cars, trucks, trains, planes and ships, as well as in homes, office buildings, power generation and the industrial sector; and (3) reducing deforestation while also planting more forest land to help "draw down" carbon dioxide levels. If we want to save our coral reefs and shellfish fisheries, the ecosystems that depend on them and the values that we derive from them, we need to start now. With a 25-to-40 percent reduction needed by the industrialized countries of the world by 2020, there is no time to waste.


U.S. Air Force

Recommendations

Adopt a Policy of Stabilizing Atmospheric Carbon Dioxide at 350 ppm

Governments must commit to stabilizing the levels of carbon dioxide in the atmosphere at 350 ppm or below. To achieve this, serious strides need to be taken within the next five years to set society on a path to zero net carbon emissions within the coming decades.

Promote Energy Efficiency and Low Carbon Fuels

Energy should be conserved at every opportunity, including through improved fuel efficiency of cars, trucks, airplanes and ships, provision of cleaner fuels, investment in efficient mass transit, and individual, institutional and corporate actions to reduce energy use.

Shift to Alternative Energy Sources

New or expanded coal-fired power plants and other expanded uses of coal should be prohibited until global warming pollution can be trapped and safely stored. In their place, governments and the private sector should implement programs to stimulate the development and use of renewable energy options such as wind and solar, and invest in upgrading the national power transmission grid so that energy produced from alternative sources can be cost-effectively moved to markets. Governments should immediately eliminate any and all subsidies that encourage the use of fossil fuels. Fossil fuels currently in the ground in sensitive ecosystems such as the Arctic and offshore should stay in the ground.

Regulate Carbon Releases

Governments should immediately begin regulating carbon releases using a system that internalizes emissions costs and prevents continued releases that harm the oceans. Under-regulated sources of carbon dioxide emissions, such as those from shipping and aircraft should be included in a post-Kyoto Agreement and regulated by the appropriate international bodies, such as the International Maritime Organization and the International Civil Aviation Organization.

Preserve Natural Resilience

The natural resilience of marine ecosystem should be maintained by curtailing other human caused threats, such as overfishing and pollution. Ocean acidification and climate change are not isolated threats, but act in concert with other impacts on ecosystems and species. Ocean ecosystems will have the best chance of surviving the pressures of ocean acidification if they are not simultaneously struggling to survive in the face of other threats.

INTRODUCTION

Our continued burning of fossil fuels is increasing the levels of carbon dioxide in the atmosphere, and what goes into the atmosphere eventually ends up in the oceans. Consequently, the oceans have been absorbing large amounts of carbon dioxide since the Industrial Revolution (approximately 1750). It is this increasing amount of carbon dioxide in the oceans that is causing ocean acidification.

When carbon dioxide enters the ocean it combines with seawater to produce carbonic acid, which increases the acidity of the water, lowering its pH.[35] Although it is unlikely that the ocean will ever become actual acid (i.e. fall below a pH of 7.0), the term acidification refers to the process of the oceans becoming more acidic.

A major consequence of increasing ocean acidity is a reduction in the amount of carbonate available for use by marine animals. One of the most important uses of carbonate in the ocean is in the formation of calcium carbonate or limestone structures like coral skeletons, shells and pearls, and the tests (shells) of some marine plankton. Ocean acidification will severely impact the ability of these creatures to create their protective calcium carbonate structures, and will likely disrupt some of the most important chemical and biological functions of the oceans.[36]

WHAT IS OCEAN ACIDIFICATION?

The absorption of carbon dioxide by the oceans moderates the impacts of climate change on terrestrial life. Since the Industrial Revolution the oceans have been acting as a “carbon sink” for carbon dioxide emissions, thereby lessening the extent of climate change. Without the oceans playing this role, the concentration of carbon dioxide in the atmosphere would have risen an additional 55 percent more than it has over the last 250 years.[37]

Prior to the Industrial Revolution the oceans were in relative equilibrium with the atmosphere, absorbing about the same amount of carbon dioxide each year as they released (2.15 billion metric tons of CO_2).[38] However, as the concentration of carbon dioxide in the atmosphere has increased, due mainly to the burning of fossil fuels, the amount of carbon dioxide the oceans have been absorbing has also increased. The oceans will continue to absorb carbon dioxide from the atmosphere as long as the concentration of carbon dioxide in the surface waters is less than that in the atmosphere.[39]

The pH of the ocean surface has already fallen 0.1 units, representing a 30 percent increase in acidity.[40] By the end of this century, if current emission trends continue, it could fall by another 0.3 units, an almost 100 percent increase in acidity.[41] The pH scale can be misleading because it is logarithmic, so its units may seem incremental, when in fact, they represent major changes in acidity. For example, a seemingly small drop of 0.4 units in pH actually represents more than a doubling (an almost 150 percent increase) in the acidity of the ocean.[42] In the last 300 million years or more, ocean pH has never fallen to more than 0.6 units below the level of 1750,[43] however if fossil fuel use continues unabated over the next couple of centuries, ocean pH could fall more than 0.7 units below the 1750 level (see Table 1).[44]

The oceans are the largest repository, or carbon sink, for anthropogenic carbon dioxide on earth.[46] Since the Industrial Revolution the oceans have absorbed over 460 billion metric tons of carbon dioxide,[47] which represents almost half of the carbon dioxide emissions from the burning of fossil fuels, or approximately 30 percent of all human-caused carbon dioxide emissions.[48] The oceans are currently taking up some 30 million metric tons of carbon dioxide daily, [49] nearly twice the amount of carbon dioxide emitted by the U.S. each day.[50]

The current concentration of carbon dioxide in the atmosphere is much higher than it has been at any time over the course of human civilization – in fact, as far back as scientists have currently determined (800,000 years), the natural range has not exceeded 300 ppm.[51] If we continue on our current emissions trajectory, by 2050 ocean pH will be lower than at any point in the last 20 million years.[52]

Even more significant is the rate at which ocean chemistry is changing. The current rate of acidification is at least 100 times faster than the maximum rate over hundreds of thousands of years.[53,54] Carbon dioxide is being absorbed so rapidly that it is unlikely the buffering capacity of the surface waters of the oceans will be able to prevent a substantial lowering of ocean pH.[55]

Table 1: Current and expected changes in ocean pH[45]

	CHANGE FROM PRE-INDUSTRIAL pH		pH CONDITIONS HAVE NOT BEEN EXPERIENCED FOR
	pH UNITS	PERCENTAGE	
Today	-0.1	30	800,000 years
Business-as-Usual at 2050	-0.2	60	20 million years
Business-as-Usual at 2250	-0.7	210	300 million years

Table 2: Past and future chemistry of surface sea water under a "Business-as-Usual" emissions scenario[56]

YEAR	ATMOSPHERIC CO_2 CONCENTRATION (ppm)	SURFACE OCEAN pH
1750	280	8.19
2008	385	8.09
2020	440	8.03
2040	510	7.97
2060	600	7.91
2080	700	7.85
2100	850	7.78

Based on geologic history, marine calcifiers and the natural biogeochemical cycles of the ocean could be adversely affected by even small changes in the concentrations of carbon dioxide in the surface waters of the oceans.[57,58] Past mass extinctions and reef gaps (periods of time, on the order of millions of years, that reefs have taken to recover from mass extinctions) can likely be attributed to ocean acidification.[59] An acidification event that occurred fifty-five million years ago at the Paleocene-Eocene Thermal Maximum (PETM) caused the extinction of a significant proportion of benthic calcifiers.[60] We are currently on a path to equal or surpass the PETM acidification event. If the entire fossil fuel reservoir is exploited, similar amounts of carbon dioxide will be absorbed by the oceans as at the PETM, however the rate at which current emissions are occurring is much faster (over the space of decades to hundreds of years, as opposed to thousands), so it is likely that the consequences of current ocean acidification could be even more catastrophic than the PETM event. This means another mass extinction may be looming.[61,62]

"It is likely that a continuation of current trends in carbon dioxide emissions will lead to an extinction of corals and may lead to the extinction of other marine species."[34]

— Dr. Ken Caldeira

How Does the pH Scale Work?

Chemists identify an acid or base by the concentration of hydrogen ions (H+) present, which is expressed using the pH scale. The scale runs from 0 (a highly acidic solution, with high concentration of H+) to 14 (a highly basic solution, with a low concentration of H+). The pH of battery acid, for example is about 0, and drain cleaner, on the other hand, is about 14. A neutral solution has a pH of 7 and pristine sea water has a pH ranging from 8 to 8.3. A change of 1 unit represents a 10 fold increase in the concentration of hydrogen ions and therefore acidity. For example, pH 5 is 10 times more acidic than pH 6 and 100 times more acidic than pH 7.

Concentrations of Hydrogen ions compared to distilled water (pH)		Examples of solutions and their respective pH
10,000,000	0	Battery Acid
1,000,000	1	Hydrochloric Acid
100,000	2	Lemon Juice, Vinegar
10,000	3	Orange Juice, Soda
1,000	4	Tomato Juice
100	5	Black Coffee, Acid Rain
10	6	Urine, Saliva
1	7	"Pure" Water
1/10	8	Sea Water
1/100	9	Baking Soda, Toothpaste
1/1,000	10	Milk of Magnesium
1/10,000	11	Household Ammonia
1/100,000	12	Soapy Water
1/1,000,000	13	Bleach, Oven Cleaner
1/10,000,000	14	Liquid Drain Cleaner

Source: Richmond River County Council www.rrcc.nsw.gov.au

OCEAN CHEMISTRY

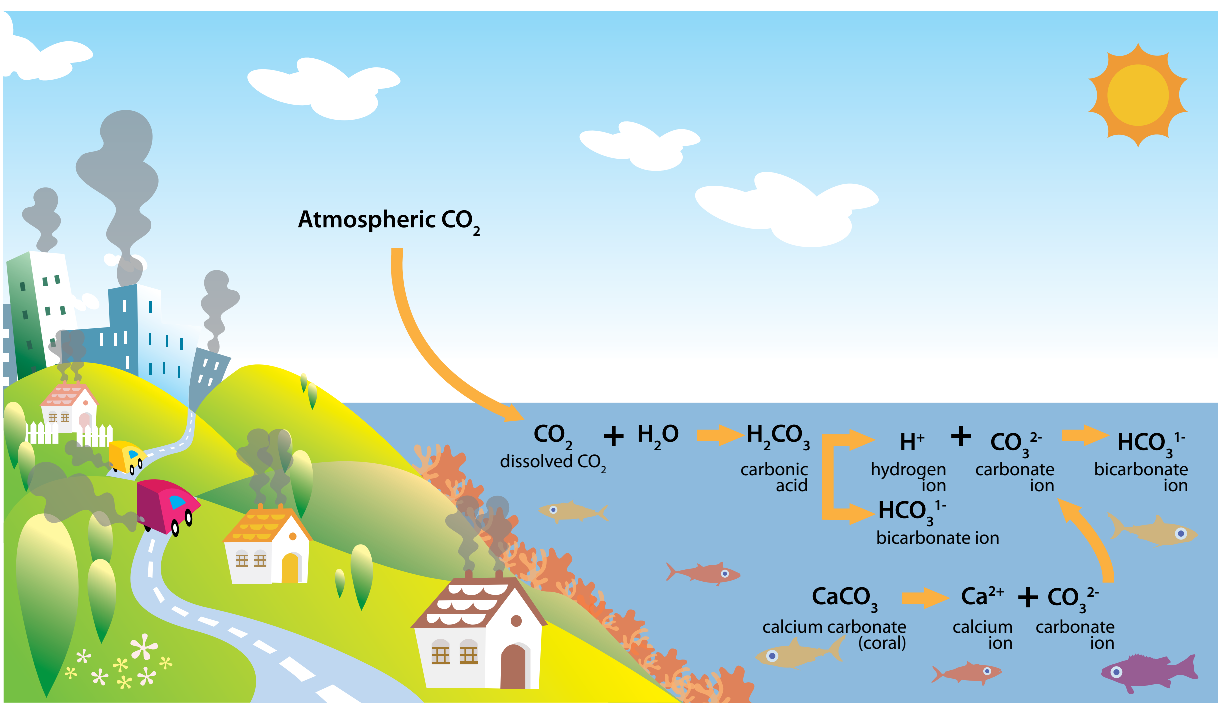
The chemical composition of seawater buffers against large shifts in pH. However, large additions of carbon dioxide can reduce the availability of carbonate, and even make the seawater corrosive to calcium carbonate structures.

High Levels of Carbon Dioxide in Seawater Lowers Carbonate Availability

Water reacts with carbon dioxide absorbed from the atmosphere to form bicarbonate ions and, in the process, depletes carbonate ions. Carbonate and bicarbonate are in equilibrium with one another in the oceans, so an increase in the abundance of one causes a decrease in the abundance of the other. Carbonate is needed by marine animals to make their calcium carbonate shells and skeletons. At typical pH levels, most of the ocean's inorganic carbon is stored in the form of bicarbonate ions but there is still enough carbonate available for the formation of calcium carbonate. When carbon dioxide absorbed by the oceans reacts with water, it forms a bicarbonate ion and a hydrogen ion. This hydrogen ion can then bind with a carbonate molecule that would otherwise be available to make calcium carbonate (see Figure 1). This tips the balance of the system away from carbonate ions, reducing the availability of this important molecule, which is vital to sea life.

Some of the species that will likely be affected by a decrease in the availability of carbonate ions include; corals, starfish, oysters, crabs, shrimp, mussels, lobsters, coccolithophores (a type of phytoplankton), pteropods (sea snails) and foraminifera (plankton related to amoebas).

Figure 1: The Chemistry of Ocean Acidification

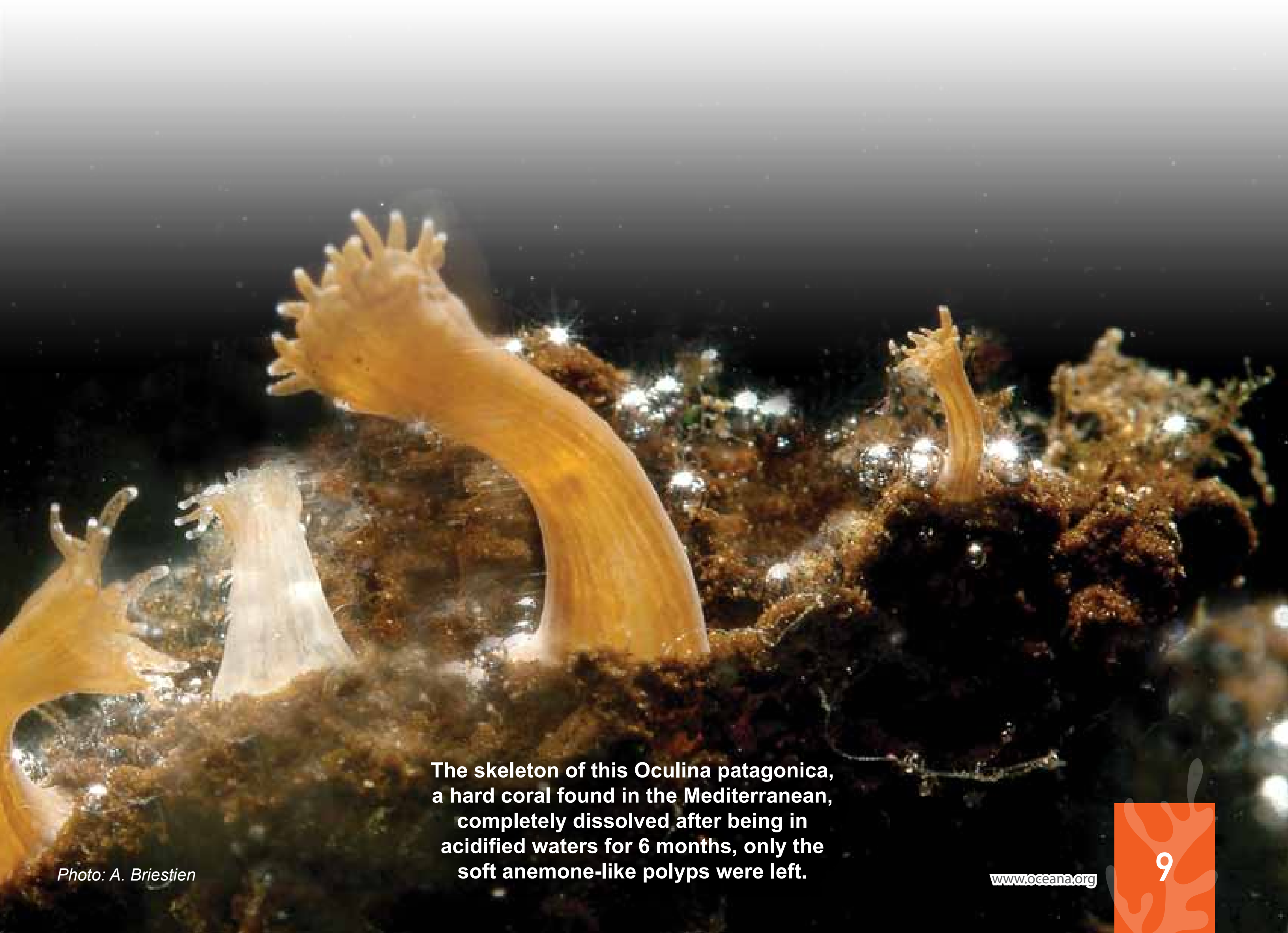


As CO_2 is absorbed by the atmosphere it bonds with sea water forming carbonic acid. This acid then releases a bicarbonate ion and a hydrogen ion. The hydrogen ion bonds with free carbonate ions in the water forming another bicarbonate ion. This free carbonate would otherwise be available to marine animals for making calcium carbonate shells and skeletons.

Seawater Becomes Corrosive

In some acidified waters, the reduction of carbonate is so significant that calcium carbonate structures can start dissolving. Since calcium carbonate structures only exist in waters where sufficient levels of carbonate ions are available, the addition of hydrogen ions to waters that already have low concentrations of carbonate ions further decreases the availability of carbonate and can actually cause existing calcium carbonate structures to begin to dissolve. With the accumulation of enough carbon dioxide, regions of the oceans that already have low enough pH to be corrosive to calcium carbonate structures will expand and more such areas are likely to develop.

Since it is the concentration of hydrogen ions that actually defines the ocean's level of acidity, the binding of hydrogen ions with carbonate ions is a buffering process against the oceans becoming more acidic. However, since such large amounts of carbon dioxide are being absorbed, the dissolution of calcium carbonate structures is the only way to return the ocean to its pre-industrial acidity levels. However, this is a slow process, which will take thousands of years to complete. In the meantime, it is currently being outpaced by the influx of carbon dioxide[63] and many vitally important calcium carbonate structures such as coral reefs and shellfish may begin to dissolve.



The skeleton of this Oculina patagonica, a hard coral found in the Mediterranean, completely dissolved after being in acidified waters for 6 months, only the soft anemone-like polyps were left.

Photo: A. Briestien

The Role of Calcite and Aragonite

While the dissolution of calcium carbonate is primarily driven by the availability of carbonate ions, it is also affected by other factors, such as the chemical structure of calcium carbonate. Calcium carbonate is commonly found in two forms: calcite and aragonite. Organisms will generally create one form or the other, and some also add magnesium to their calcite structures. Aragonite and magnesium calcite are at least 50 percent more soluble than calcite and are therefore more vulnerable to the effects of increasing acidity.[64] As a result of their greater sensitivity to acidic conditions, organisms such as corals and pteropods that build their skeletons and shells out of aragonite, and coralline algae that produce magnesium calcite are particularly threatened by ocean acidification.[65]

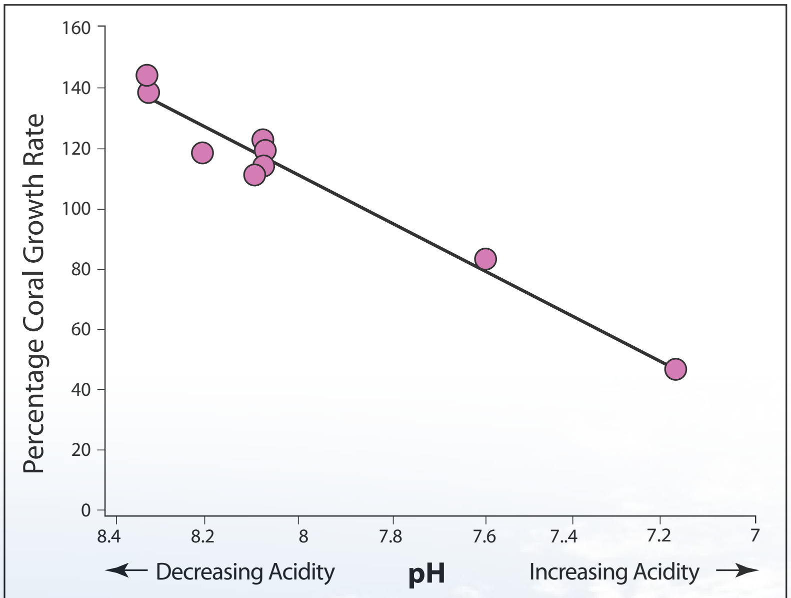
Calcification strongly depends on the "saturation state" of the surrounding water. This depends on a variety of factors including water temperature and pressure.[66] Currently, seawater near the surface is "super-saturated" with respect to all forms of calcium carbonate (i.e., the carbonate ion concentration is so high that calcium carbonate is easily created) so surface waters are therefore the most calcium carbonate 'friendly' areas of the oceans[67]. Cold and deep waters hold higher levels of carbon dioxide and therefore are naturally more acidic and less calcium carbonate friendly than warm surface waters. Calcification rates, which are a measure of the ability of an animal to build a calcium carbonate structure, are higher when the pH is higher and water is "saturated" with respect to carbonate ions. As the saturation level decreases, as it does in deeper water, the growth of these species declines (see Figure 2).[68] Once "under-saturation" is reached, calcium carbonate will begin to dissolve. However, calcification rates can decline long before under-saturation is reached so some calcifiers may not even survive to reach the point of under-saturation.[69]

As more carbon dioxide enters the oceans, the saturation horizons (the boundary between saturated and under-saturated waters) for both aragonite and calcite move closer to the surface, thereby shrinking the area in which calcification can take place.[70] The amount of carbon dioxide already absorbed by the oceans has caused the saturation horizons to rise between 50 and 200 meters closer to the surface than they were before the Industrial Revolution.[71]

The Southern Ocean, due to its cold water, has the lowest concentrations of carbonate of all the world's oceans, and is the least hospitable to calcium carbonate structures, even near the surface.[72] As a result, the calcifiers of the Southern Ocean are most at risk from increasing carbon dioxide levels.

If we continue burning fossil fuels at the current rate, the entire Southern Ocean could become under-saturated with aragonite by the middle to the end of this century.[73] With an atmospheric carbon dioxide concentration of 450 ppm, 7 percent of the Southern Ocean, below 60°S, would be under-saturated with respect to aragonite.[74] With a carbon dioxide concentration of 560 ppm, aragonite, under-saturation will spread through the polar oceans, the sub-polar Southern Ocean and portions of the sub-Arctic North Pacific[75] making it almost impossible for aragonite structures to exist in these areas, which would have devastating consequences for cold-water corals, pteropods and other organisms that create their shells and skeletons out of aragonite or magnesium calcite.

Figure 2: Tropical Coral Calcification (growth rate) Decreases as Acidity Increases



For every 0.1 decrease in pH there is an approximate 8% decrease in calcification.

Source: Fernand, L. and Brewer, P. (Eds) (2007) Report of the Workshop on the Significance of Changing Ocean CO2 and pH in Shelf Sea Ecosystems, defra and ICES CIEM, with changes made with permission from author, F.Marubini

Photo: Ted Dintersmith

EFFECTS OF OCEAN ACIDIFICATION

The biological and physiological processes of many organisms will be challenged by increasingly acidic conditions[76] which, in turn, will result in changes to many marine ecosystems. According to The Royal Society's report on ocean acidification, the impacts on ecosystems could be severe and long lasting.

A swimming pteropod (Limacina helicina)

Oyster and Pearl

Calcification

Calcifying organisms are found throughout the oceans in shallow, deep and open-water ecosystems. Calcification is the physiological process by which organisms create structures, such as shells and skeletons, out of calcium carbonate. Some calcifiers build large structures, such as coral reefs, while others are minute, like coccolithophore tests that can only be seen with a microscope. Calcifying organisms include some of the most abundant and important species in the oceans including shallow and deep water corals; clams, oysters, pteropods and other mollusks; crustaceans, including lobsters and crabs; echinoderms like starfish; and even some types of phytoplankton.[77,78]

These organisms create calcium carbonate structures by taking calcium (Ca^{2+}) and carbonate (CO_3^{2-}) ions from the surrounding water. Calcium ions are generally abundant throughout the oceans, so they are not a limiting factor for growth. Carbonate ion availability, on the other hand, is more variable and scarce and therefore can limit calcification.[79] As mentioned earlier, increasing levels of carbon dioxide cause a decrease in carbonate ions which can slow or stop calcification altogether.[80,81]

Marine organisms produce calcium carbonate structures for various reasons at different stages of their lives. Corals, for example, produce calcium carbonate skeletons not only as an anchor and protective housing, but also to elevate their polyps toward the light and into the flowing currents. This allows them to more easily obtain the light, nutrients and minerals they need for growth.[82] It has also been suggested that some life phases, such as reproductive maturity, are triggered by the ability to calcify. Reproductive maturity in the coral, *Goniastrea aspera*, for example, is reached when the animal grows to a certain size which depends on its ability to calcify.[83] As a result, the inability of many organisms to calcify could affect their fitness and survivorship,[84] which could trigger significant secondary effects throughout marine ecosystems and food webs.[85]

Spotted Spiny Lobster (Panulirus guttatus)

Smooth-skinned Red Starfish (Hacelia attenuata)

Tropical Corals

A 20 percent increase above current carbon dioxide levels, which could occur within the next two decades, could significantly reduce the ability of corals to build their skeletons and some could become functionally extinct within this same timeframe.[86] According to Dr. Ken Caldeira:

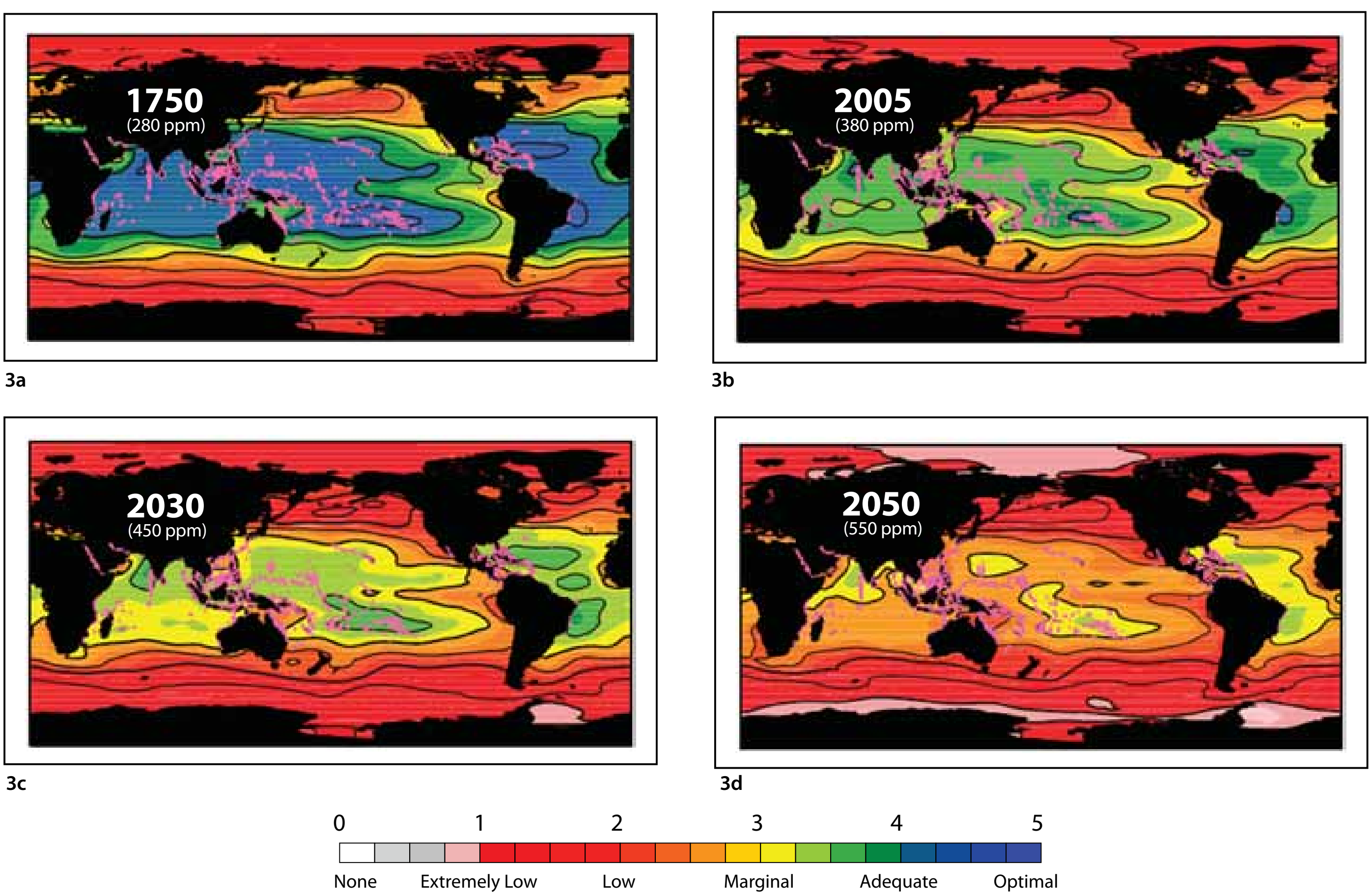
> *"There is at least a reasonable expectation that if current carbon dioxide emission trends continue, corals will not survive this century."*[87]

Experiments on shallow water corals found that concentrations of carbon dioxide of 560 ppm (twice pre-industrial levels) reduced calcification up to 66 percent.[88] On a business-as-usual emissions path, this level of atmospheric carbon dioxide can be expected around the middle of this century.

In real terms this does not just mean corals grow more slowly, but also that they will be less able to overcome typical pressures. Coral reefs are constantly engaging in a battle to grow. Many reef dwellers actually break apart pieces of the corals' skeletons, either to feed upon or to create homes. This process is known as bioerosion. Even the healthiest reefs are constantly trying to grow faster than they are being eroded.[89] In a high carbon dioxide world not only is coral growth slower, it is also less robust, so the skeletons that are produced are weaker.[90] Consequently, coral reefs in more acidic conditions may not be able to overcome the typical amount of destruction and may start to shrink much earlier than otherwise predicted.

Prior to the Industrial Revolution around 98 percent of coral reefs were surrounded by waters with adequate or optimal aragonite saturation states (see Figure 3a), however this has rapidly changed with increasing ocean acidification. At today's carbon dioxide concentrations about 60 percent of coral reefs are surrounded by waters that have less than adequate saturation states (see Figure 3b) and if carbon dioxide concentrations increase to 450 ppm, more than 90 percent of coral reefs will be surrounded by such waters (see Figure 3c). No corals that exist today will be near waters with adequate saturation states if carbon dioxide concentrations are allowed to reach 550 ppm (see Figure 3d).[91]

Figure 3: Aragonite Saturation State of the Ocean and Adequacy for Coral Growth



Source: Adapted from: Cao L., & Caldeira K, (2008) Atmospheric CO2 stabilization and ocean acidification. Geophysical Research Letters, in press, with permission from the authors.

In fact, an atmospheric carbon dioxide concentration of 560 ppm could produce ocean conditions so inhospitable to corals that almost all of the sites where corals grow today will be under-saturated with respect to aragonite causing the corals to dissolve.[92] However, coral calcification could virtually end before we reach 560 ppm because aragonite structures will likely be eroding due to acidification once carbon dioxide concentrations reach 480 ppm (see Table 3).[93] It is likely that under a business-as-usual scenario, only a few tiny areas in the oceans will remain optimal for coral growth by 2040, and by the end of this century no adequate conditions will remain.[94] It is for this reason that scientists have recommended that carbon dioxide concentrations in the atmosphere be stabilized at 350 ppm or below to maintain the coral dominated ecosystems we know today.[95]

Table 3: Coral Reef Devastation has Begun and will Worsen as CO_2 Concentrations Increase[96]

CO_2 CONCENTRATION (ppm)	CONDITION OF CORAL REEFS
380	Reefs will change due to ocean acidification, however they will remain coral dominated.
450	Density and diversity of corals on reefs will decline, including the loss of coral associated fish and invertebrates.
450-500	Reefs will likely become "rapidly eroding rubble banks". This may be seen as the tipping point for corals, beyond which reefs as we know them would be extremely rare, if not non-existent. It would be millions of years before coral reefs returned to their former diversity and density.

The loss of coral reefs would mean a loss of habitat and services for many millions of species. Reefs provide homes, nurseries, feeding grounds and spawning sites to a diversity of life that is virtually unparalleled anywhere else in the world. Unfortunately, due to the threats of ocean acidification and climate change, coral reef communities will become much less common.[97] Without reefs, severe consequences would result for as many as nine million species (including four thousand species of fish) that rely on reefs for shelter and nourishment.[98]

The chemistry of the oceans is changing so quickly it is unlikely that corals will be able to adapt to these new conditions.[99] Already, almost 30 percent of the world's tropical corals have vanished since 1980, predominantly due to ocean warming events.[100] If reefs continue to disappear at this rate, by the middle to end of this century no warm-water corals will remain.[101]

Cold-Water Corals

While tropical corals are probably the best known and most widely loved calcifiers in the oceans, they are not the only type of corals that will be hit hard by ocean acidification. Cold-water or deep sea calcifying corals are possibly the most vulnerable marine ecosystems when it comes to anthropogenic carbon dioxide emissions.[102]

Although cold-water corals have been known to exist for more than two hundred years, most of what we know today we have learned only over the last few decades.[103] Cold-water, reef-forming corals have extremely high biodiversity and provide habitat and nursery areas for many deep-sea organisms, including several commercially important fish species.[104] There is still much that we do not know about these organisms and yet with the current rate of ocean acidification we may cause their disappearance before we even fully appreciate their true beauty and importance.[105]

Cold-water corals, sponges and their associated ecosystems have been recognized as important sources of new medical treatments for diseases as varied as cancer, arthritis, Alzheimer's and skin conditions.[106] For example, bamboo corals, a type of sea fan, have been used to synthesize human bone analogs for grafting, and may provide a model for artificial synthesis for collagen.[107]

There are six species of cold-water, reef building, stony corals that create calcium carbonate skeletons out of aragonite.[108] As some of the slowest growing corals on earth, acidification poses a real and immediate threat to these species.[109]

Photo: Jan Helge Fossa

Stony cold-water corals , such as Lophelia, rely on their hard skeletons to support their polyps so that they can capture food and nutrients from the surrounding water.

Photo: NOAA/MBARI

Deep-sea sponges along with corals provide important habitat for crabs and many other species.

Cold-water corals are found in oceans around the world, some at depths of more than five and a half kilometers below the ocean's surface. Cold-water corals live in cold, often deep areas that are generally less favorable to calcification.[110] The maximum depth for the cold-water corals that create aragonite skeletons appears to coincide with the depth of the aragonite saturation horizon.[111] While some species of reef-forming corals are found in the North Pacific, the reefs they create are not, which could be due to the shallow depth of the aragonite saturation horizon in this area.[112] The continued reduction in aragonite saturation state will likely affect cold water corals before shallow water reef builders.[113,114] Cold-water corals probably have such slow growth and calcification rates, at least in part, because of the low aragonite conditions in which they live.[115]

The aragonite saturation state could decrease enough to be too low to support the deepest cold water corals within a decade or less.[116,117] Assuming they react to lowered pH in the same way as shallow-water corals, cold-water corals could be facing significant reduction in growth rates well before 2020.[118] By 2040 all cold-water corals that we currently know to exist could be located in marginal growing conditions or worse,[119] and by the end of the century at least two-thirds of all cold-water corals could be in waters that are corrosive to aragonite.[120] Before the end of this century if we continue emitting carbon dioxide at current levels, it is likely that most of the world's oceans will be "completely uninhabitable" for these corals.[121,122]

Other Critical Calcifiers

It is not only corals that are going to be severely affected, and possibly eliminated, by ocean acidification. For example, mollusks, oysters, crustose coralline algae and huge numbers of planktonic calcifiers create skeletons, shells and tests out of calcium carbonate. Some of these organisms may be tiny, but they play very important roles in the ocean and in marine food webs.[123]

Crustose Coralline Algae

Crustose coralline algae are the primary calcifiers on coral reefs and play an important role in the growth and stabilization of these reefs, make significant contributions to reef sediments and serve as an important food source for sea urchins, parrot fish and several species of mollusks.[124,125] One recent study found an 86 percent reduction in the growth of crustose algae in acidified waters.[126] These algae make their skeletons out of magnesium calcite and are therefore likely to be among the first organisms on coral reefs to be affected by acidification.[127] Decreases in their ability to calcify and grow could severely impact the stability and diversity of coral reefs.

Photos: David Littschwager, National Geographic Image Collection

Dissolution of pteropod shell in acidified water

Pteropods

Pteropods, or swimming sea snails, are an integral part of the base of the polar and sub-polar food webs, where they serve as important prey for much of the ecosystem, including whales and top predators.[128] For instance, they account for up to 45 percent of the diet of Alaskan pink salmon.[129] Some preliminary studies suggest that a 10 percent reduction in pteropod production could result in a 20 percent reduction in mature pink salmon body weight.[130] Since their shells are made of aragonite and they are found in the cooler high-latitudes which will be among the first areas to become under-saturated, pteropods may be one of the first calcifiers to be threatened by acidification.[131] In a series of experiments, live pteropods were exposed to the level of aragonite under-saturation expected in the Southern Ocean by 2100. Within 48 hours their shells began to dissolve, despite the animal itself still being alive.[132] Increasing acidity could result in lower calcification rates in pteropods, which could produce a disruption near the base of ocean food webs causing major ecosystem shifts and a decoupling of predator-prey interactions. This could ultimately affect even the largest of top predators in the oceans along with many commercial fisheries.[133]

Coccolithophores

Coccolithophores are single-celled algae encased in calcite layers. Studies in some species have found declines in calcification when exposed to acidified waters, while others have not. One species actually increased its rates of calcification in higher carbon dioxide conditions.[134] However, a decrease in the calcification of even some species of coccolithophores could amplify climate change. Coccolithophores create massive algal blooms that have a lighter coloration than the surrounding water due to their chalky tests. This increases the amount of sunlight reflected back to the atmosphere and not absorbed by the oceans. Without these lighter shells to reflect sunlight, the Earth's albedo (reflectivity) could decrease by 0.13 percent.[135] In this way, a reduction in coccolithophore calcification could act to accelerate climate change.

Coccolithophores also produce dimethylsulfide (DMS), which reacts in the atmosphere to stimulate the development of clouds. It is possible that production of DMS by coccolithophores may be disrupted by ocean acidification. This could greatly reduce atmospheric concentrations of DMS, decreasing cloud cover over the oceans that reflects sunlight back to space, and resulting in even further warming of the planet.[136,137] Reductions in DMS could also have wide ranging ecosystem effects, as this compound is an important signal used by many animals such as seabirds, [138] reef fish[139] and seals[140] to navigate toward feeding grounds. Reductions in DMS could cause disruptions in the feeding patterns and ability of these animals to find adequate food.

Planktonic Calcifiers

Many species produce calcium carbonate during their larval phases, so increasing ocean acidification may also affect species that are not likely to be affected as adults. The larvae of two sea urchins, for example, showed decreased calcification and decreased developmental rate when exposed to increased carbon dioxide.[141] Other species, such as mussels, oysters, sea stars, brittle stars and crustaceans have shown decreases in larval phase calcification rates in elevated carbon dioxide conditions.[142,143] Disruption of the early development and life history of marine organisms will likely result in reduced fitness and survivorship, with potentially serious consequences for marine ecosystems.

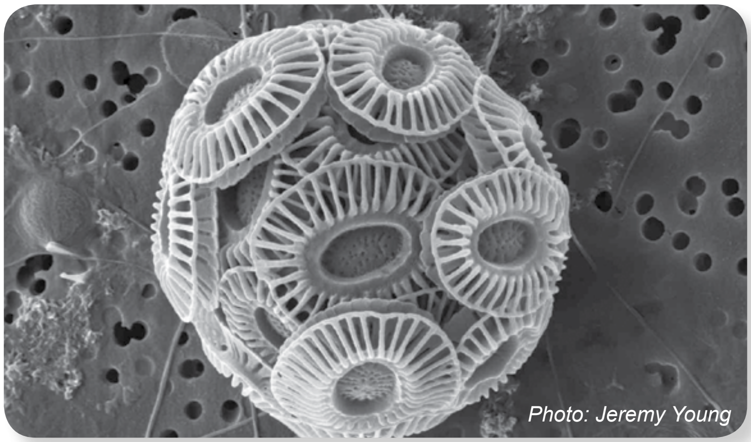


Photo: Jeremy Young

Coccolithophores surround themselves in layers of tiny calcium carbonate plates called tests.


Photo: Steve Groom, Plymouth Marine Laboratories

Massive, lightly colored coccolithophore blooms reflect light back to space and have a cooling effect.


Photo: Dave Burdick

Brittle stars have shown decreases in larval phase calcification under high CO_2 conditions.

PHYSIOLOGICAL EFFECTS ON MARINE LIFE

Along with a decrease in the ability to calcify, many other biological and physiological processes will be disrupted by ocean acidification.[144] These impacts could include decreased growth rates,[145] reduced reproduction[146] and increased susceptibility to disease,[147,148] all of which could produce ripple effects through food webs and ecosystems.[149] Fundamental physiological functions, such as respiratory and nervous system functions could also be disrupted by ocean acidification.[150] In addition, ocean acidification may result in behavioral changes in some species.[151]

Purple Sea Urchin
(*Heliocidaris erythrogramma*)

Effects on Reproduction

Larvae and juveniles are often most sensitive to increased acidity. For example, the fertilization rate of two species of sea urchin eggs (*Hemicentrotus pulcherrimus* and *Echirometra mathaei*) decreased with increasing ocean acidification. They also had malformed skeletons caused by the increased levels of carbon dioxide.[152] Another species of sea urchin, *Heliocidaris erythrogramma*, had a 25 percent reduction in fertilization success at acidification levels that are expected by the year 2100 on a "business-as-usual" emission path.[153] High levels of carbon dioxide caused a number of other reproductive effects including declines in the sperm motility of Pacific oysters, reduced numbers of hatchlings of a species of sea snail (*Babylonia areolata)*, and a lowered number of eggs produced by copepods.[154,155,156] If ocean acidification impacts reproduction, reductions in community size would likely follow.[157]

Squid
(Sepioteuthis sp.)

Effects on Respiration

Ocean acidification in conjunction with climate change may cause oxygen stress in many marine organisms. As the oceans become warmer they will hold less oxygen, and this low oxygen along with the higher levels of carbon dioxide may cause the oxygen transport mechanisms in some species (like hemoglobin in humans) to bind more readily with carbon dioxide than with oxygen, making it difficult for the animals to breathe.[158] Squid are especially sensitive to oxygen stress since they require high levels of oxygen for their energy intensive form of swimming.[159] Inability to swim adequately could have severe consequences for individual fitness and ability to survive. Along with oxygen stress the metabolic functions of many organisms may be altered as they attempt to adapt to new acidity levels around them.[160] While this may not always kill individuals, it could impact growth and reproduction rates, which may result in harmful consequences at the population and species scales.[161]

Photo: Kwansei Shell Database

Common Periwinkle
(Littorina littorea)

Effects on Behavior

With increasing acidity and its consequent changes to the physiological and biological processes in some species, resultant changes in behavior may occur to compensate for depressed functions. For example, a recent study showed that the common periwinkle (*Littorina littorea*) increased its avoidance behavior in response to the presence of crabs in high carbon dioxide conditions.[162] Under normal conditions this species relies on the ability to thicken its calcium carbonate shell when it senses crabs. However, when high acidity levels prevented the periwinkles from thickening their shells, they compensated by increasing their avoidance behavior.[163] While it is difficult to predict the effects such a change in behavior could have, it could plausibly compromise the fitness of the individuals that may now spend more time avoiding predators than feeding or performing other important tasks, and it could also have other unforeseen consequences for predators and ecosystems.

Some organisms will scale back important activities in order to maintain calcification when carbonate is scarce. For example, a type of brittlestar, *Amphiura filiformis*, spent less time ventilating its burrow and feeding in order to focus on regenerating lost arms. The brittlestars in more acidified waters also had smaller arm muscles as they were converting muscle mass into energy.[164] In this case ocean acidification prompted these animals to increase their rates of calcification in order to keep pace with decreasing availability of carbonate ions. But these actions came at a cost, one that may also reduce fitness and survival of the species.

EFFECTS ON ECOSYSTEMS

It is currently unclear how acidification will affect community structure and ecosystem functioning; however, as a report of the Royal Society stated:

> *"Without significant action to reduce carbon dioxide emissions into the atmosphere, this may mean that there will be no place in the future oceans for many of the species and ecosystems that we know today."*[165]

The reduction in planktonic calcifiers is likely to result in changes in the species composition within communities, which could have ripple effects throughout food webs.[166] Planktonic calcifiers form an important part of the base of many food webs in the oceans. If these species shift, become less nutritious, or disappear as a result of ocean acidification, the species that rely on them, including whales, turtles, and commercial fish species, could suffer from a lack of adequate prey. This could result in massive changes in the way that organisms interact throughout the oceans.

Even if the adults of some species are more resistant to the effects of ocean acidification, the heightened sensitivity of larvae and young will likely have significant impacts throughout populations and on ecosystem structure.[167] The impacts of ocean acidification will be varied among species, with many being chronically affected by increases in acidity.[168] Even species not directly affected biologically or physiologically are likely to be adversely affected by changes in food webs and ecosystem structure.

Photo: NOAA/ David Burdick

Poisonous Sea Urchin (Toxopneustes pileolus)

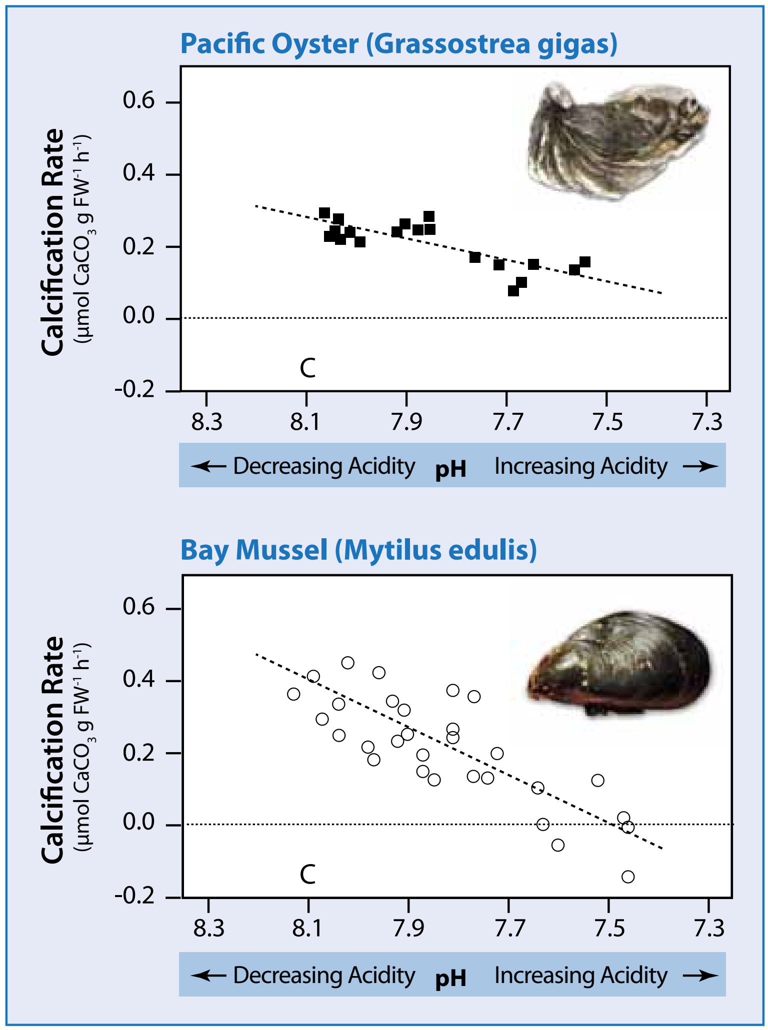
Oyster (Crassostrea gigas)

Mussel (Mytilus edulis)

Many calcifiers play important ecosystem roles, such as sea stars that act as keystone predators, balancing community diversity by feeding on species that would otherwise out-compete other species in the community. Other examples include urchins which are important grazers and oysters and mussels which are vital ecosystem engineers since they create or modify the habitats they live in.

With increasing levels of carbon dioxide the calcification rates of Pacific oysters (*Crassostrea gigas*) and bay mussels (*Mytilus edulis*) decreased linearly (see Figure 4).[169] If atmospheric concentrations of carbon dioxide reach 740 ppm, which could happen before 2100, the calcification rates in these species are expected to decline 10 and 25 percent, respectively.[170] The loss of oysters and mussels could be quite severe since they are vitally important to the ecosystems they live in and make up significant proportions of global aquaculture production.[171]

Figure 4: Increasing Acidity Decreases Calcification Rates



Source: Adapted from Gazeau, Frederic et al. (2007) Impact of Elevated CO2 on Shellfish Calcification, Geophysical Research Letters, 34 , with changes made by permission from author.

Oysters provide important habitat for other benthic organisms and help to govern the flow of nutrients and energy in coastal ecosystems.[172] They are filter feeders, which means they filter their food out of the water they live in. This provides an added service by filtering out excess phytoplankton, along with chemicals and other pollutants that could otherwise cause harm in the surrounding water. If acidification results in a reduction in these important species, waterways can rapidly become polluted and unsafe and there could be significant changes in coastal biodiversity and ecosystem functioning.

Marine mussels provide habitat for smaller invertebrates, enhance sediment stability and serve as an important food source for many species, including sea birds and humans.[173] Increased acidification is expected to reduce mussel calcification,[174] reduce metabolic activity,[175] and growth rates,[176] and even suppress immune function.[177] If these species and others like them that provide important ecosystem services are severely affected by rising acidity levels, the loss of the benefits these species provide could be catastrophic to the wildlife and humans alike that depend upon them.

Maxima clam
(Tridacna maxima)

Photo: © Christoph Specjalski

IMPACTS OF OCEAN ACIDIFICATION ON HUMANS

Not only do the oceans govern some of the most important geochemical cycles that make the planet inhabitable, they also serve as an important provider of food, livelihood, recreation and rejuvenation for billions of people. Unfortunately, ocean acidification could completely change the oceans as we know them today. Less diverse and vibrant oceans could in various ways negatively impact life as we know it.

For example, more than 100 million people are economically dependent upon corals reefs, with many more reliant on reefs for protection, resources and pleasure.[178] The disappearance of coral reefs could result in the loss of many billions of dollars every year since the reefs provide some 30 billion dollars annually to the global economy through coastal protection, tourism, fishing and other goods and services.[179] Many subsistence fishing communities rely on the fish found in reef ecosystems for vital proteins,[180] the loss of which could result in serious health consequences and food security concerns for these communities.

Coastal Protection

Coastal communities across the globe depend on the protection of reefs from storm surges, tsunamis and coastal erosion.[181] In the December 2004 tsunami, coastlines that had less robust coral reefs experienced greater loss of life and damage to infrastructure than those with well-developed reefs.[182,183] A scientific model developed by researchers at Princeton University showed that coasts with healthy reefs were at least twice as protected from tsunamis as coasts with dead reefs.[184] The loss of coral reefs due to ocean acidification could result in increased threats to the health, safety and well-being of many coastal communities.

Tourism

Coastal communities will also suffer significant economic losses from the degradation of coral reefs. As reefs decline and their associated ecosystems become less diverse, many tourists will find new, less affected areas in which to spend their money. This will likely mean major losses to coastal communities that are dependent upon tourism for their incomes. The coastal reefs in Hawaii alone are estimated to generate 364 million dollars annually in net business revenues.[185] The loss of this income could severely harm the economy of Hawaii.

Photo: E. Harrould-Kolieb

Fisheries

In 2004, about 85.5 million metric tons of marine fish worth 76.4 billion dollars were caught globally.[186] While it is difficult to estimate the impact that increasing acidity will have on fish and shellfish populations, it is likely that many will be adversely affected.

As tropical coral reefs begin to disappear due to acidification, many commercially important fish species that rely upon these reefs for critical habitat could also be in danger since many species depend on coral reefs for shelter and food.[187] There have already been some examples of fish that have disappeared from reefs during bleaching events. In 1998, after a bleaching event on the Okinawan reefs, the orange-spotted filefish (*Oxymonacanthus longirostris*) was unable to survive without the living coral.[188] While this filefish was not particularly important commercially it provides an example of what could happen to important fish species as acidification worsens.

Deep-water reefs, like their shallow-water counterparts, are biodiversity hotspots providing important habitat to many species, including many commercially important species of fish like grouper.[189,190] More than half of the total U.S. fishery landings (an over 4 billion dollar per year industry) is derived from Alaskan waters.[191] Many of the commercially important species in this region rely upon the cold-water corals off the Alaskan Aleutian Islands.[192] These corals are likely to be severely affected and may even begin to dissolve before the end of this century, a situation that would undoubtedly harm their dependant fish populations and fisheries.[193] The cold-water coral reefs of the Atlantic coast of the United States also form a veritable oasis of corals, sponges, crabs, lobsters, sea stars and fish.

Many of the world's commercial fisheries are likely to be threatened by ocean acidification either directly, by biological and physiological changes due to increased acidity, or indirectly through changes in habitat and prey availability. Many of the areas where acidification is predicted to be most severe within the coming century are highly productive and support some of the world's most important commercial fisheries.[194]

The effects of ocean acidification on mollusks (e.g. clams, oysters and mussels) and crustaceans (e.g. lobsters, crabs, crayfish and shrimp) are likely to present great losses both economically and to ecosystem services. Shellfish farming has increased at around 8 percent per year over the last 30 years and in 2004 the market was worth over 9.8 billion dollars.[195] Crustaceans will be particularly vulnerable to ocean acidification as they require carbonate ions to harden their new shells after molting.[196] The calcification rates of both edible bay mussels (*Mytilus edulis*) and Pacific oysters (*Crassostrea gigas*) have been found to decrease with increasing acidity.[197] In 2005, U.S. fishermen captured over 330 thousand metric tons of crustaceans and over 877 thousand metric tons of mollusks.[198] The 2005 U.S. revenue from shellfish was close to 17 million dollars.[199] Decreases in these populations due to ocean acidification could have massive economic repercussions.


Photo: © OCEANA / ZOEA

Horse eyed jacks (Caranx latus)

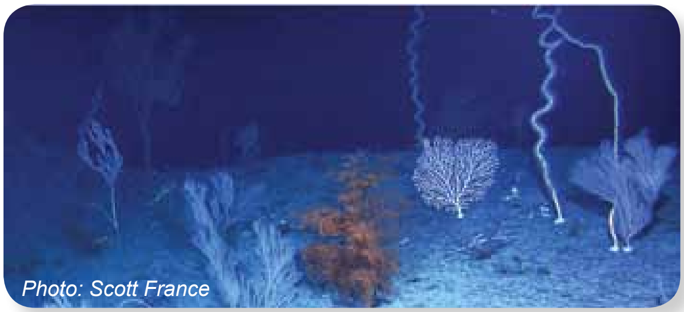


Photo: Scott France

Cold-Water Coral Garden


Photo: Feron Benjamin

Common Cockle (Cerastoderma edule)

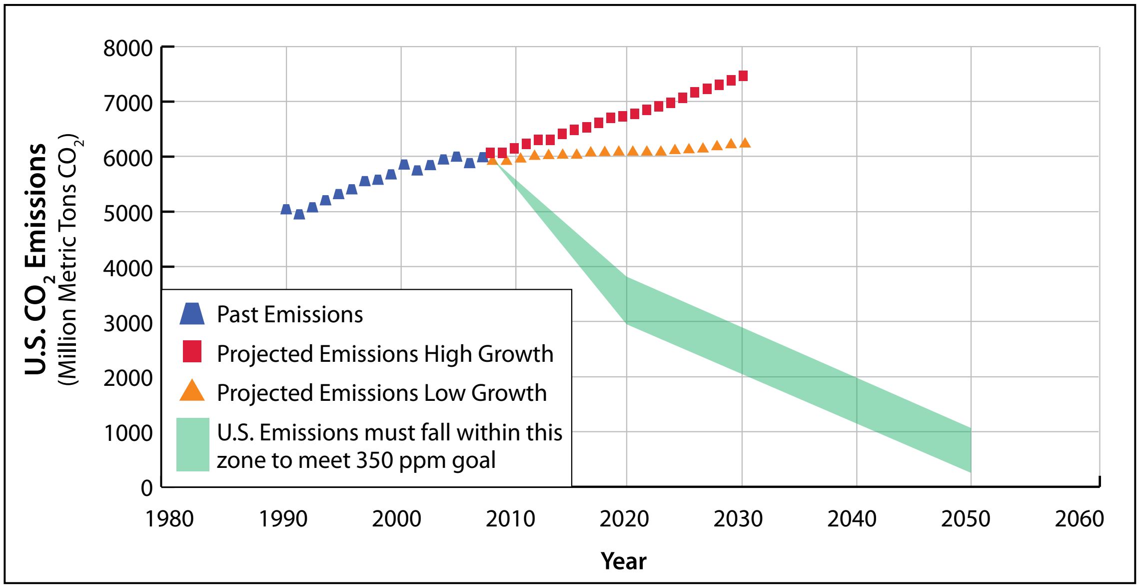

Photo: © OCEANA / ZOEA

Channel clinging crab (Mithrax spinosissimus)

REACHING THE LIMITS

"If there's no action before 2012, that's too late. What we do in the next two to three years will determine our future. This is the defining moment." Dr. Rajendra Pachauri, scientist, economist and Chair of the IPCC. (2007)

Figure 5: Projected U.S. CO_2 Emissions vs. Emissions Trajectory for 350 ppm



Source: Oceana, based on EIA (2008) and IPCC (2007)

Current atmospheric carbon dioxide concentrations are already above safe levels and as a result we are seeing significant changes taking place throughout the oceans, from decreasing growth rates of corals on the Great Barrier Reef to massive coral bleaching events across the tropics. Coral reefs are acutely vulnerable to ocean acidification and climate change. They provide important habitat to a quarter of all marine species and are significant to the lives and livelihoods of many humans. Allowing coral reefs to disappear would result in intolerable changes throughout the oceans as well as major disruptions in the lives of hundreds of millions of people. What happens to coral reefs will foreshadow other catastrophic changes that are likely to take place around the world due to ocean acidification and climate change.

To prevent the loss of coral reefs, and ultimately avert a climate crisis, we must reduce atmospheric carbon dioxide levels to below 350 ppm.[200] Unfortunately, carbon dioxide in the atmosphere has already exceeded this safe level, having reached 385 ppm and climbing.[201] Besides being too high to protect the planet's coral reefs, this current level is also much higher than it has been at any time over the course of human civilization.[202] In fact, as far back as scientists have currently determined (800,000 years), the natural range has not exceeded 300 ppm.[203]

If we stay on our current emissions trajectory we will far exceed the 350 ppm goal and we will not prevent the extinction of the corals. In today's society, carbon dioxide emissions are directly tied to our need for energy, and that need is growing. Recent figures released by the U.S. Energy and Information Administration (EIA) indicate that staying on the current business-as-usual path, where current laws and policies remain unchanged will result in world energy consumption in 2030 increasing by 50 percent above 2005 levels.[204] This will result in a steady increase in anthropogenic carbon dioxide emissions, with 51 percent more carbon dioxide in the atmosphere by 2030 than there was in 2005, resulting in an atmospheric carbon dioxide concentration of over 570 ppm.[205]

With carbon dioxide levels this high, ocean acidification will be extremely severe within the next few decades. We have already entered the danger zone and reefs are already starting to decline. It is unlikely that reefs will be able to sustain themselves for many decades at the currently high carbon dioxide conditions. However, if we continue along our current emissions path reefs could be pushed passed a tipping point, likely to occur around 450 ppm, at which point reefs as we know them would be extremely rare, if not non-existent. Once we surpass this tipping point coral reefs will shrink rapidly,[206] at least half of coral-associated wildlife will become rare or extinct, and the services reefs provide to millions of people will grind to a halt. Shortly after that, coral reef ecosystems will likely be reduced to crumbling frameworks with few calcareous corals remaining.[207] Since coral reefs take decades and even centuries to form, once such damage is done, the impacts will be irreversible for generations.

However, this does not have to be the future of the oceans. By making the correct choices we can save coral reefs, and the wildlife and humans that depend upon them, and ultimately the Earth as we currently know it, from ocean acidification and climate change. By choosing a low carbon future, atmospheric carbon dioxide concentrations can be stabilized at safe levels below 350 ppm.[208] At these levels changes will still take place across reef ecosystems; however, they will remain coral dominated and continue to create calcium carbonate.[209]

To save coral reefs from ocean acidification we must stabilize atmospheric carbon dioxide at or below 350 ppm. Scientists looking at other vulnerable ecosystems have identified similar limits beyond which positive feedback loops could prevent full recovery. By preventing ocean acidification and stabilizing the climate at safe levels we will also be preventing other climate-related catastrophes.

Since we can not expect to simply halt all emissions immediately we must expect there will be some overshoot of the ultimate 350 ppm stabilization goal.[210] However, remaining in the current danger zone we are in for longer than a couple of decades will result in intolerable changes taking place. This means that it is vital to get on the right trajectory within the next few years and to make sure that carbon emissions peak and begin to decline in less than a decade.

The Intergovernmental Panel on Climate Change (IPCC) concluded that in order to stabilize carbon dioxide in the atmosphere at 350 ppm by 2050 global carbon dioxide emissions would need to be cut by 85 percent below 2000 levels,[211] and in order to achieve this, Annex I countries (industrialized countries and countries with economies in transition, such as the Russian Federation) would need to reduce their carbon emissions by 25 to 40 percent below 1990 levels by 2020 and 80 to 95 percent by 2050. (see Figure 5). These are not easy goals to achieve and consequently, the United States and the international community must make immediate serious commitments to meet them.

Our ability to set and meet short-term goals over the coming years will determine how successful we will be at safely stabilizing the climate. In order to realize the greatly needed cuts of 25 to 40 percent by 2020 countries will need to act immediately. The longer we wait to act the more difficult averting catastrophe becomes.

Photo: © David Burdick

SOLUTIONS

Many of the foremost scientific thinkers on this issue have demonstrated that it is possible to prevent runaway climate change, though there is certainly no silver bullet and doing so will not be easy. James Hanson of NASA has argued that the critical 350 ppm target needed to protect corals is achievable. It should come as no surprise that this will require a concerted effort by individuals, companies and institutions throughout the world. In their study Pacala and Socolow propose a "wedge-based" approach involving some combination of fifteen viable solutions and concluded:

> *"Humanity already possesses the fundamental scientific, technical, and industrial know-how to solve the carbon and climate problem for the next half-century."*[212]

While our carbon dioxide reductions need to be significant and timely, there are many, varied options ranging from conservation and increasing energy efficiencies to advanced reduction technologies, the use of alternative energy options and renewable fuels. The diverse array of solutions available require our shifting to a less carbon dependent energy economy which means building an infrastructure for energy alternatives such as solar, wind, and hydrogen, and scaling back or even stopping the use of coal, unless carbon capture is effectively employed. They also include increasing energy efficiency efforts in cars, trucks, trains, planes and ships, as well as in homes, office buildings, power generation and industrial sectors; and cutting down on deforestation while also planting more forest land to help "draw down" carbon dioxide levels.

In the meantime, when the use of carbon fuels is unavoidable, technologies such as end of the pipe scrubbers and carbon capture devices would play an important role in reducing the amount of carbon dioxide released to the atmosphere. Placing a cost on carbon dioxide emissions would allow these alternatives to enter the market and be truly competitive.[213]

To prevent future ocean acidification we need to switch from a trajectory of rapidly increasing carbon dioxide emissions to one in which net emissions have been reduced to zero.[214] However, some alternative measures have been suggested to address ocean acidification, such as adding chemicals to ocean waters to lower their acidity. But these are at best short-term, local stop-gap measures, which will not prevent ocean acidification on a global scale.[215]

Furthermore, such geo-engineering solutions could wreak havoc on already fragile ecosystems causing a whole host of other unintended and unforeseen consequences.

Geo-engineering solutions have also been proposed to address carbon dioxide levels in the atmosphere. These include iron fertilization and deep ocean sequestration, both of which are likely to exacerbate ocean acidification.[216,217,218] These approaches should be viewed with caution and only employed if and when they are proven effective and their impacts on the oceans are understood and known to be negligible.

Unfortunately, the acidity of the oceans has already increased by 30 percent due to anthropogenic carbon dioxide released since the Industrial Revolution. There will be some lag time between the time when human emissions are reduced to appropriate levels and the point at which level of acidity of the ocean decreases. Therefore, it is vitally important that we cut emissions as soon as possible so that ocean conditions do not become unbearable for many marine animals. We must also do all we can to reduce other pressures on ocean ecosystems to ensure their resilience and give them every possible chance to survive. Threats such as overfishing and destructive fishing techniques, pollution and climate change all act in concert to weaken ocean ecosystems and make survival even more tenuous. By stopping these and other threats we can provide the ocean with a fighting chance to survive the looming dangers of ocean acidification.

Essentially, every decision we make from here on out must be influenced by the need to make these changes. Debate continues about whether and how market approaches will work, and how to place a price on carbon, but one thing is clear: If we want to save our coral reefs and shellfish fisheries, the ecosystems that depend on them and the values that we derive from them as humans, we need to start now. With a 25 to 40 percent reduction needed by the industrialized countries of the world by 2020, there is no time to waste.

At the same time, ocean acidification should not be seen as a reason to throw up our hands and cry that saving the oceans is hopeless; it is not. Rather we should realize the seriousness of this threat and take immediate appropriate actions to move society away from our dependence on carbon-based fossil fuels to a low carbon future in which coral reefs and other marine organisms will not be threatened by acidic waters.

RECOMMENDATIONS

Adopt a Policy of Stabilizing Atmospheric Carbon Dioxide at 350 ppm

Governments must commit to stabilizing the levels of carbon dioxide in the atmosphere at 350 ppm or below. To achieve this, serious strides need to be taken within the next five years to set society on a path to zero net carbon emissions within the coming decades.

Promote Energy Efficiency and Low Carbon Fuels

Energy should be conserved at every opportunity, including through improved fuel efficiency of cars, trucks, airplanes and ships, provision of cleaner fuels, investment in efficient mass transit, and individual, institutional and corporate actions to reduce energy use.

Shift to Alternative Energy Sources

New or expanded coal-fired power plants and other expanded uses of coal should be prohibited until global warming pollution can be trapped and safely stored. In their place, governments and the private sector should implement programs to stimulate the development and use of renewable energy options such as wind and solar, and invest in upgrading the national power transmission grid so that energy produced from alternative sources can be cost-effectively moved to markets. Governments should immediately eliminate any and all subsidies that encourage the use of fossil fuels. Fossil fuels currently in the ground in sensitive ecosystems such as the Arctic and offshore should stay in the ground.

Regulate Carbon Releases

Governments should immediately begin regulating carbon releases using a system that internalizes emissions costs and prevents continued releases that harm the oceans. Under-regulated sources of carbon dioxide emissions, such as those from shipping and aircraft should be included in a post-Kyoto Agreement and regulated by the appropriate international bodies, such as the International Maritime Organization and the International Civil Aviation Organization.

Preserve Natural Resilience

The natural resilience of marine ecosystem should be maintained by curtailing other human caused threats, such as overfishing and pollution. Ocean acidification and climate change are not isolated threats, but act in concert with other impacts on ecosystems and species. Ocean ecosystems will have the best chance of surviving the pressures of ocean acidification if they are not simultaneously struggling to survive in the face of other threats.

Photo: E. Harrould-Kolieb

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1350 Connecticut Ave., NW, 5th Floor
Washington, DC 20036 USA

April 17, 2010

The Honorable Maria Cantwell, Chair
The Honorable Olympia Snowe, Ranking Member
Committee on Commerce, Science, and Transportation
Subcommittee on Oceans, Atmosphere, Fisheries, and Coast Guard
United States Senate
Washington, DC 20510

Dear Madam Chairwoman and Ranking Member Snowe:

As shellfish growers, commercial fishing and seafood industry representatives from all over the United States, we are very concerned about ocean acidification. Together with scientists whose research has been instrumental in bringing to light the urgent threat that ocean acidification poses to fisheries and marine ecosystems, we respectfully request help from policy makers to mitigate the causes and reduce the economic harm resulting from ocean acidification.

It has been proven that ocean acidification results from an excess of CO_2 dissolving into the ocean from the atmosphere. This CO_2 is primarily from the burning of fossil fuels followed by deforestation, cement manufacture, and other human activities.

Acidification from fossil fuel emissions is compounded by the effects of local acidifying factors, such as river runoff containing high loads of nitrogen and carbon, greatly accelerating impacts that scientists predicted from ocean acidification. This confluence of global and local acidification poses grave risk (and in some cases outright harm) to the marine food web and commercially important species. Changes exhibited in parts of Alaska, the East Coast and the West Coast raise serious concerns for fisheries in other regions, such as the Gulf of Mexico, where CO_2-driven acidification may compound the already serious impacts attributed to hypoxia.

A few examples:

1. Clams are dissolving before they can grow beyond their larval stage in parts of many East Coast bays, where impacts of river-borne effluents and eutrophication are aggravated by effects of global CO_2 emissions. This dissolution of young clams now represents a leading cause of mortality for these shellfish in many bays (Green et al). Scientists who documented this mortality say that it offers a preview of conditions that are expected to prevail throughout much of the ocean if CO_2 emissions are not sharply reduced.
2. On the West coast, upwelling of acidified water to a degree not anticipated until 2050 was documented in 2007 in a North American Carbon Program (NCAP) West Coast Cruise that surveyed the length of the west coast from Canada to Baja California (Feely et al 2008). Concurrently, natural oyster beds in the Pacific Northwest have experienced a multi-year recruitment failure, producing no commercially significant oyster sets. Acidification poses a severe threat to hatcheries that supply most of the region's $100 million+ oyster industry. Because this corrosive seawater kills oyster larvae, one of the region's largest hatcheries (Whiskey Creek Shellfish Hatchery at Netarts Bay) suffered a 70- 80% decline in oyster larval production in 2007 and 2008.
3. Laboratory studies subjecting sea urchins and other shellfish to CO_2–enriched seawater situations also have demonstrated larval shell deformation, reduced recruitment and settlement (Hofmann et al 2008); the tipping point for purple sea urchins is 540 ppm. In

the 2007 NOAA cruise, Feely et al found surface pCO_2 at about 850 µatm near the shelf break and higher inshore on some transects in northern California. Coincidentally, a 20-year data set of sea urchin larval recruitment in California indicates diminished recruitment in northern California during high upwelling events.

4. Seasonally acute acidification has now been observed in key fishing areas off Alaska, including the Bering Sea and the Gulf of Alaska (Fabry et al 2009), raising concerns for fisheries in a state that produces more than half the U.S. seafood catch. As in severely acidified waters along the West Coast and East Coast, these corrosive conditions are linked to compounding local acidifying influences from upwelling and river borne effluents. Scientists note that rising CO_2 emissions can be expected to make these corrosive conditions more persistent and widespread in the future.

Globally, ocean acidification has been identified as a serious threat to marine life and fisheries, and scientists have issued a series of unusually clear and urgent warnings about this problem. In the Monaco Declaration (2008), 155 scientists from around the world wrote: “Ocean acidification is accelerating and severe damages are imminent.” Representatives from more than 70 national academies of science (including the United States, China, India, the U.K., Germany, France, and many others) signed a joint statement that read in part: “Marine food supplies are likely to be reduced with significant implications for food production and security in regions dependent on fish protein, and human health and wellbeing” (Inter-Academy Panel 2009).

While some organisms are likely to be more adaptive than others in a high-CO_2 ocean, seafood producers and consumers cannot afford to “whistle in the dark” about these changes. The U.S. seafood industry generates approximately $70 billion annually, fueling jobs and businesses that sustain many thousands of families along the Gulf, Atlantic, the Pacific and Alaskan coasts. Even for fisheries where no direct harm from acidification has yet been documented, the disturbing signs of trouble on the “front lines” reveal a compelling case to prevent the impacts from spreading and growing more severe.

POLICY RESPONSES

If seafood production is to be sustained and the oceans protected for future generations, federal political action is required now:

• **Adequate funding is urgently needed** to develop monitoring and research systems to track biological and ocean-chemistry changes in key areas, including estuaries. By utilizing and building on currently available studies we can create baseline data. From this we will have an accurate characterization of current water conditions thus enabling us to recognize “early warning” signs that may appear in the future. Data, current and future, should be coordinated with existing monitoring effort, such as NOAA’s Integrated Ocean Observing System [IOOS] and the regional partners. Only by knowing what’s coming at us can we hope to protect the resources that provide our food and livelihood.

• **Develop shellfish hatchery techniques and other methods of protecting important finfish and shellfish resources** from acute impacts of acidification. Small-scale experiments have shown that shellfish hatcheries, for example, can dodge some harm by halting production during periods when corrosive water is present and by maximizing production during “good water” periods. Within shellfish hatchery systems, certain water treatments show promise to reduce mortality of larval oysters. Brood stock programs have identified strains of shellfish that appear better able to survive in acidified seawater. Research and development is also needed to create methods of protecting other fish stocks during vulnerable early life stages. If hatchery techniques can shelter juvenile animals (including finfish if in a hatchery situation) when they are most vulnerable, it may be possible to sustain seafood production while solutions to the global carbon problem are developed.

• **Finance energy efficiency and other measures where needed to reduce carbon emissions within the seafood industry, and encourage private investment that improves carbon efficiency in the sector.** The seafood industry is a small source of carbon emissions, but seafood enterprises recognize the need do their part. Many of the necessary investments to curtail emissions will be initially costly but ultimately cost-effective. For example, to repower with more efficient engines and equipment, or to switch to lower-carbon fuels will require capital that vessel operators, producers, and seafood vendors may not be able to obtain on their own. Programs will need to be in place to encourage these upgrades. The seafood industry also should be encouraged to consider and permitted to improve its carbon and energy efficiency through reforms in fishery management. For example, in many cases rebuilding fish stocks can result in more energy-efficient harvesting. In some cases significant emissions reductions may be obtained by enabling vessel replacement, fleet renewal, downsizing overbuilt fleets, or implementing other management reforms. These changes are not “a one size fits all solution” and can have complex socio-economic effects. Not all communities and segments of the industry will choose them nor should the changes be implemented without regional industry involvement.

Critically important, the United States must lead in the search for global solutions, including:

• Research in and support of alternative energy initiatives

• **Cut emissions of carbon dioxide** in order to minimize future harm to fishery resources from ocean acidification. Research on “tipping points” for marine ecosystems and organisms shows that preventing irreversible harm will require limiting maximum atmospheric concentration of CO_2 at no higher than 450 ppm, and then reducing this concentration significantly in the decades ahead. This will require bold steps to place the United States in a position to lead (not lag) in solving this problem globally. To protect fishery resources, as well as future life on this planet, it will be necessary to:

1) cap emissions throughout the U.S. economy,
2) improve energy efficiency,
3) enhance low-carbon energy sources, and
4) negotiate a commensurate international agreement to control emissions throughout the global economy.

In closing, the undersigned shellfish growers and commercial fishing representatives and scientists respectfully request your help to address the urgent threat of ocean acidification.

Sincerely,

(Names are for identification only, do not represent or imply official endorsement from our employers.)

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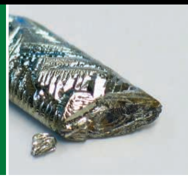

LETTERS

edited by Jennifer Sills

Climate Change and the Integrity of Science

WE ARE DEEPLY DISTURBED BY THE RECENT ESCALATION OF POLITICAL ASSAULTS ON SCIENTISTS in general and on climate scientists in particular. All citizens should understand some basic scientific facts. There is always some uncertainty associated with scientific conclusions; science never absolutely proves anything. When someone says that society should wait until scientists are absolutely certain before taking any action, it is the same as saying society should never take action. For a problem as potentially catastrophic as climate change, taking no action poses a dangerous risk for our planet.

Scientific conclusions derive from an understanding of basic laws supported by laboratory experiments, observations of nature, and mathematical and computer modeling. Like all human beings, scientists make mistakes, but the scientific process is designed to find and correct them. This process is inherently adversarial—scientists build reputations and gain recognition not only for supporting conventional wisdom, but even more so for demonstrating that the scientific consensus is wrong and that there is a better explanation. That's what Galileo, Pasteur, Darwin, and Einstein did. But when some conclusions have been thoroughly and deeply tested, questioned, and examined, they gain the status of "well-established theories" and are often spoken of as "facts."

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For instance, there is compelling scientific evidence that our planet is about 4.5 billion years old (the theory of the origin of Earth), that our universe was born from a single event about 14 billion years ago (the Big Bang theory), and that today's organisms evolved from ones living in the past (the theory of evolution). Even as these are overwhelmingly accepted by the scientific community, fame still awaits anyone who could show these theories to be wrong. Climate change now falls into this category: There is compelling, comprehensive, and consistent objective evidence that humans are changing the climate in ways that threaten our societies and the ecosystems on which we depend.

Many recent assaults on climate science and, more disturbingly, on climate scientists by climate change deniers are typically driven by special interests or dogma, not by an honest effort to provide an alternative theory that credibly satisfies the evidence. The Intergovernmental Panel on Climate Change (IPCC) and other scientific assessments of climate change, which involve thousands of scientists producing massive and comprehensive reports, have, quite expectedly and normally, made some mistakes. When errors are pointed out, they are corrected. But there is nothing remotely identified in the recent events that changes the fundamental conclusions about climate change:

(i) The planet is warming due to increased concentrations of heat-trapping gases in our atmosphere. A snowy winter in Washington does not alter this fact.

(ii) Most of the increase in the concentration of these gases over the last century is due to human activities, especially the burning of fossil fuels and deforestation.

(iii) Natural causes always play a role in changing Earth's climate, but are now being overwhelmed by human-induced changes.

(iv) Warming the planet will cause many other climatic patterns to change at speeds unprecedented in modern times, including increasing rates of sea-level rise and alterations in the hydrologic cycle. Rising concentrations of carbon dioxide are making the oceans more acidic.

(v) The combination of these complex climate changes threatens coastal communities and cities, our food and water supplies, marine and freshwater ecosystems, forests, high mountain environments, and far more.

Much more can be, and has been, said by the world's scientific societies, national academies, and individuals, but these conclusions should be enough to indicate why scientists are concerned about what future generations will face from business-as-usual practices. We urge our policy-makers and the public to move forward immediately to address the causes of climate change, including the unrestrained burning of fossil fuels.

We also call for an end to McCarthy-like threats of criminal prosecution against our colleagues based on innuendo and guilt by association, the harassment of scientists by politicians seeking distractions to avoid taking action, and the outright lies being spread about them. Society has two choices: We can ignore the science and hide our heads in the sand and hope we are lucky, or we can act in the public interest to reduce the threat of global climate change quickly and substantively. The good news is that smart and effective actions are possible. But delay must not be an option.

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Notes

1. The signatories are all members of the U.S. National Academy of Sciences but are not speaking on its behalf.
2. Signatory affiliations are available as supporting material at www.sciencemag.org/cgi/content/full/328/5979/689/DC1.

Shifting the Debate on Geoengineering

AS DISCUSSED IN THE RECENT POLICY FORUM "The politics of geoengineering" (J. J. Blackstock and J. C. S. Long, 29 January, p. 527), there is growing recognition that avoiding dangerous climate change during the 21st century may require society to adopt geoengineering technologies to supplement CO_2 emission reduction efforts. Unfortunately, despite the essential role that CO_2 removal (CDR) and solar radiation management (SRM) technologies may play in reducing the risks of dangerous climate change, discussions of the necessary research and development [including the Policy Forum and others (*1*, *2*)] frequently turn into debates about the environmental costs and benefits of SRM. A more productive approach would shift the debate to comparing the relative costs and benefits of CDR and SRM.

CDR approaches are frequently discounted because, as Blackstock and Long explain, "technical challenges and large uncertainties [surround] large-scale CDR deployment." Although this may be true for human-built systems that capture CO_2 from air at ambient concentrations, there are other technologies based on biological carbon fixation that could be fast-tracked for rapid deployment during the next few decades (*3*). Most major international energy corporations are investing in algal-based biofuel technologies because of the tremendous production potential of algae relative to terrestrial energy crops (*4*). Commercial-scale production of algal biofuels will begin during the next 5 years, and rapid scaling up can be expected afterward if the economic incentives are favorable. However, becoming carbon negative will require society to develop plans for retrofitting existing coal-fired power plants and building future ones so that they can burn algal biomass and capture the emitted CO_2 for subsequent sequestration. The basic technologies described here are not novel; rather, I am proposing a conceptual rearrangement that may enable society to transition more gracefully

CORRECTIONS AND CLARIFICATIONS

Research Articles: "Doc2b is a high-affinity Ca^{2+} sensor for spontaneous neurotransmitter release" by A. J. Groffen *et al.* (26 March, p. 1614). Several author affiliations were not footnoted properly; three corrected affiliations follow. Y. Takai, Department of Biochemistry and Molecular Biology, Kobe University Graduate School of Medicine, Kobe 650-0017, Japan. J. G. Borst, Department of Neuroscience, Erasmus MC, University Medical Center, Rotterdam, 3000 CA, Netherlands. N. Brose, Max-Planck-Institut für Experimentelle Medizin, Abteilung Molekulare Neurobiologie, 37075 Göttingen, Germany.

Letters: "Oil and water do mix" by J. L. Kavanau (19 February, p. 958). Due to an editorial error, the title was incorrect. It should have been "Opposites attract."

Reports: "100-million-year dynasty of giant planktivorous bony fishes in the Mesozoic seas" by M. Friedman *et al.* (19 February, p. 990). The author Matt Friedman's affiliation should have been "Committee on Evolutionary Biology, University of Chicago, 1025 East 57th Street, Chicago, IL 60637, USA." The affiliation that was listed is his present address.

News of the Week: "*DSM-V* at a glance" by G. Miller and C. Holden (12 February, p. 770). In the sidebar, it was reported that the term "gender identity disorder" has been retained. In fact, a different term—"gender incongruence"—has been proposed.

Research Articles: "PRDM9 is a major determinant of meiotic recombination hotspots in humans and mice" by F. Baudat *et al*. (12 February, p. 836). M. Lichten was incorrectly listed as an author in references 18 and 19. The correct authors for reference 18 are C. Grey, F. Baudat, and B. de Massy; for reference 19, the correct authors are E. D. Parvanov, S. H. Ng, P. M. Petkov, and K. Paigen.

Reports: "Epigenetic transgenerational actions of endocrine disruptors and male fertility" by M. D. Anway *et al*. (3 June 2005, p. 1466). As clarification of the abstract to Anway *et al*., the F_1 to F_4 generations were examined after vinclozolin treatment, and F_1 and F_2 generations were examined after methoxychlor treatment. To clarify data referred to in the last paragraph of the Report, serum testosterone measurements after vinclozolin treatment were shown in reference 21 (Uzumcu *et al.*) for the F_1 generation. Data for the F_1 to F_4 generations were subsequently published in Anway *et al*., *J. Androl*. **27**, 868 (2006). Serum testosterone measurements after methoxychlor treatment were shown in reference 20 (Cupp *et al.*) for the F_1 generation, but measurements of the F_2 generation have not been published. The *Science* Anway *et al*. manuscript showed DNA methylation analysis after vinclozolin treatment, but the DNA methylation data after methoxychlor treatment have not been published.

from fossil to modern carbon fuel sources while simultaneously reducing CO_2 levels in the atmosphere and ocean.

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Response

GREENE SUGGESTS THAT CO_2 REMOVAL methods deserve expanded evaluation and research. We agree. In the long run, these methods may be the only way to reduce atmospheric concentrations of CO_2 to values closer to those of the preindustrial era. Greene suggests a scheme for using biomass to generate electricity combined with carbon capture and storage. This idea has merit. Even schemes that capture CO_2 directly from the air deserve expanded research.

However, Greene's statement that "discussions of the necessary research and development…frequently turn into debates about the environmental costs and benefits of SRM [solar radiation management]" misses a key point motivating all three of the articles he cites [our Policy Forum and (*1*, *2*)]. The two approaches differ in both strategic impact and risks. Most CO_2 removal schemes, including those suggested by Greene, would be slow acting and expensive, and would pose no transboundary risks. In contrast, SRM techniques appear inexpensive and could have rapid climatic impact, but present a host of global climatic and political risks.

The low cost and technical feasibility of some SRM technologies (particularly stratospheric aerosol injection) mean that SRM might be our only response if a "climate emergency" develops. However, these traits also mean that SRM could be globally tested unilaterally by a single country, to the possible detriment of others (*3*). Beyond the climatic risks this presents, such actions could also severely disrupt progress on international climate policy.

The discussion of urgent governance challenges in the articles Greene cites is not a distraction; it is central to figuring out how to safely and prudently conduct research into SRM technologies. No such acute research governance challenges exist for most CO_2 removal techniques.

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Letters to the Editor

Letters (~300 words) discuss material published in *Science* in the previous 3 months or issues of general interest. They can be submitted through the Web (www.submit2science.org) or by regular mail (1200 New York Ave., NW, Washington, DC 20005, USA). Letters are not acknowledged upon receipt, nor are authors generally consulted before publication. Whether published in full or in part, letters are subject to editing for clarity and space.