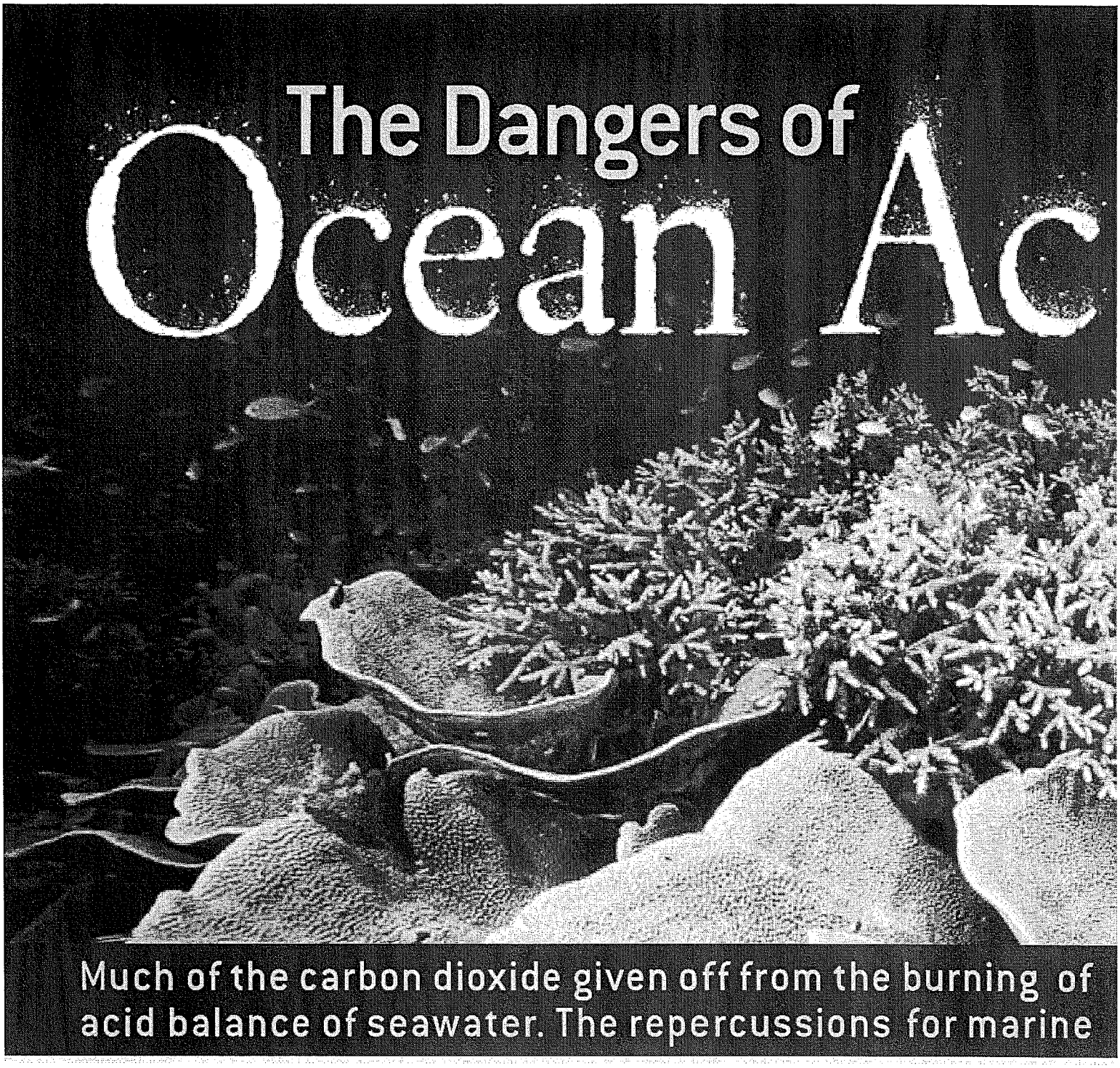
The Dangers of Ocean Ac



Much of the carbon dioxide given off from the burning of acid balance of seawater. The repercussions for marine

In 1956 Roger Revelle and Hans Suess, geochemists at the Scripps Institution of Oceanography in California, pointed out the need to measure carbon dioxide in the air and ocean so as to obtain "a clearer understanding of the probable climatic effects of the predicted great industrial production of carbon-dioxide over the next 50 years." In other words, they wanted to figure out how dire the situation would be today. That they had to argue the importance of such observations now seems astonishing, but at the time scientists did not know for certain whether the carbon dioxide spewing out of tailpipes and smokestacks would indeed accumulate in the atmosphere. Some believed that it would all be absorbed benignly by the sea or be happily taken up by growing plants on land.

Revelle and the young researcher he hired for this project, the late Charles David Keeling, realized that they had to set up equipment at remote locations, far from local sources and sinks of carbon dioxide, which would cause the measurements to vary erratically. One spot they chose was about as far from industrial activity and vegetation as anyone could get: the South Pole. Another was at a newly established weather station atop Mauna Loa in Hawaii.

The Mauna Loa monitoring has continued (with just one brief interruption) from 1958 to this day. Being not so remote as Antarctica, Hawaii sees carbon dioxide levels rise and fall sharply in step with the Northern Hemisphere's growing season, but at the end of each and every year, the concentration of this heat-trapping gas always ends up higher than it was 12

FRED BAVENDAM *Minden Pictures*

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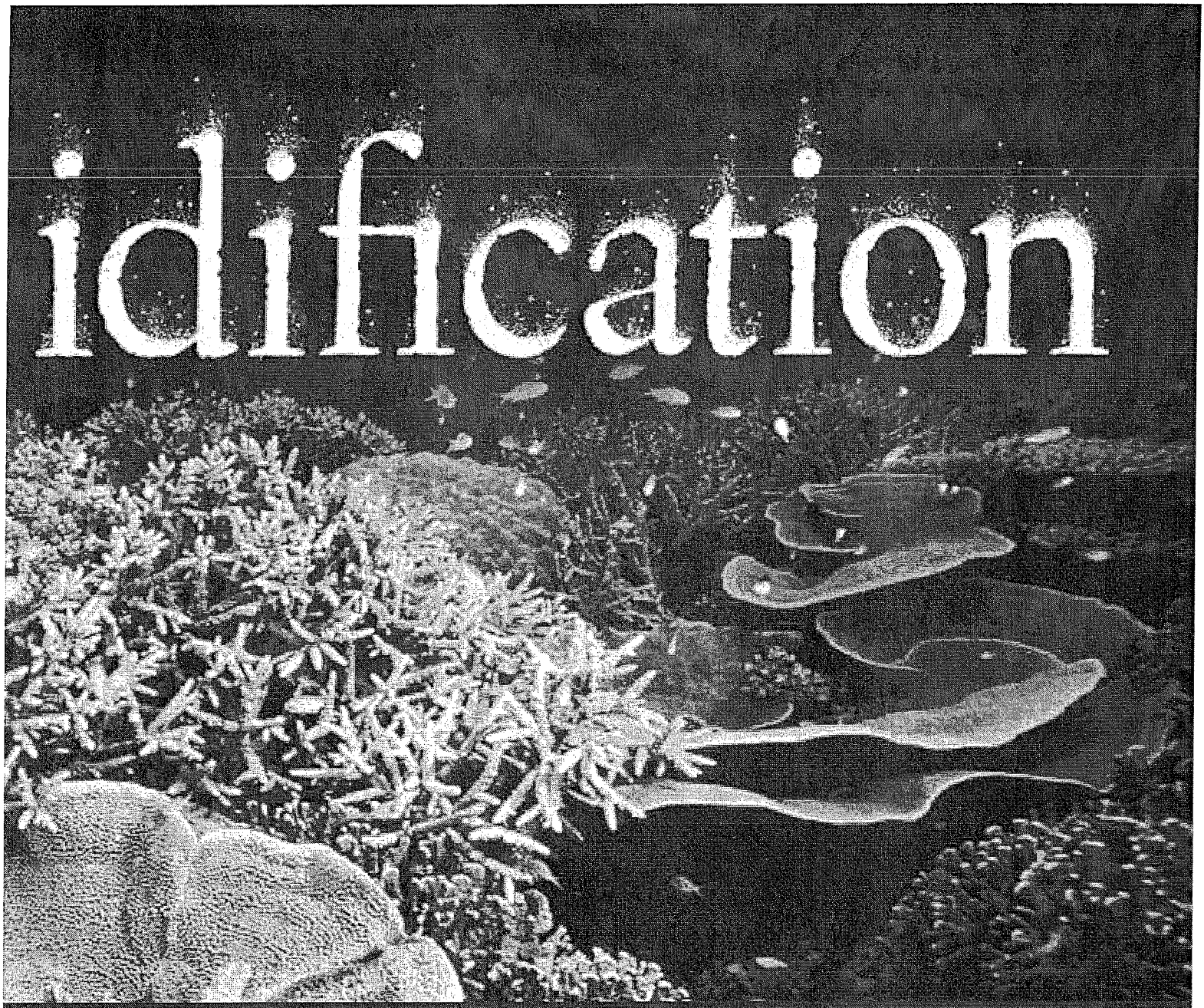

fossil fuels goes into the ocean, where it changes the life may be enormous

BY SCOTT C. DONEY

CORAL REEFS—and the extraordinary biodiversity they support—are under siege from many forces, including exposure to toxic chemicals and direct physical destruction. A less known but perhaps greater threat is the change in ocean chemistry caused by the burning of fossil fuels. Today one third of the carbon dioxide given off in that process enters the ocean, reducing its naturally alkaline pH. This shift toward more acidic conditions diminishes the ability of corals (and many other marine organisms) to grow.

months before. So it did not take long for the scientific community to realize that Revelle was right—much of the carbon dioxide released into the atmosphere was destined to remain there. But his calculations were also correct in showing that a substantial fraction would end up in the sea. And it was clear to Revelle long ago that the part that went into the ocean would fundamentally alter the chemistry of seawater. Unlike some aspects of climate change, the reality of this effect—essentially the acidification of the ocean—is not much debated, although its full implications are just now being revealed.

How Unnatural?

THE HALF-CENTURY RECORD that Keeling produced is extremely valuable, but it is too short to place the current situation in context. Scientists have, however, been able to obtain a longer-term perspective by measuring air bubbles trapped in ice cores. From this natural archive they have learned that the atmospheric concentration of carbon dioxide was approximately constant for several thousand years and then began to grow rapidly with the onset of industrialization

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in the 1800s. This gas is now about 30 percent more abundant than it was a few hundred years ago, and it is expected to double or triple its former level by the end of this century.

This burgeoning supply of carbon comes largely from the burning of fossil fuels—coal, oil and natural gas. (Cement production and the burning of tropical forests add some, too, but to simplify things, let me gloss over such secondary contributions for the sake of clarity.) Unlike the constituents of living organisms, fossil fuels contain little or none of the radioactive form of carbon: the carbon 14 isotope, which has eight neutrons in the nucleus rather than the usual six. Fossil fuels also display a unique ratio of the two stable isotopes of carbon (carbon 12 and 13). The combustion of these fuels thus leaves a distinctive isotopic signature in the atmosphere. So no one can question where the growing surplus of carbon dioxide comes from.

The ocean has absorbed fully half of all the fossil carbon released to the atmosphere since the beginning of the Industrial Revolution.

Absorption rates can vary, but today about 40 percent of the carbon dioxide derived from fossil fuel remains in the atmosphere; the rest is taken up by vegetation on land or by the ocean, currently in about equal proportions. The injection of fossil-fuel carbon into the sea is, as of yet, a relatively small addition to the ocean's huge natural reservoir of this element. Detecting and quantifying the uptake, therefore, requires especially precise measurements, ones good to at least one part in 1,000. And because the amounts vary substantially from place to place, the task also demands the resources and perseverance to map carbon concentrations throughout the world.

Overview/CO_2 in the Ocean

- About a third of the carbon dioxide (CO_2) released by the burning of fossil fuels currently ends up in the ocean.
- Absorbed CO_2 forms carbonic acid in seawater, lowering the prevailing pH level (which is slightly alkaline) and changing the balance of carbonate and bicarbonate ions.
- The shift toward acidity, and the changes in ocean chemistry that ensue, makes it more difficult for marine creatures to build hard parts out of calcium carbonate. The decline in pH thus threatens a variety of organisms, including corals, which provide one of the richest habitats on earth.
- Within a century, the surface of the Southern Ocean will become corrosive to the shells of tiny snails that form a key link in the marine food chain within this highly productive zone.

Oceanographers did exactly that in the late 1980s and 1990s, as part of a global assessment that went by two acronyms: JGOFS (for Joint Global Ocean Flux Study) and WOCE (for World Ocean Circulation Experiment).

Those surveys, however, did not in themselves identify what part of the carbon measured is natural and what part derives from the carbon dioxide that people have dumped into the air. In 1996 Nicolas Gruber, now at the University of California, Los Angeles, and two of his colleagues developed an innovative technique for doing so. The application of Gruber's method to all the JGOFS and WOCE data, an exercise completed in 2004, suggests that the ocean has absorbed fully half of all the fossil carbon released to the atmosphere since the beginning of the Industrial Revolution.

Another way to document this process is to make repeated measurements of carbon on the same piece of ocean. One must be careful to distinguish the fossil carbon from the various biological sources of this element in the sea. And the observations need to span a decade or more to reveal the overall trend brought on by the burning of fossil fuels against the background of natural variability. Last year Rik Wanninkhof of the National Oceanic and Atmospheric Administration's Atlantic Oceanographic and Meteorological Laboratory and I led a research expedition to do just such an experiment.

With a party of 31 scientists, technicians and students onboard our research vessel, we spent almost two months sampling the physical and chemical properties of the western South Atlantic, from top to bottom, starting near Antarctica and ending near the equator. This is the very same slice of ocean that I and other scientists had first measured in 1989, when I was a graduate student.

When we compared our observations from 2005 with those made 16 years earlier, we found that the upper few hundred meters of the South Atlantic in general have higher carbon concentrations today than in the recent past, which is consistent with the notion that the sea is taking in atmospheric carbon dioxide. Other oceanographers have found similar trends in the Pacific and Indian oceans as well. But what exactly does this change portend for the marine environment?

Ocean Chemistry 101

EXPLAINING THE IMPLICATIONS of these shifts in oceanic conditions requires, alas, a review of some freshman chemistry. But bear with me; it is really not that painful. Carbon dioxide (CO_2) combines with water to form carbonic acid (H_2CO_3), the same weak acid found in carbonated beverages. Like all acids, this one releases hydrogen ions (H^+) into solution, in this case leaving both bicarbonate ions (HCO_3^{-1}) and, to a lesser extent, carbonate ions (CO_3^{-2}) also swimming around. A small fraction of the carbonic acid remains in solution without dissociating, as does a little carbon dioxide. The resulting brew of carbon compounds and ions is thus rather complex.

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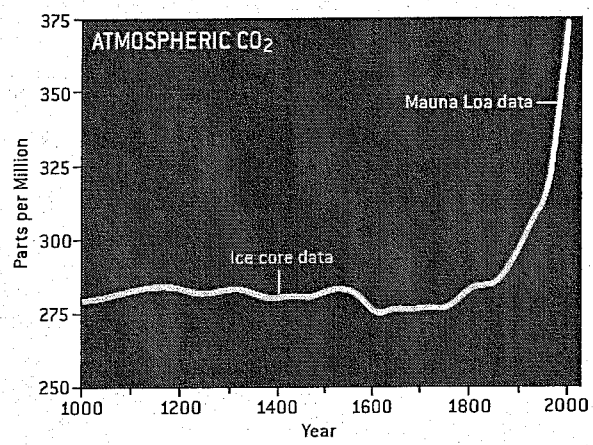
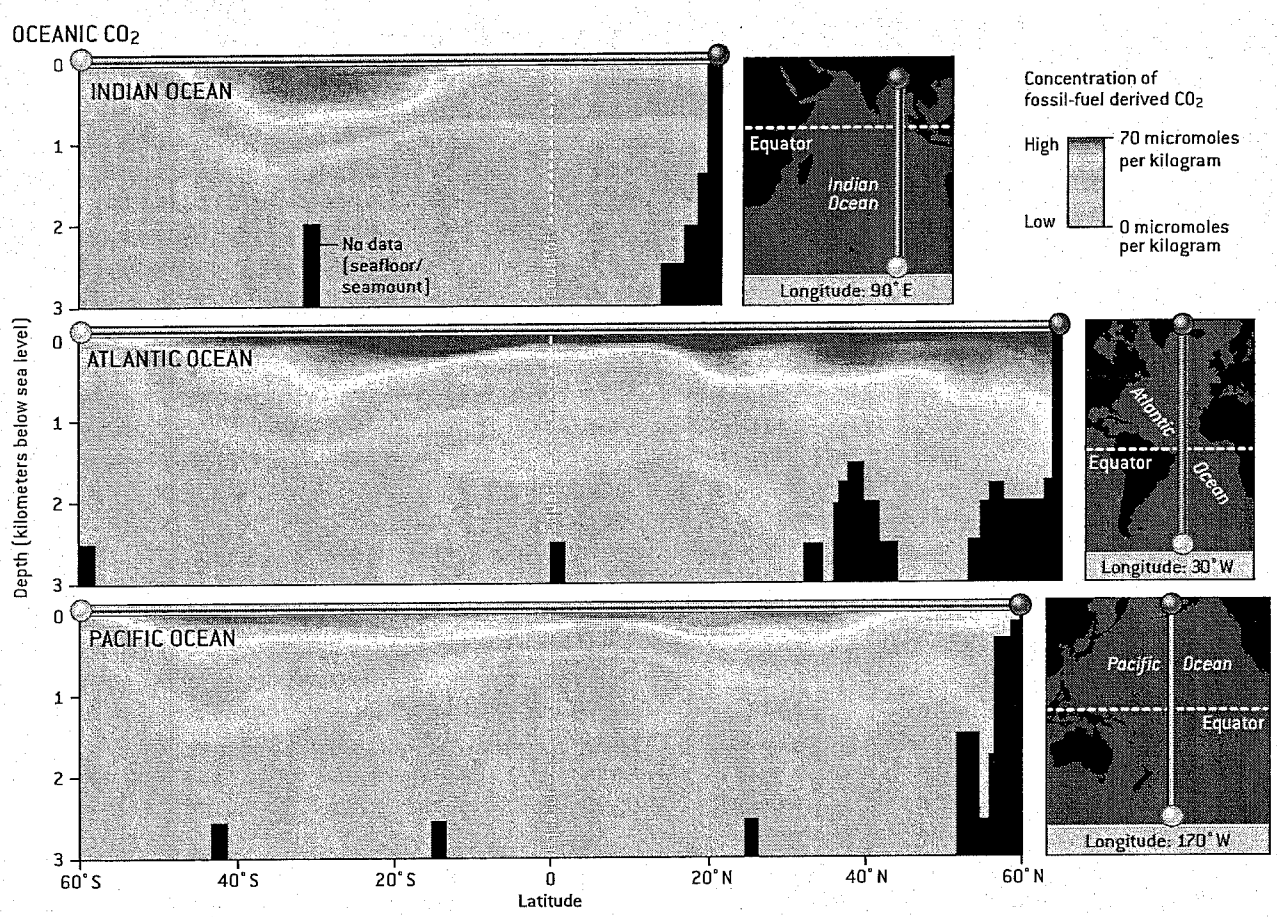
CO_2: FROM ATMOSPHERE TO OCEAN

The concentration of carbon dioxide in the atmosphere has mounted considerably over the past century or so. This worrisome trend is well documented (*right*) by a combination of two techniques: the examination of air bubbles trapped in glacial ice (*green segment*, which shows 75-year averages) as well as direct measurements of the atmosphere (*white segment*, which reflects the annual average determined at a weather station situated atop Mauna Loa on the big island of Hawaii).

Large as it is, the increasing concentration of carbon dioxide in the atmosphere would have been even greater had not much of it been absorbed by the sea, a phenomenon that detailed oceanographic surveys have now documented. The cross sections below show where about half of this fossil-fuel effluent now resides—in the upper portions of the world's oceans.





JEN CHRISTIANSEN; SOURCES: CARBON DIOXIDE INFORMATION ANALYSIS CENTER AT OAK RIDGE NATIONAL LABORATORY (http://cdiac.ornl.gov/ftp/trends/co2/lawdome.combined.dat and http://cdiac.ornl.gov/ftp/ndp001/maunaloa.co2) (*atmospheric CO_2 data*); ROBERT KEY *Princeton University* (*oceanic CO_2 cross section data*)

One simple result of all this dissolving and dissociating is the increase in hydrogen ion concentration, which chemists normally quantify in terms of the familiar pH scale. A drop by one pH unit corresponds to a 10-fold increase in the concentration of hydrogen ions, making the water more acidic, whereas a change of one unit upward corresponds to a 10-fold decrease, making the water more alkaline. Neutral pH (that of pure water) is 7. The pH of pristine seawater measures from 8 to 8.3, meaning that the ocean is naturally somewhat alkaline.

The absorption of carbon dioxide has already caused the pH of modern surface waters to be about 0.1 lower (less alkaline) than it was in preindustrial times. Unless civilization modifies its appetite for fossil fuels soon and in a significant way, ocean pH will fall an additional 0.3 by 2100. In a troubling prediction of the more distant future, Ken Caldeira, an oceanographer at the Carnegie Institution of Washington, suggests that ocean pH several centuries from now will be lower than at any time in the past 300 million years.

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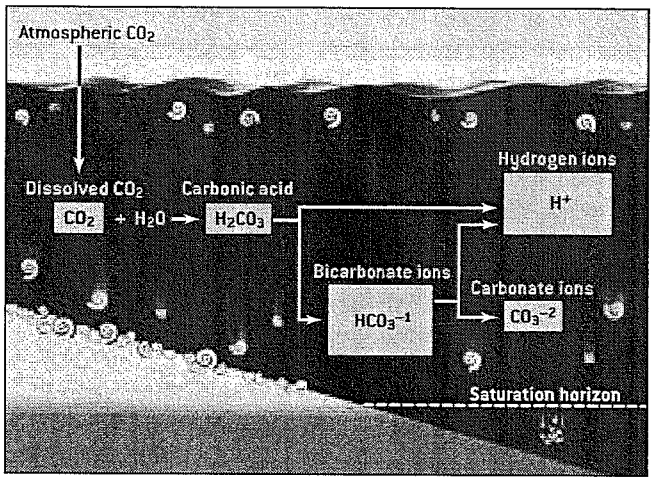


CARBON DIOXIDE absorbed from the air combines with water to form carbonic acid. A portion of this compound persists in the ocean, but most of it dissociates into acidifying hydrogen ions along with bicarbonate ions. Some of the latter also dissociate, forming carbonate ions and yet more hydrogen ions. These chemical changes cause an upward shift in the "saturation horizons" for calcite and aragonite—the water levels deep in the sea below which shells of marine organisms made of these minerals dissolve.

These shifts in pH may seem small, but they provide ample cause for alarm. Notably, recent experiments indicate that the change will prove harmful to some forms of marine life—in particular, to organisms that depend on the presence of carbonate ions to build their shells (or other hard parts) out of calcium carbonate ($CaCO_3$).

At first this concern appears paradoxical. After all, if some of the carbon dioxide absorbed by the sea dissociates into carbonate ions, one might expect that there should be plenty to go around, even more than would have been available otherwise. That logic, though, is flawed because it neglects the effect of all the hydrogen ions that are also created, which tend to combine with carbonate ions, forming bicarbonate ions. The net result is thus a reduction in the concentration of carbonate ions.

The worry is that a lowering of pH (and thus of carbonate ion concentration, which is expected to drop by half over this century) will hamper the ability of certain organisms to make calcium carbonate, so much so that these organisms will then have difficulty growing. Some of the most abundant lifeforms that could be affected in this way are a type of phytoplankton called coccolithophorids, which are covered with small plates of calcium carbonate and are commonly found floating near the surface of the ocean (where they use the abundant sunlight for photosynthesis). Other important examples are planktonic organisms called foraminifera (which are related to amoeba) and pteropods (small marine snails). These tiny creatures constitute a major food source for fish and marine mammals, including some species of whales.

Biologists also fear what might happen to corals, which despite their plantlike appearance are actually colonies of small animals related to sea anemones. They feed by filtering plankton out of the water, and they secrete calcium carbonate skeletons, which accumulate over time to form coral reefs—some of the most productive and biologically diverse ecosystems in the ocean. Coralline algae (algae that also secrete calcium carbonate and often resemble corals) contribute to the calcification of many reefs, too. The Great Barrier Reef off the coast of Australia, for instance—the largest biological structure in the world—is simply the accumulation of generation after generation of coral and coralline algae. Less obvious examples occur deeper down in the sea, where cold-water coral communities dot continental margins and seamounts, forming important fish habitats.

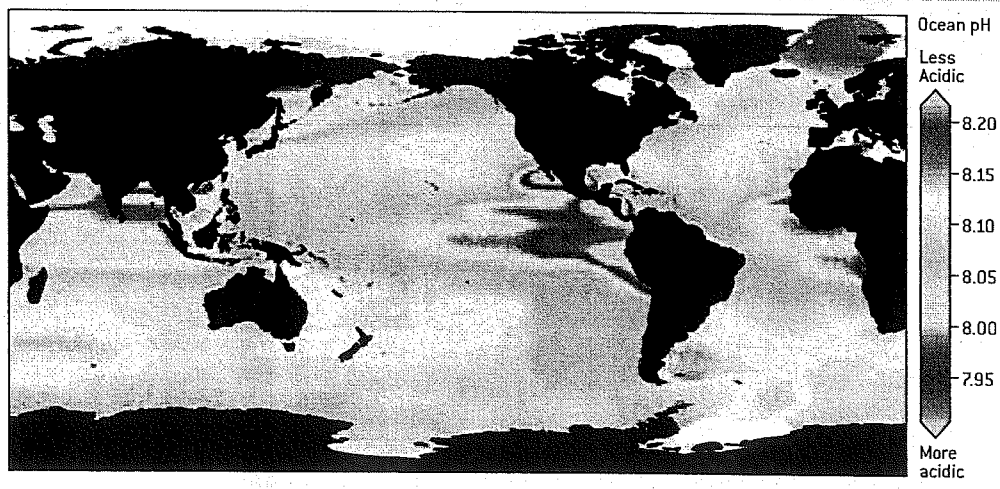
Shallow-water corals owe their beautiful colors in part to symbiotic algae, which live inside the coral cells. In response to various forms of environmental stress, these algae sometimes leave their hosts, exposing the white calcium carbonate skeleton underneath. Such "bleaching" events can be brought on by extreme warmth, for example. And some scientists sus-

JEN CHRISTIANSEN (top); CHRIS SABINE NOAA Pacific Marine Environment Laboratory (bottom)

THE OCEAN'S CHANGING ACIDITY

Measurements taken in the top 50 meters of the ocean reveal that pH varies considerably from place to place. Scientists expect oceanic pH to decrease in the years ahead.

Areas of relatively low pH (signifying more acidic conditions) arise mostly through the natural upwelling of deeper waters. Those zones, such as in the east equatorial Pacific, might be good places for scientists to study the effects expected to prevail over wider areas in the future.



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pect that the acidification of the ocean (or more properly, the reduction in the ocean's slightly alkaline state) also tends to prompt such episodes.

Survival of the Thickest?

BUT CORALS and other calcifying marine organisms could be affected by acidification in even more significant ways—their shells might actually disintegrate. Drop a piece of chalk (calcium carbonate) into a glass of vinegar (a mild acid) if you need a demonstration of the general worry: the chalk will begin dissolving immediately. Gaining a fuller understanding of which life-forms are most at risk of such a fate requires another short chemistry lesson.

The calcium carbonate in corals or in the shells of other marine creatures comes in two distinct mineral forms: calcite and aragonite. And some calcite-secreting organisms also add magnesium to the mix. Aragonite and magnesium calcite are more soluble than normal calcite. Thus, corals and pteropods, which both produce aragonitic shells, and coralline algae, which manufacture magnesium calcite, may be especially susceptible to harm from ocean acidification.

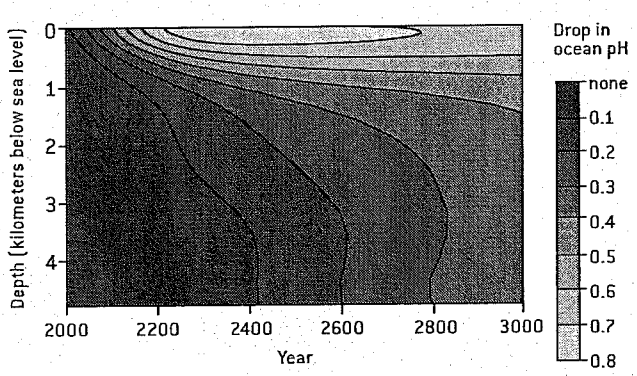
The solubility of calcium carbonate depends fundamentally on the carbonate ion concentration (and therefore indirectly on pH), but it also hinges on several other variables, including temperature and pressure. Under modern conditions, many deep, cold waters are acidic enough to dissolve calcium carbonate shells. They are said to be "undersaturated." Shallow, warm surface waters are described as "supersaturated" with respect to both calcite and aragonite, meaning that these minerals have no tendency to dissolve. The transition between supersaturated and undersaturated conditions is referred to as the saturation horizon: the level below which things begin to dissolve.

The influx of carbon dioxide from the atmosphere has caused the saturation horizons for aragonite and calcite to shift closer to the surface by 50 to 200 meters compared with where they were positioned in the 1800s. And recent studies indicate that further widespread shoaling will take place over the next several decades. Thus, as the ocean becomes more and more acidic, the upper, shell-friendly portion will become thinner. That is to say, less and less of the sea will remain hospitable for calcifying organisms.

Early on, many scientists reasoned that ocean acidification would pose only a minor problem, because surface waters would remain supersaturated—at least with respect to calcite, the robust form of calcium carbonate. In the late 1990s Christopher Langdon, a marine biologist at the University of Miami, conducted an elegant experiment to test this surmise: he manipulated the water chemistry over an artificial coral reef that had been set up in a huge tank at Columbia University's Biosphere II laboratory (which, rather incongruously, is located in the middle of the Arizona desert). Strikingly, he found that the rate of calcium carbonate production in the corals declined with lower pH, although the water remained considerably supersaturated with respect to aragonite. Shortly afterward, Ulf Riebesell of the Alfred Wegener Institute for Polar and Marine Research in Germany and his colleagues demonstrated a similar stunting of planktonic coccolithophorids. Laboratory experiments are now available to show the deleterious effects of increased carbon dioxide (and the lower pH that results) for all the major groups of marine organisms that have hard parts made of calcium carbonate.

As the ocean becomes more and more acidic, the upper, shell-friendly portion will become thinner.

Because cold waters are naturally less supersaturated than warm ones for the various forms of calcium carbonate, high-latitude and deep water ecosystems may be the first to suffer from ocean acidification. Polar surface waters most likely will



Although acidification of the sea (as measured by the drop in pH) has so far been small, scientists expect larger shifts in the future. The greatest changes will take place near the surface, but over time the full depth of the ocean will feel these effects.

JEN CHRISTIANSEN; SOURCE: "ANTHROPOGENIC CARBON AND OCEAN pH," BY K. CALDEIRA AND M. E. WICKETT IN *NATURE*, VOL. 425; SEPTEMBER 25, 2003

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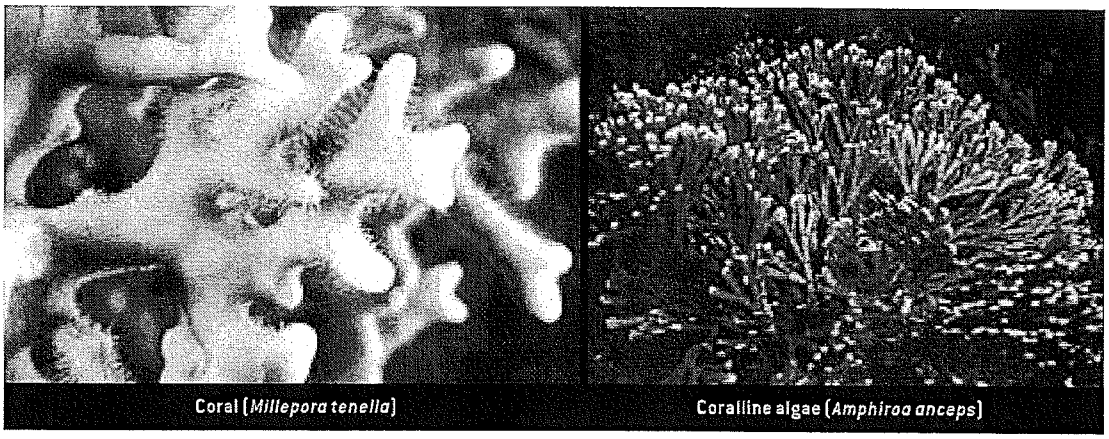
MARINE ORGANISMS at risk from the increasing acidification of the ocean include the corals and coralline algae commonly found in reef communities, as well as foraminifera and coccolithophorids, which are abundant in most surface waters. Also under threat, particularly in cold, polar waters, are a variety of small marine snails called pteropods.

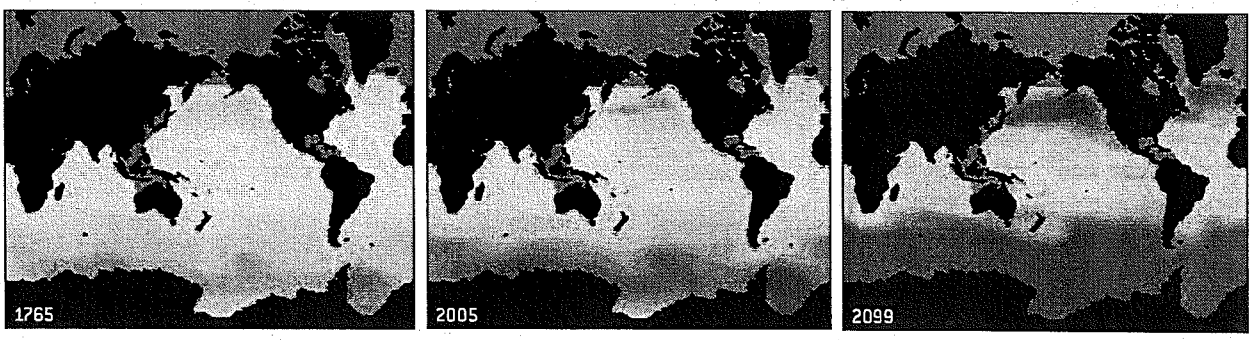


become undersaturated for aragonite before the end of this century. One worrisome possibility, based on the work of Victoria J. Fabry of California State University, San Marcos, is that polar pteropods will simply disappear altogether. Or perhaps they will be forced to migrate to lower, warmer latitudes, assuming that they can adapt to those environments. No one knows how a sharp decrease in pteropod numbers will affect other parts of the marine ecosystem. But the fact that these small snails are a key link in the food chain in the Southern Ocean (which supports large populations of fish, whales and seabirds) is ample cause for concern.

High-latitude calcareous phytoplankton and zooplankton might share a similar fate, although their declines would come decades later because their shells are formed from calcite, the less soluble form of calcium carbonate. Deep coral communities will probably suffer, too, particularly those in the western North Atlantic along the path of water that contains high concentrations of carbon from fossil-fuel emissions.

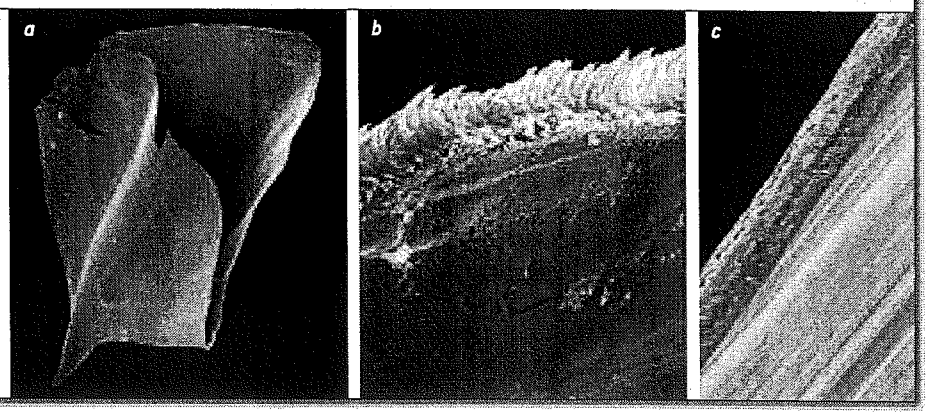
THE (RAGGED) FUTURE OF ARAGONITE

Diminishing pH levels will weaken the ability of certain marine organisms to build their hard parts and will be felt soonest and most severely by those creatures that make those parts of aragonite, the form of calcium carbonate that is most prone to dissolution. The degree of threat will vary regionally.



Before the Industrial Revolution (*left*), most surface waters were substantially "oversaturated" with respect to aragonite (*light blue*), allowing marine organisms to form this mineral readily. But now (*center*), polar surface waters are only marginally oversaturated (*dark blue*). At the end of this century (*right*), such chilly waters, particularly those surrounding Antarctica, are expected to become undersaturated (*purple*), making it difficult for organisms to make aragonite and causing aragonite already formed to dissolve.

Pteropods form a key link in the food chain throughout the Southern Ocean. For these animals (and creatures that depend on them), the coming changes may be disastrous, as the images at the right suggest. The shell of a pteropod kept for 48 hours in water undersaturated with respect to aragonite shows corrosion on the surface (*a*), seen most clearly at high magnification (*b*). The shell of a normal pteropod shows no dissolution (*c*).



ALEXIS ROSENFELD *Photo Researchers, Inc.* (*fire coral*); KEOKI STENDER *Fishpics Hawaii* (*coralline algae*); WOODS HOLE OCEANOGRAPHIC INSTITUTION (*foraminifer*); STEVE GSCHMEISSNER *Photo Researchers, Inc.* (*coccolithophorid*); RUSS HOPCROFT *University of Alaska–Fairbanks/NOAA* (*pteropod*); JAMES C. ORR *Laboratory of the Science of Climate and the Environment, UMR CEA-CNRS, France* (*map data and pteropod shell images*)

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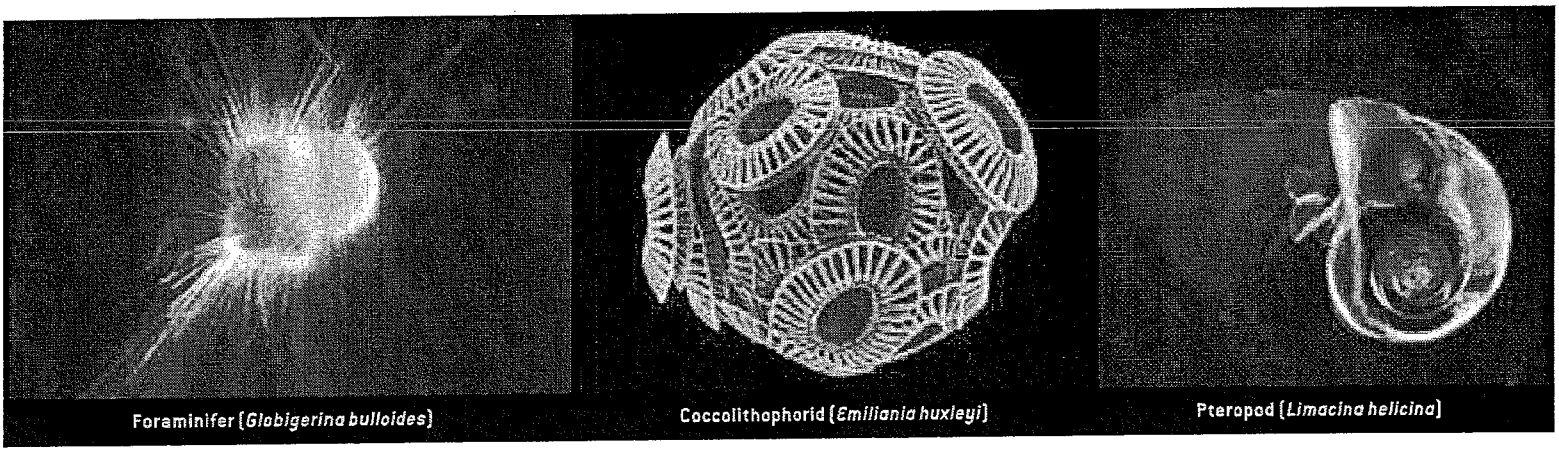

Foraminifer (*Globigerina bulloides*) Coccolithophorid (*Emiliania huxleyi*) Pteropod (*Limacina helicina*)

The outlook for coral reefs is even bleaker. For those precious ecosystems, ocean acidification is but one of many environmental stresses, an onslaught that includes greenhouse warming, local pollution, overfishing and habitat destruction. Many coral reefs are already in decline, and ocean acidification may push some over the edge into nonexistence.

Coming Sea Change

AS BAD AS CONDITIONS are expected to be for many marine organisms, there will be some winners, too. Right now very little of the carbon in seawater takes the form of dissolved carbon dioxide, and this scarcity limits the growth of some types of phytoplankton. Many of these species devote precious energy to concentrate carbon dioxide inside their cells, so one might guess that increases in dissolved carbon dioxide will be beneficial to them. Perhaps that will be the case. Not enough is known, however, about this "fertilization" effect to make firm predictions for the future of phytoplankton or to say whether higher carbon dioxide levels will benefit the photosynthetic algae that live inside corals. Many species of marine phytoplankton use HCO_3^{-1} for photosynthesis. And because the concentration of this ion will remain largely unchanged, biologists do not expect that these organisms will experience a significant boost. Some higher plants (sea grasses, for example) use dissolved carbon dioxide directly and probably will benefit from its rising levels, just as plants on land are expected to gain as the atmospheric concentration of this gas increases.

How can scientists better gauge the response of ocean ecosystems to acidification? Most current efforts in this area involve short-term laboratory experiments on single species. Scientists have also mounted small-scale field studies to examine the acute effects that would accompany the deliberate disposal of atmospheric carbon dioxide in the deep sea, one of the various strategies being considered to sequester carbon dioxide and keep it out of the air [see "Can We Bury Global Warming?" by Robert H. Socolow; SCIENTIFIC AMERICAN, July 2005]. Although this work is informative, the results do not translate easily into an understanding of the consequences of long-term, chronic exposure to modestly lower pH. Nor is it straightforward to extrapolate from laboratory studies to whole ecosystems, where many different organisms interact.

One possibility for gaining a more realistic assessment of the problem would be to elevate carbon dioxide levels artificially for months to years in a patch of the ocean or on a coral reef. Experiments involving the large-scale manipulation of carbon dioxide levels are commonly carried out on land, but marine scientists and engineers are just now beginning to explore the logistics for extending this approach to the ocean. Another tactic is to study how marine organisms fare in regions that have long had lower pH, such as the Galápagos Islands, which are bathed in waters that are naturally rich in carbon dioxide.

Yet a third strategy might be to examine the geologic record of times when carbon dioxide concentrations reached much higher levels than that of the present and when ocean pH was presumably much lower—such as during an interval of anomalously warm climate that took place some 55 million years ago (the Paleocene-Eocene Thermal Maximum), when many marine organisms died off. The concern of many scientists today is that the current episode of acidification is taking place more rapidly than anything that has transpired in the past, leaving oceanic species no time to adapt. Although the effects may be hidden from people's view, dramatic alterations in the marine environment appear to be inevitable. SA

Many coral reefs are already in decline, and ocean acidification may push some over the edge into nonexistence.

MORE TO EXPLORE

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Anthropogenic Ocean Acidification over the Twenty-First Century and Its Impact on Calcifying Organisms. James C. Orr et al. in *Nature*, Vol. 437, pages 681–686; September 29, 2005.

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Washington State Blue Ribbon Panel on Ocean Acidification

Ocean Acidification: From Knowledge to Action

Washington State's Strategic Response

November 2012

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Summary

BETWEEN 2005 AND 2009, DISASTROUS production failures at Pacific Northwest oyster hatcheries signaled a shift in ocean chemistry that has profound implications for Washington's marine environment. Billions of oyster larvae were dying at the hatcheries, which raise young oysters in seawater. Research soon revealed the cause: the arrival of low-pH seawater along the West Coast, which created conditions corrosive to shell-forming organisms like young oysters. The problem, in short, was ocean acidification.

What is Ocean Acidification?

Ocean acidification is a reduction in the pH[1] of seawater for an extended period of time due primarily to the uptake of carbon dioxide from the atmosphere by the ocean. Local sources of acidification such as nitrogen oxides and sulfur oxide gases, or nutrients and organic carbon from wastewater discharges and runoff from land-based activities, can also contribute to ocean acidification in marine waters.

Since the beginning of the industrial era more than 250 years ago, the rapid growth in fossil fuel burning (for example, coal and oil) and land use changes have caused a dramatic rise in carbon dioxide emissions. About one-quarter of these human-generated emissions have been absorbed by the oceans. Through a well-understood series of chemical reactions, carbon dioxide gas has an acidifying effect when dissolved in seawater. As a result, the average acidity (as measured by the hydrogen ion concentration) of the surface ocean has increased about 30 percent since 1750.

Today's ocean acidification is important not only for the amount of change that has occurred thus far but also for how quickly it is happening. The current rate of acidification is nearly ten times faster than any time in the past 50 million years, outpacing the ocean's capacity to restore oceanic pH and carbonate chemistry. The rapid pace of change also gives marine organisms, marine ecosystems, and humans less time to adapt, evolve, or otherwise adjust to the changing circumstances. At the current rate of global carbon dioxide emissions, the average acidity of the surface ocean is expected to increase by 100–150 percent over pre-industrial levels by the end of this century.

1 pH is defined as the negative log of the hydrogen ion concentration in a solution. Neutral pH is 7.0. Solutions with pH values less than 7.0 are "acidic," and those with pH values greater than 7.0 are "basic." Because pH is expressed on a logarithmic scale, a small change in pH corresponds to a large change in acidity. This means that a pH of 7 is ten times more acidic than a pH of 8.

Why Does Washington Need to Act on Ocean Acidification?

As will be explained below, Washington is particularly vulnerable to ocean acidification. In addition, acidification has significant implications for Washington's marine environment, our state and local economies, and tribes.

Washington is Particularly Vulnerable to Ocean Acidification

Washington's marine waters are particularly vulnerable to ocean acidification because of regional factors that exacerbate the acidifying effects of global carbon dioxide emissions. One of the most important regional factors is coastal upwelling, which brings offshore water that is rich in carbon dioxide and low in pH up from the deep ocean and onto the continental shelf.

Because upwelled water has spent decades circulating at depth, the carbon dioxide content in today's upwelled water reflects naturally occurring carbon dioxide generated by biological processes in the ocean as well as carbon dioxide absorbed from the atmosphere 30 to 50 years ago when the water was last in contact with the atmosphere. The half-century transit time between contact with the atmosphere and re-emergence along the coast means that today's upwelled water bears the imprint of the atmosphere in about 1970, when the concentration of carbon dioxide in the atmosphere was much lower relative to today's concentration. Since then carbon dioxide concentrations have continued to climb and so has the "carbon loading" of the waters making their way to the Washington coast. Consequently, we will continue to see more acidifying conditions coming from upwelled waters for several decades to come.

Other regional factors affecting ocean acidification in Washington include runoff of nutrients and organic carbon (such as plants and freshwater algae) from land, and local emissions of carbon dioxide, nitrogen oxides, and sulfur oxides, which are absorbed by seawater from the atmosphere. The relative importance of these local drivers varies by location. For example, acidification along the outer coast of Washington and Puget Sound is strongly influenced by coastal upwelling while acidification in shallow estuaries, including those in Puget Sound, may be particularly influenced by inflows of fresh water (which is naturally lower in pH than seawater) carrying nutrients and organic carbon from human and natural sources. The added organic carbon, as well as nutrients that stimulate excessive algal growth, can make seawater more acidic when algae and other organic matter decompose.

Ocean Acidification is a Risk to Washington's Marine Species and Ecosystems

Many life processes, including photosynthesis, growth, respiration, recruitment, reproduction, and behavior are sensitive to carbon dioxide and pH. As a result, ocean acidification has the potential to affect a wide range of organisms, from seagrasses to fish, in many different ways.

Research shows that organisms that use the mineral calcium carbonate (usually in the form of calcite or aragonite) to make shells, skeletons, or other vital body parts are particularly affected. These organisms, known generally as calcifiers, are found throughout Washington's marine environment (Box S-1).

Ocean acidification leads to conditions that are chemically corrosive for shellfish and other calcifiers. When carbon dioxide concentrations in seawater increase, the availability of carbonate ions (a key component of calcium carbonate) decreases, making it more difficult for calcifiers to form, build, and maintain calcium shells and other calcium carbonate-based body parts. If the carbonate ion concentration dips too low, the seawater becomes chemically corrosive to calcium carbonate. Some calcifiers will therefore experience greater difficulty in making or maintaining their shells, slower growth rates, and higher mortality. Shellfish larvae and juveniles are especially vulnerable.

Box S-1. Ocean acidification can affect many Puget Sound species.

More than 30 percent of Puget Sound's marine species are vulnerable to ocean acidification by virtue of their dependency on the mineral calcium carbonate to make shells, skeletons, and other hard body parts. Puget Sound calcifiers include oysters, clams, scallops, mussels, abalone, crabs, geoducks (pictured above), barnacles, sea urchins (pictured below), sand dollars, sea stars, and sea cucumbers. Even some seaweeds produce calcium carbonate structures.

Ocean acidification also has implications for the broader marine environment. Many calcifiers provide habitat, shelter, and/or food for various plants and animals. For example, rockfish and sharks rely on habitat created by deepwater corals off the Washington coast. Pteropods, the delicate free-swimming snails eaten by seabirds, whales, and fish (especially Alaska pink salmon), can experience shell dissolution and grow more slowly in acidified waters (Figure S-1). Some species of copepods, the small crustaceans eaten by juvenile herring and salmon, experience similar problems with growth. Impacts on species like pteropods and copepods are a significant concern because of their ability to affect entire marine food webs.

Figure S-1. The pteropod, or "sea butterfly," is a tiny sea snail about the size of a small pea that plays an integral role in marine food webs. The photos above show what happens to a pteropod's shell when placed in seawater with pH and carbonate levels projected for the year 2100. The shell slowly dissolved over 45 days. *Used with permission from National Geographic.*

Ocean Acidification is a Risk to Washington's Marine Economy and Tribes

Washington is the country's top provider of farmed oysters, clams, and mussels. Annual sales of farmed shellfish from Washington account for almost 85 percent of U.S. West Coast sales (including Alaska).[2] The estimated total annual economic impact of shellfish aquaculture is $270 million, with shellfish growers directly and indirectly employing more than 3,200 people.[3] Shellfish are also an integral part of Washington's commercial wild fisheries, generating over two-thirds of the harvest value of these fisheries.[4] Shellfish of ecological and economic importance include oysters, mussels (native and Mediterranean), clams (e.g., geoduck, razor, littleneck, Manila), scallops, Dungeness crab, shrimp (e.g., spot prawns, pink shrimp), pinto abalone, and urchins.

Pike Place Market, Seattle. Local seafood is an important economic driver for the state's economy.

The economic benefits of Washington's wild and hatchery-based seafood harvests extend well beyond the value of the harvest when it arrives on shore. For example, licensing for recreational shellfish harvesting generates $3 million annually in state revenue and recreational oyster and clam harvesters contribute more than $27 million annually to coastal economies.[5] Overall, Washington's seafood industry generates over 42,000 jobs in Washington and contributes at least $1.7 billion to gross state product through profits and employment at neighborhood seafood restaurants, distributors, and retailers.[6] While our understanding of how ocean acidification affects the range of species driving this economic activity is limited at this time, it is clear that the impacts of ocean acidification on Washington's marine industry could extend far into and beyond the state's local and regional economies.

2 See Pacific Coast Shellfish Growers Association table of production statistics, 2011, **http://pcsga.net/wp-content/uploads/2011/02/production_stats.pdf**

3 Washington Shellfish Initiative white paper, December 2011, **http://www.governor.wa.gov/news/shellfish_white_paper_20111209.pdf**

4 National Marine Fisheries Service, Office of Science and Technology. (2012). Commercial Fisheries Statistics: Annual Landings by Species for Washington, accessed 9/28/12. **https://www.st.nmfs.noaa.gov/commercial-fisheries/index**

5 See Washington Shellfish Initiative white paper, December 2011, referenced above

6 U.S. Department of Commerce, National Atmospheric and Oceanographic Administration. (2011). Fisheries Economics of the U.S. 2009: Economics and Sociocultural Status and Trends Series. **www.st.nmfs.noaa.gov/st5/publication/index.html**

Ocean acidification also has important cultural implications. To Washington's tribal communities, ocean acidification is a natural resource issue and a significant challenge to their continued identity and cultural survival. With salmon at just a fraction of their former abundance, tribal fishers are depending more on shellfish to support their families; almost all of the commercial wild clam fisheries in Puget Sound are tribal. The tribes also harvest wild shellfish for ceremonial and subsistence purposes.

A Lummi family digs clams in Puget Sound. Shellfish are an important source of nutrition for Indian people in western Washington.

Ocean Acidification: From Knowledge to Action

Recognizing the risks of ocean acidification to Washington, Governor Christine Gregoire created the Washington State Blue Ribbon Panel on Ocean Acidification (referred to here as "the Panel") to chart a course for addressing the causes and consequences of acidification. The Panel, convened in February 2012, was assembled under the auspices of the Washington Shellfish Initiative, a regional partnership established to implement the National Oceanic and Atmospheric Administration's (NOAA) National Shellfish Initiative.[7] Members included scientists; public opinion leaders; industry representatives; state, local, federal, and tribal policymakers; and conservation community representatives. The Governor charged the Panel to:

- Review and summarize the current state of scientific knowledge of ocean acidification,
- Identify the research and monitoring needed to increase scientific understanding and improve resource management,
- Develop recommendations to respond to ocean acidification and reduce its harmful causes and effects, and
- Identify opportunities to improve coordination and partnerships and to enhance public awareness and understanding of ocean acidification and how to address it.

7 NOAA's National Shellfish Initiative recognizes the broad suite of benefits provided by shellfish production and restoration. Its goal is to stimulate coastal economies and improve the health of estuaries by increasing commercial shellfish production and native shellfish populations.

This report, and the accompanying technical document *Scientific Summary of Ocean Acidification in Washington State Marine Waters*,[8] constitute the Panel's report of its findings and recommendations for action.

Panel Recommendations

The strategies and actions recommended by the Panel recognize the need for action across a range of areas (Box S-2).

First is the urgent need to slow the pace of ocean acidification by reducing the sources that cause the problem. Global carbon dioxide emissions are the biggest driver of acidification in the oceans overall and, broadly speaking, in Washington's marine waters. The Panel calls on Washington to continue its efforts to reduce carbon dioxide emissions while providing leadership in regional, national, and international forums to advocate for comprehensive carbon dioxide emissions reductions.

Washington's shellfish industry and native ecosystems cannot rely on emissions reductions alone, however. Our marine waters are continuing to acidify and reducing carbon dioxide emissions takes time. To rely solely on those reductions would result in significant—and in some cases irreversible—economic, cultural, and environmental impacts. Additional local actions, including local source reduction and adaptation and remediation, are necessary to "buy time" while society collectively works to reduce global carbon dioxide emissions.

Box S-2. Major Action Areas.

The Panel recommends 42 actions in the following areas. Collectively, these focal points form the structure of a comprehensive strategy for addressing ocean acidification in Washington's marine waters.

1. Reduce emissions of carbon dioxide;
2. Reduce local land-based contributions to ocean acidification;
3. Increase our ability to adapt to and remediate the impacts of ocean acidification;
4. Invest in Washington's ability to monitor and investigate the causes and effects of ocean acidification;
5. Inform, educate, and engage stakeholders, the public, and decision makers in responding to ocean acidification; and
6. Maintain a sustainable and coordinated focus on ocean acidification at all levels of government.

Each action includes a brief description. Implementation leads, partners, time frame, and estimated costs are included in Appendix 1.

8 Available at **https://fortress.wa.gov/ecy/publications/SummaryPages/1201016.html**

Local source reduction requires reducing local land-based pollutants that enhance acidification in marine waters by generating additional carbon dioxide. Most notable are inputs of nitrogen and organic carbon from point, nonpoint, and natural sources. Panel recommendations in this area focus on strengthening existing local source control programs to achieve the needed reductions in nutrient and organic carbon pollutants. In some cases, more stringent controls of nutrients and organic carbon pollutants may be required.

Adaptation and remediation help ensure the continued viability of native and commercial shellfish species and healthy marine ecosystems in Washington. The adaptation and remediation actions recommended by the Panel provide tools and information that resource managers and shellfish growers can use to strategically adjust to changing conditions and to restore and enhance the resilience of Washington's shellfish and natural systems. The recommendations also utilize both new and tested technologies for remediating local seawater conditions.

Critical to all of these efforts is research, monitoring, and public engagement. While we have a broad foundation of information on which to build recommendations, important knowledge gaps remain. Investing in research and monitoring will help fill those gaps and ensure that our efforts to reduce the risks of ocean acidification are appropriately focused and effective. Major objectives in the Panel's research and monitoring recommendations include increasing our understanding of the status and trends of ocean acidification in Washington's marine waters, characterizing biological responses of local species to acidification, and developing capabilities for short-term forecasting and long-term prediction.

Outreach and public engagement connects Washingtonians to the problem of ocean acidification by informing them about the science and the significance of changing ocean chemistry for Washington's economy, environment, and tribes. This can empower citizens and businesses to help develop and implement solutions. Key elements of the Panel's outreach and public education recommendations include sharing information on acidification with the public and other audiences, facilitating the exchange of information and ideas between stakeholders, and increasing ocean acidification literacy.

Finally, the Panel recognizes that ocean acidification is not a one-time problem with quick and easy solutions. It is a long-term challenge that requires a sustained effort across all these fronts—global and local source reduction, adaptation and remediation, research and monitoring, and public education—and continued engagement by and with governmental and non-governmental entities, industry, and the public. Maintaining a sustainable and coordinated focus on ocean acidification is necessary for ensuring our long-term success. To that end, the Panel recommends creating a coordinating mechanism

to facilitate implementation of the Panel's recommendations, continued engagement with stakeholders, and scientific collaboration.

The recommended strategies and actions included in this report each have a role in reducing the impacts of ocean acidification and action should be taken on each of them. The Panel recognizes, however, that it is not possible to implement all the recommendations simultaneously. Consequently, it has designated a subset of actions as "Key Early Actions" (KEAs). KEAs are actions the Panel considers to be essential next steps for reducing the risks associated with acidification and are independent of assumptions about the availability of funding or political feasibility. A list of KEAs is provided in Table S-1. A complete list of the Panel's strategies and actions is provided in Table 1.

A Time to Act

Washington State will need to respond vigorously to ocean acidification if we are going to avoid significant and possibly irreversible losses to our marine environment and all it supports, including shellfish farming and wild harvest of shellfish and other commercially and culturally important marine species. Public investment by the state is needed, as are public-private partnerships that promote innovative solutions to acidification. Additionally, the Panel calls on Congress, the White House, NOAA, and other federal agencies to support our efforts to address acidification and, in particular, to take a leading role in the recommended research agenda so the nature of the problem facing Washington and the majority of other coastal states can be better understood and more effectively addressed.

Washington has many resources to leverage in implementing the Panel's recommended actions. We have world-class scientists in our region who are already working in a variety of applicable fields. Additionally, we have an important source of understanding in the traditional and historical knowledge of tribes. State agencies, businesses, and tribes are taking the lead in developing innovative approaches that reduce carbon dioxide and nutrient runoff in Washington, and state and tribal leaders are actively engaging with our federal partners to find solutions to ocean acidification. We also have a shellfish industry committed to protecting native ecosystems as well as farmed resources, and a diverse nonprofit community ready to work with the public on understanding the problem of ocean acidification and how we might solve it. Finally, we have citizens who value the rich and diverse ecosystems in Washington's marine waters.

It is time to coordinate and harness these resources and start tackling the many challenges that will come with ocean acidification. It is time to act.

Table S-1. Blue Ribbon Panel Recommendations: Key Early Actions

Reduce Carbon Dioxide Emissions	Work with international, national, and regional partners to advocate for a comprehensive strategy to reduce carbon dioxide emissions. *(Action 4.1.1)*
	Enlist key leaders and policymakers to act as ambassadors advocating for carbon dioxide emissions reductions and protection of Washington's marine resources from acidification. *(Action 4.1.4)*
Reduce Local Land-Based Contributions	Implement effective nutrient and organic carbon reduction programs in locations where these pollutants are causing or contributing to multiple water quality problems. *(Action 5.1.1)*
	Support and reinforce current planning efforts and programs that address the impacts of nutrients and organic carbon. *(Action 5.1.2)*
Increase Our Ability to Adapt to and Remediate the Impacts of Ocean Acidification	Develop vegetation-based systems of remediation for use in upland habitats and in shellfish areas. *(Action 6.1.1)*
	Ensure continued water quality monitoring at the six existing shellfish hatcheries and rearing areas to enable real-time management of hatcheries under changing pH conditions. *(Action 6.2.1)*
	Investigate and develop commercial-scale water treatment methods or hatchery designs to protect larvae from corrosive seawater. *(Action 6.2.3)*
	Identify, protect, and manage refuges for organisms vulnerable to ocean acidification and other stressors. *(Action 6.3.2)*

Invest in Washington's Ability to Monitor and Investigate the Effects of Ocean Acidification	Establish an expanded and sustained ocean acidification monitoring network to measure trends in local acidification conditions and related biological responses. *(Action 7.1.1)*
	Quantify key natural and human-influenced processes that contribute to acidification based on estimates of sources, sinks, and transfer rates for carbon and nitrogen. *(Action 7.2.1)*
	Determine the association between water and sediment chemistry and shellfish production in hatcheries and in the natural environment. *(Action 7.3.1)*
	Conduct laboratory studies to assess the direct effects of ocean acidification, alone and in combination with other stressors, on local species and ecosystems. *(Action 7.3.2)*
	Establish the ability to make short-term forecasts of corrosive conditions for application to shellfish hatcheries, growing areas, and other areas of concern. *(Action 7.4.1)*
Inform, Educate, and Engage Stakeholders, the Public, and Decision Makers in Addressing Ocean Acidification	Identify key findings for use by the Governor, Panel members, and others who will act as ambassadors on ocean acidification. *(Action 8.1.1)*
	Increase understanding of ocean acidification among key stakeholders, target audiences, and local communities to help implement the Panel's recommendations. *(Action 8.1.2)*
	Provide a forum for agricultural, business, and other stakeholders to engage with coastal resource users and managers in developing and implementing solutions. *(Action 8.1.4)*
Maintain a Sustainable and Coordinated Focus on Ocean Acidification	Charge, by gubernatorial action, a person in the Governor's Office or an existing or new organization to coordinate implementation of the Panel's recommendations with other ocean and coastal actions. *(Action 9.1.1)*
	Create an ocean acidification science coordination team to promote scientific collaboration across agencies and organizations and connect ocean acidification science to adaptation and policy needs. *(Action 9.1.2)*

1

Introduction

BETWEEN 2005 AND 2009, SEVERAL major commercial Pacific Northwest oyster hatcheries experienced disastrous production failures when billions of oyster larvae (the youngest oysters), mysteriously died. The Whiskey Creek Shellfish Hatchery in Netarts Bay, Oregon—the primary supplier to independent Washington State oyster growers—reported that larvae dissolved in their tanks. At the same time, reproduction by Pacific oysters in Willapa Bay, Washington, which is a major source of wild oyster seed, was also very poor.

The problem was first thought to be disease associated with a naturally occurring bacterium, and one hatchery alone spent more than $250,000 to remove the suspect pathogen. Larvae continued to die even in pathogen-free waters, however. Recent research[12] has identified changing ocean chemistry—specifically, ocean acidification—as the primary cause of this massive mortality. Additional research[13] also showed that the problem of increasing ocean acidity will worsen significantly along the Pacific Northwest coastline in the coming years.

Nisbet Oyster Company, Willapa Bay, Washington

Ocean acidification poses a serious threat to Washington's marine economy, cultures, and environment. The Pacific Northwest shellfish industry has been among the first to feel significant, recognizable effects (Box 1). Washington is the country's leading producer of farmed oysters, clams, and mussels. Annual sales of shellfish grown in Washington exceed $107 million, accounting for almost 85 percent of West Coast sales (including Alaska).[14] Oysters alone account for more than 80 percent of the state's farmed shellfish harvest and more than 50 percent of its total annual sales ($58 million).[15] Geoduck and other clam sales contribute an additional $20 million each.[16]

12 Barton, A., Hales, B., Waldbusser, G. G., Langdon, C., & Feely, R. (2012). The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: Implications for near-term ocean acidification effects. *Limnology and Oceanography, 57*(3), 698-710. doi: **http://dx.doi.org/10.4319/lo.2012.57.3.0698**

13 Gruber, N., Hauri, C., Lachkar, Z., Loher, D., Frölicher, T. L., & Plattner, G.-K. (2012). Rapid progression of ocean acidification in the California Current System. *Science, 337*(6091), 220–223. doi: **http://dx.doi.org/10.1126/science.1216773**

14 Pacific Coast Shellfish Growers Association table of production statistics (2011), **http://pcsga.net/wp-content/uploads/2011/02/production_stats.pdf**

15 See Pacific Coast Shellfish Growers Association table of production statistics, referenced above

16 See Pacific Coast Shellfish Growers Association table of production statistics, referenced above

Box 1. Northwest Pacific oyster larvae: "canaries in the coal mine"?

Just as caged canaries once alerted underground coal miners to bad air, so too have Pacific oyster larvae signaled the advent of what hatchery workers call "bad water."

Even in optimal conditions, shellfish larvae must spend a great deal of energy to build their protective shells and grow to the next life stage, and many die. In acidified seawater, the task of building a protective shell is even more difficult. The newest shells are also especially prone to chemical dissolution. This combination of factors makes oyster larvae particularly vulnerable to changes in their environment.

The impacts of ocean acidification in Washington were first noticed in the shellfish industry because of the drastic collapse in hatchery larvae between 2005 and 2009. The collapse not only disrupted seed supplies for oyster farms coast-wide; it constituted the first documented loss to seafood producers and consumers from today's rapidly increasing ocean acidity. Similarly important changes could be occurring in our estuarine and open marine waters. For this reason, Washington's oysters truly are "canaries in the coal mine."

The estimated total annual economic impact of shellfish aquaculture is $270 million, and shellfish growers directly and indirectly employ more than 3,200 people.[17] But this is only part of the picture. Commercial harvests of wild seafood also contribute significantly to Washington's economy. Shellfish generate more than two-thirds of the harvest value of Washington's commercial wild fisheries.[18] Notable is the value of wild-harvested Pacific geoduck clam (about $32 million)[19] and Dungeness crab (about $49 million).[20]

The economic impact of Washington's wild and farmed seafood harvests extends well beyond the value of the harvest when it reaches shore. For example, tourists and residents pay $3 million annually for state licenses to harvest wild shellfish, and recreational oyster and clam harvesters contributing more than $27 million annually to coastal economies.[21]

17 Washington Shellfish Initiative white paper, December 2011, **http://www.governor.wa.gov/news/shellfish_white_paper_20111209.pdf**

18 National Marine Fisheries Service, Office of Science and Technology. (2012). *Commercial fisheries statistics: Annual landings by species for Washington*, accessed 9/28/12. **https://www.st.nmfs.noaa.gov/commercial-fisheries/index**

19 Washington Department of Fish and Wildlife. (2011). *Commercial wild stock geoduck fishery landings and ex-vessel value in Washington*, accessed 10/29/12. **http://wdfw.wa.gov/fishing/commercial/geoduck/geoduck_historic_landings_value_table.pdf**

20 See National Marine Fisheries Service (2012), referenced above.

21 See Washington Shellfish Initiative white paper, December 2011, referenced above

Washington's seafood industry generates profits and employment at neighborhood seafood restaurants, distributors, and retailers, contributing over 42,000 jobs in Washington and at least $1.7 billion to the gross state product.[22] While our understanding of how ocean acidification affects the full range of species driving this economic activity is limited at this time, it is clear that the impacts of ocean acidification on Washington's marine industry could reach far into and beyond the state's local and regional economies.

Suquamish and Port Gamble S'Klallam tribes and Point No Point Treaty Council staff spread manila clam seed on Indian Island in Puget Sound.

To Washington's tribal communities, ocean acidification is both a natural resource issue and a significant challenge to their continued identity and cultural survival. Shellfish are a key part of an ecosystem that has continuously supported human civilization here since shortly after the glaciers receded. To the tribes, increasing ocean acidity is the latest of many threats to that life-sustaining ecosystem. A half dozen fish species are already gone from Puget Sound and more are threatened, and salmon habitat and wetlands continue to be degraded and lost to development. With salmon populations just a fraction of their former abundance, tribal fishers are depending more on shellfish to support their families; almost all of the commercial wild clam fisheries in Puget Sound are tribal. The tribes also harvest wild shellfish for ceremonial and subsistence purposes.

Finally, as described in Chapter 2, ocean acidification is not only a threat to shellfish; it also threatens Washington's broader marine ecosystem. A growing catalog of scientific studies indicates that many other saltwater plants and animals are adversely affected by acidification. This includes species that are direct drivers of economic activity (such as salmon or rockfish) as well as species that indirectly affect the marine environment and all that it supports via food web interactions.

22 U.S. Department of Commerce, National Atmospheric and Oceanographic Administration (2011). *Fisheries Economics of the U.S. 2009: Economics and Sociocultural Status and Trends Series*. **www.st.nmfs.noaa.gov/st5/publication/index.html**

Washington's Blue Ribbon Panel on Ocean Acidification

Recognizing the threat to Washington's shellfish industry, its tribal communities, and its broader marine environment, Governor Christine Gregoire created the Washington State Blue Ribbon Panel on Ocean Acidification (referred to as the "Panel"). The Panel was convened in February 2012 under the auspices of the Washington Shellfish Initiative,[23] the regional partnership created to implement the National Oceanic and Atmospheric Administration's (NOAA) National Shellfish Initiative.[24] The Panel consisted of scientists; public opinion leaders; industry representatives; state, local, federal, and tribal policymakers; and conservation community representatives. It was strongly supported by Dr. Jane Lubchenco, Administrator of NOAA.

Governor Gregoire charged the panel with the responsibility to:

- Review and summarize the current state of scientific knowledge about ocean acidification,
- Identify the research and monitoring needed to increase scientific understanding and improve resource management,
- Develop recommendations to respond to ocean acidification and reduce its harmful causes and effects, and
- Identify opportunities to improve coordination and partnerships and to enhance public awareness and understanding of ocean acidification and how to address it.

This report, and the accompanying technical document, *Scientific Summary of Ocean Acidification in Washington State Marine Waters*,[25] constitute the Panel's report of its findings and recommendations for action. The report begins with a brief scientific overview of ocean acidification based on the technical document prepared by and for the Panel. The remaining chapters present the Panel's recommendations, which focus on the need to reduce carbon dioxide emissions and local land-based contributions to acidification, increase our ability to adapt to and remediate the impacts of ocean acidification, invest in our ability to monitor and further investigate the causes and consequences of acidification, inform the public and other key stakeholders about acidification and what it means for Washington, and maintain a sustainable and coordinated focus on ocean acidification. Implementation leads, partners, time frame, and estimated costs for each of the Panel's recommendations are included in Appendix 1.

23 For more on the Washington Shellfish Initiative, see: **http://www.psp.wa.gov/shellfish.php**

24 For more on the National Shellfish Initiative, see **http://www.nmfs.noaa.gov/aquaculture/policy/shellfish_initiative_homepage.html**

25 Available at **https://fortress.wa.gov/ecy/publications/SummaryPages/1201016.html**

2

Ocean Acidification in Washington State Marine Waters

THIS CHAPTER SUMMARIZES CURRENT SCIENTIFIC understanding of the causes and consequences of ocean acidification in Washington's marine waters. This understanding, described in greater detail in *Scientific Summary of Ocean Acidification in Washington State Marine Waters*,[26] constitutes the basis for the Panel recommendations that follow.

2.1 Ocean Acidification: Causes and Trends

Ocean acidification is a reduction in the pH of seawater for an extended period of time due primarily to the uptake of carbon dioxide from the atmosphere by the ocean. Local sources of acidification such as nitrogen oxides and sulfur oxide gases, or nutrients and organic carbon from wastewater discharges and runoff from land-based activities, can also contribute to ocean acidification in marine waters. For more on pH, see Figure 1.

Carbon dioxide emissions are the leading cause of ocean acidification. Since the beginning of the industrial era in the mid-1700s, the atmospheric concentration of carbon dioxide has increased 40 percent, primarily because of burning fossil fuels such as oil and coal and changing land uses. Today's concentration of carbon dioxide—392 parts per million (ppm)—far exceeds the natural range of atmospheric carbon dioxide over the last 800,000 years.[27] About one-quarter of these human-generated emissions have been absorbed by the oceans.

Through a well-understood series of chemical reactions, carbon dioxide has an acidifying effect when dissolved in seawater. As a result, upper-ocean pH has decreased, gradually at first and now more rapidly (Box 2). Over the last 250 years, the average upper-ocean pH has decreased by about 0.1 units, from about 8.2 to 8.1. This drop in pH corresponds to an increase in the average acidity (as measured by the hydrogen ion concentration) of the surface ocean of about 30 percent. At the current rate of carbon dioxide emissions, the average acidity of the surface ocean is expected to increase by 100 to 150 percent over preindustrial levels by the end of this century.

26 Available at: **https://fortress.wa.gov/ecy/publications/SummaryPages/1201016.html**

27 NOAA Earth System Laboratory (**http://www.esrl.noaa.gov/gmd/ccgg/trends/**); *Global Climate Change Impacts in the United States*, Thomas R. Karl, Jerry M. Melillo, and Thomas C. Peterson (eds.). Cambridge University Press, 2009, p.13, **http://downloads.globalchange.gov/usimpacts/pdfs/climate-impacts-report.pdf**

Ocean Acidification is About More Than pH

As ocean water becomes more acidic, several direct chemical consequences—all important to marine life—occur.

First, the amount (or concentration) of carbonate ion in seawater decreases. Carbonate ion is an essential building block required by many marine animals and some plants to form the mineral calcium carbonate, which the organisms use to build shells, skeletons, or other hard parts. Such organisms are known as calcifiers. As the amount of carbon dioxide in seawater increases, the amount of carbonate ions in seawater decreases, making it more difficult for calcifiers to build calcium carbonate-based body parts. Since the beginning of the industrial era, the average carbonate ion concentration in the upper ocean has fallen approximately 16 percent.

Second, the water becomes more chemically corrosive to two important forms of calcium carbonate: calcite and aragonite. Carbonate saturation state is a metric used to provide an estimate of how readily calcite and aragonite dissolve or form in seawater. When

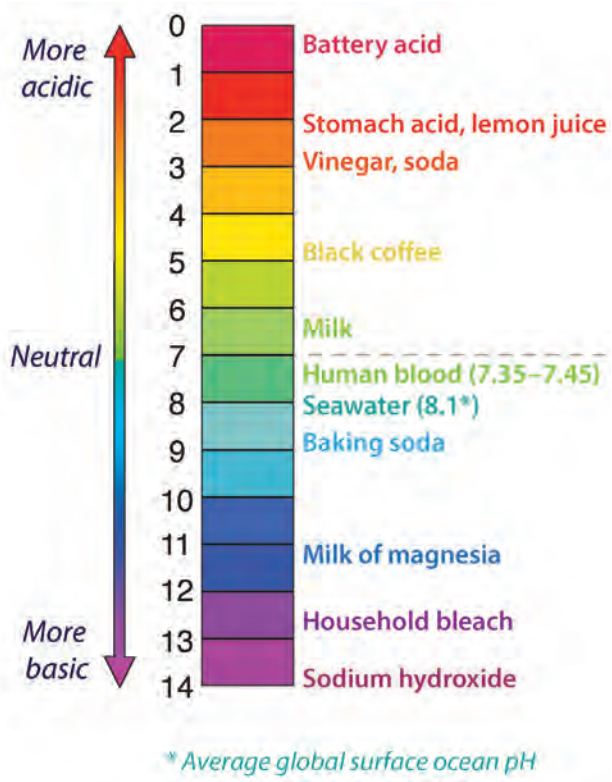


Figure 1. The pH Scale. pH is defined as the negative log of the hydrogen ion concentration in a solution. Neutral pH is 7.0. Solutions with pH values less than 7.0 are "acidic," and those with pH values greater than 7.0 are "basic." Because pH is expressed on a logarithmic scale, a small change in pH corresponds to a large change in acidity. This means that a pH of 7 is ten times more acidic than a pH of 8. The pH value of common liquids is also shown.

the carbonate saturation state drops below a critical threshold value of 1.0, seawater becomes corrosive to shell material. Aragonite, the mineral used by pteropods, corals, and most larval bivalves, is about twice as susceptible to dissolution as calcite. In the northeast Pacific Ocean, aragonite-corrosive conditions are rapidly expanding into shallower, more biologically sensitive areas at a rate of about five feet per year. The spread of calcite-corrosive conditions, by contrast, is still largely confined to deeper waters.

Box 2. Ocean acidification is progressing very rapidly.

The current rate of ocean acidification is nearly ten times faster than any time in the past 50 million years. Such rapid change can outpace the ocean's natural ability to restore oceanic pH and carbonate chemistry. The rapid pace of change also gives marine organisms, marine ecosystems, and humans less time to adapt, evolve, or otherwise adjust to the changing circumstances.

2.2 Local Ocean Acidification: Contributing Processes and Regional Distinctions

2.2.1 Contributing Processes

Ocean acidification due to the absorption of carbon dioxide from the atmosphere is a global phenomenon, but several factors, some unique to Washington, increase our vulnerability to regional acidification (Figure 2). Local processes that drive ocean acidification in our marine waters include seasonal upwelling of Pacific Ocean water rich in carbon dioxide and nutrients, deliveries of nutrients and organic carbon from land, and absorption of other (non-carbon dioxide) acidifying gases from the atmosphere.

Ocean Upwelling. When strong northerly winds blow along Washington's outer coast, surface seawater is pushed away from the coastline and deeper offshore water is drawn up to replace it. This upwelled water is naturally rich in nutrients, high in carbon dioxide, and low in pH due to biological processes in the ocean. However, today's upwelled waters are also carrying an ever-growing load of human-generated carbon dioxide picked up from the atmosphere 30 to 50 years ago when the water was last in contact with the atmosphere. As a result, today's upwelled water is more corrosive to calcifying organisms like oysters, clams, scallops, mussels, crabs, abalone, and pteropods than would be seen from natural conditions alone. It also means that this water will become increasingly corrosive in coming decades as water with more recent (and higher) human-generated carbon dioxide content upwells (Box 3).

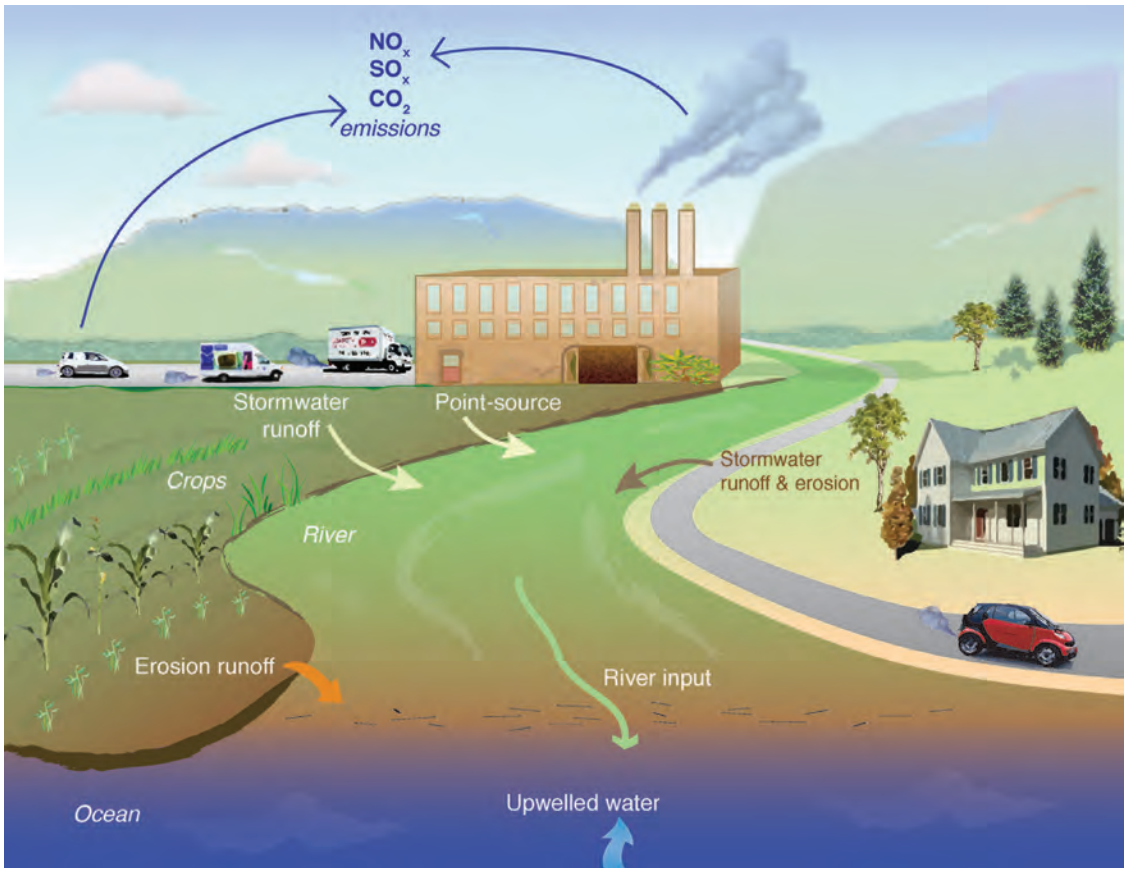


Figure 2. A range of sources, including upwelled seawater rich in carbon dioxide (CO_2) and excess nutrients and organic carbon from point and nonpoint sources, can contribute to acidification of marine waters. Absorption of carbon dioxide, nitrogen oxides (NO_X), and sulfur oxides (SO_X) from the atmosphere into marine waters may also be important in some local areas (adapted from Kelly et al., 2011).[29]

Upwelling has a strong influence on marine chemistry in Puget Sound as well as on the outer coast. Upwelled water enters Puget Sound through the Juan de Fuca submarine canyon in the summer and fall months, when wind patterns create favorable conditions for upwelling. The result is a decline in the pH of water near the sea bottom in Puget Sound, particularly in Hood Canal.

Deliveries of Nutrients, Organic Carbon, and Fresh Water from Land to the Sea. The near-surface waters off the Washington coast are unusually productive due to nitrogen

28 Kelly, R., Foley, M., Fisher, W., Feely, R., Halpern, B., Waldbusser, G., & Caldwell, M. (2011). Mitigating local causes of ocean acidification with existing laws. *Science, 332*(6033), 1036.

and other nutrients delivered from deeper offshore waters and from rivers. In the sunlit waters of the upper ocean, this "fertilizer" stimulates vigorous algal growth that sometimes explodes into intense blooms. Human activities often increase the flow of nutrients from land to marine waters, strengthening the potential for algal blooms. When the bloom ends, the dying algal material sinks into deeper water and decays, consuming oxygen and releasing large amounts of carbon dioxide into the water. In some cases, this can lead to hypoxia (Box 4). The carbon dioxide released from this process of growth and decay has the same acidifying effect as carbon dioxide absorbed into seawater from the atmosphere—both processes lower pH and make water more corrosive to calcium carbonate.

Another important land-to-sea input is dissolved organic carbon delivered by rivers and streams. Rivers are typically lower in pH than seawater, with values ranging from approximately 6.5 to 8.5 due to minerals leached from soils or the decomposition of organic matter (such as plant material, freshwater algae, and some types of sewage effluents) in the river water itself or in the local streams that feed them. Municipal and industrial wastewater can also reduce pH in the immediate vicinity of a discharge point, especially in poorly flushed areas. When fresh water and seawater mix at river mouths or in estuaries, the water can sometimes be corrosive to calcifying organisms. This is the case for the Columbia River in summer and in Puget Sound in winter.

Box 3. Washington's acidification problem will get worse before it gets better.

Today's upwelled waters bear the imprint of contact with the atmosphere in about 1970, when the concentration of carbon dioxide in the atmosphere was only about 325 ppm. Since then, atmospheric carbon dioxide has continued to climb and so has the "carbon loading" of the waters that will eventually make their way to our coast. The half-century transit time between contact with the atmosphere, sinking and circulation at depth, and re-emergence along the Washington coast means that we will continue to see more acidifying conditions coming from upwelled waters for several decades after atmospheric levels of carbon dioxide begin to decline.

Absorption of Acidifying Gases Other Than Carbon Dioxide. In some coastal areas, other acidifying gases may be locally important. For example, nitrogen oxides and sulfur oxides may contribute to local acidification downwind from their primary sources. Contributors of these gases include motor vehicles, ships, and electric utilities.

Box 4. Hypoxia and ocean acidification.

In estuaries with little mixing between surface water and water at depth, the decay of organic matter can create high carbon dioxide, low-oxygen ("hypoxic") conditions at depth that are stressful or fatal to marine species. Hypoxic conditions indicate high rates of decomposition, which produce carbon dioxide and reduce the pH of water just as the accumulation of atmospheric carbon dioxide reduces pH. Thus, hypoxia is an indicator of areas where the process of decomposition is contributing to ocean acidification. Furthermore, because the acidification associated with hypoxia is in addition to the acidification caused by the absorption of carbon dioxide from the atmosphere, hypoxia is also an indicator of areas where we may see more pronounced ocean acidification.

2.2.1 Regional Distinctions

Different combinations of acidifying processes, and varying degrees of contribution from each, influence acidification in Washington's major marine regions. These include the outer coast, the Columbia River Estuary, Puget Sound and the Strait of Juan de Fuca, and other shallow estuaries such as Willapa Bay and Totten Inlet.

The Outer Coast. A number of processes contribute to acidification on Washington's outer coast but not all have been quantified. The human contribution is almost entirely due to atmospheric carbon dioxide from global sources that has increased the carbon dioxide content of upwelled ocean water. Upwelling waters also bring rich stores of nitrogen into the sunlit upper ocean, thus kicking off vigorous algal bloom events that lead to summertime hypoxia and acidification at depth as a result of decomposition.

Another major feature of the outer coast is outflow from the Columbia River, which delivers more than three-quarters of the freshwater that feeds into the Pacific Ocean along the U.S. West Coast north of San Francisco. This affects pH in at least three ways. First, the pH of Columbia River water is generally lower than surface seawater (R.A. Feely, unpublished data). Second, the river delivers iron and silicates that can stimulate intense algal bloom events, leading to hypoxia and acidification. Third, when the river plume (outflow) flows northward, it can temporarily shield the southern Washington coast from upwelled water or it can press recently upwelled waters against the coastline. The Columbia River therefore can either prevent or prolong the outer coast's exposure to potentially corrosive seawater, depending on conditions.

The Columbia River Estuary. The wide, shallow Columbia River estuary is unique within Washington. Although 2.5 miles wide at the river-mouth bar, the estuary is only 60 feet

deep, roughly one-tenth as deep as Puget Sound. Levels of photosynthesis are limited in the Columbia River estuary because its turbid (cloudy) waters limit light penetration. As a result, river inputs of organic carbon are important to fueling the estuary ecosystem. The primary influence on ocean acidification conditions in the Columbia River estuary is the naturally low pH of the Columbia River and its tributaries. Decomposition of organic carbon can drive the pH even lower.

Puget Sound and the Strait of Juan de Fuca. Acidification in Puget Sound and the Strait of Juan de Fuca is strongly influenced by the ocean, with corrosive upwelled water flowing in at depth and lingering in subsurface layers. In estuarine environments within Puget Sound, inputs of nutrients and organic carbon can further reduce pH, dissolved oxygen, and carbonate saturation state by stimulating microbial respiration. In developed or urbanized regions, localized high concentrations of atmospheric carbon dioxide, nitrogen oxides, and sulfur oxides can also acidify marine waters, but whether this local enhancement has resulted in significant increases of local acidity is not known.

Bainbridge Island in Puget Sound

Acidification conditions in Puget Sound vary strongly from place to place and across the seasons. Winter observations show well-mixed, corrosive waters, while summer and fall are characterized by less well-mixed, layered waters that tend to confine corrosive waters to deeper subsurface areas. Many parts of Puget Sound are corrosive to aragonite in the deeper waters. Some of the lowest pH levels and aragonite saturation states observed in Washington marine waters have been measured in the southern part of the Hood Canal basin.

Other Shallow Estuaries.[29] Estuaries such as Willapa Bay (on the outer coast) and Totten Inlet (in Puget Sound) tend to be well-mixed and physically different from the deep, layered estuaries of Puget Sound like Hood Canal, Dabob Bay, and the Main Basin. Because of their relatively small size, upwelling and fresh water inputs can strongly influence acidification in shallow estuaries. Additionally, photosynthesis and respiration rates can be very high in shallow estuaries because good light penetration allows for the growth of algae and other plants within the water and on the sea floor. High rates of plant and algal growth can in turn lead to increased carbon dioxide at depth via decomposition of the resulting organic matter. These growth rates are further stimulated when rivers transport land-based nutrients and organic carbon from natural and human sources to marine waters. All of these inputs can lead to increased carbon dioxide, reduced pH, and lower aragonite and calcite saturation states in shallow estuaries. Local atmospheric carbon dioxide emissions are not likely to be a significant driver of ocean acidification in shallow estuaries along the outer coast because the urban corridor is distant, but these could be a factor in Puget Sound's shallow estuaries.

2.3 Species Responses to Ocean Acidification

Many life processes, including photosynthesis, growth, respiration, recruitment, reproduction, and behavior are sensitive to carbon dioxide and pH. As a result, acidification can affect a wide range of organisms, from seagrass to fish, in diverse ways. Much of our scientific understanding of species responses comes from experimental studies. These studies reveal positive, negative, and unexpected impacts. For example, some seagrass species appear to benefit from carbon dioxide enrichment, and some macroalgae (for example, kelp) also could respond positively to elevated carbon dioxide.

Many calcifying species are vulnerable to ocean acidification by virtue of their dependence on the mineral calcium carbonate (in the form of calcite or aragonite) to build, grow, and maintain shells, skeletons, and other vital body parts. More than 30 percent of Puget Sound's marine species are calcifiers, including such familiar seashore animals as barnacles, sea urchins, sand dollars, sea stars, sea cucumbers, and crabs. Shellfish—including oysters, geoducks and other clams, mussels, and abalone—are also calcifiers, as are many of the most common types of tiny single-celled organisms and protists (foraminifera) that are prey for many small marine invertebrates and fish. Even some local seaweeds produce calcium carbonate structures.

29 Shallow estuaries are less than 65 feet deep

As noted in Section 2.1, ocean acidification makes an essential component of calcium carbonate—the carbonate ion—scarce. Calcifiers can therefore experience greater difficulty in making and maintaining their shells, slower growth rates, and higher mortality rates (Figures 3 and 4). Researchers have observed, for example, that experimentally elevated carbon dioxide impairs development and reduces survival among larvae of the increasingly rare northern abalone. The shellfish industry, as previously noted, has seen increased larval mortality of oysters as seawater carbon dioxide levels have risen.

Some examples of Puget Sound calcifiers (clockwise from upper left): blue mussels; juvenile king crab and pink calcifying algae; Dungeness crab.

Many calcifiers are valued not only for their economic significance but also for the important services they provide to society and other organisms. For example, oysters, clams, and crabs improve water quality by removing floating organic particles. Deepwater corals off the Washington coast provide habitat, shelter, and host food for many plants and animals, including rockfish and sharks. Pteropods are an important food source for young salmon and other high-latitude animals, such as seabirds and whales. The future of these tiny swimmers is of particular concern. Among all pteropod species studied to date, shell-building and growth rates decline when pH decreases and shell corrosion occurs when waters are under-saturated with aragonite (Figure 5).

Pteropods are tiny swimming snails that are an important source of food for young salmon.

Some animals important to marine food webs, community structure, and diversity are potentially sensitive to acidification in ways unrelated to shell-building. Some species of copepods, the small crustaceans eaten by juvenile herring and salmon, experience decreased growth, egg production, and

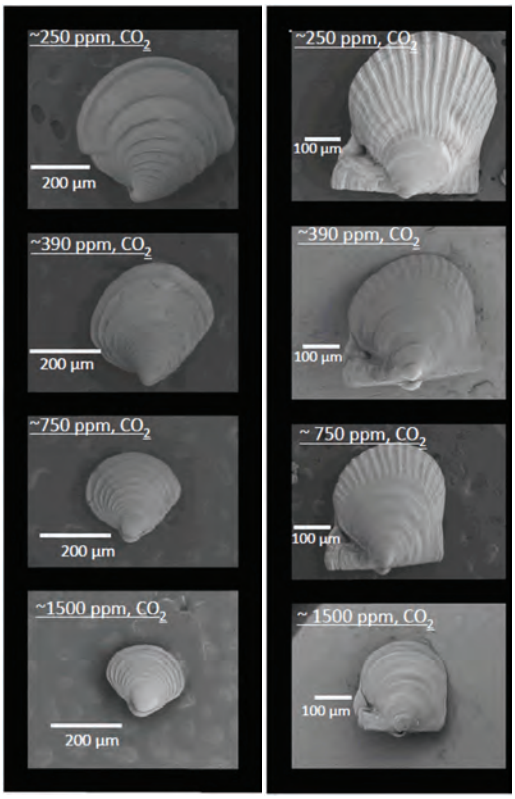


Figure 3. Scanning electron microscope images of 36-day-old hard clam larvae (*Mercenaria mercenaria*, left) and 52-day-old bay scallop larvae (*Argopecten irradians*, right) grown under different carbon dioxide levels: near-preindustrial atmosphere (about 250 ppm), ambient present-day atmosphere (about 390 ppm), a moderate atmospheric level predicted for the year 2100 (about 750 ppm), and a high future atmospheric level (about 1500 ppm). Animals grown under near-preindustrial atmosphere carbon dioxide levels had thicker, more robust shells than those grown under present-day conditions. Animals exposed to levels expected later this century had malformed and eroded shells. *Image reprinted with permission from S. Talmage and C. Gobler, 2010.*[31]

30 Talmage, S.C. and C. Gobler, 2010. Effects of past, present, and future ocean carbon dioxide concentrations on the growth of larval shellfish, *Proceedings of the National Academy of Sciences, vol. 107*, pp. 17,246–17,251.

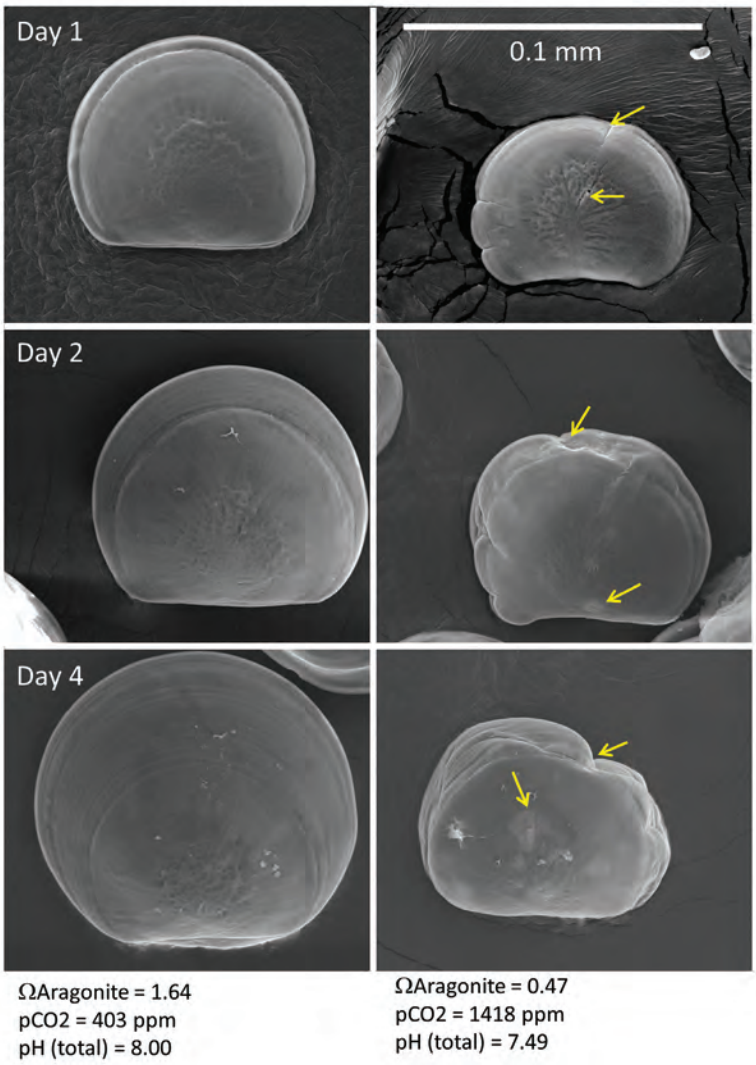


Figure 4. Pacific oyster larvae from the same spawn, raised by the Taylors Shellfish Hatchery in natural waters of Dabob Bay, Washington under favorable (left column, pH (total) = 8.00) and unfavorable (right column, pH (total) = 7.49) carbonate chemistry. The carbonate chemistry conditions shown below the columns are of the incoming waters used to spawn larvae; similarly unfavorable water conditions occur at Dabob Bay and Netarts Bay, Oregon, due to regional upwelling of high pCO_2 waters to the surface. Images are Scanning Electron Microscopy (SEM) of representative larval shells from each condition from 1 to 4 days post-fertilization. Because the sampling is destructive, each larva shown is a different organism, and should not be interpreted as the same larva ageing through time. Under more acidified conditions (right column) development of shell is impaired; arrows show defects (creases) and some features (light patches on shell) that are suggestive of dissolution. The extent of deformation shown would result in mortality of larvae were they not sampled; larval shell shape is a commonly used metric of biological fitness for bivalves. The scale bar in the upper right panel is 0.1 mm, or approximately the diameter of a human hair. *Photo credit- Brunner/Waldbusser. Used with permission.*

Figure 5. The pteropod, or "sea butterfly," is a tiny sea snail about the size of a small pea eaten by a variety of species, including seabirds, fish, and whales. The photos above show what happens to a pteropod's shell when placed in seawater with pH and carbonate levels projected for the year 2100. The shell slowly dissolved over 45 days. *Used with permission from National Geographic.*

hatching success as well as increased mortality. High carbon dioxide also negatively affects sea urchin egg fertilization. Urchins are important in local food webs because they consume kelp and can severely limit its abundance.

The responses of many groups of plants and animals to ocean acidification remain unstudied or under-studied. Moreover, co-occurring stressors can be important in heightening or otherwise modifying acidification's effects. Marine microbes, algae, plants, and animals are experiencing rapid ocean acidification together with other stress-inducing environmental changes, including rising temperatures, decreasing oxygen, and increasing pollution. The few studies on these interacting factors indicate that co-occurring stresses often increase an organism's sensitivity to ocean acidification.

2.4 Ecosystem Responses to Ocean Acidification

Understanding the implications of ocean acidification means more than learning about the responses of individual species, such as a particular type of clam, octopus, or crab. While scientists have primarily studied the direct effects of ocean acidification on laboratory algae, plants, and animals, indirect effects mediated by food webs or changes in species interactions can also be important. For example, young salmon consume pteropods, and people consume salmon; consequently, declines in the abundance of pteropods could indirectly affect people by changing the number of salmon available for humans.

Some animals, known as keystone species, are of particular interest because their fates can determine the fates of whole communities. Removing a single important predator, for example, can have effects that reverberate throughout the food web. In a Mukkaw Bay experiment (on the Makah Reservation in Washington), removal of a predatory sea star led to major changes; with predation eased, competition for intertidal space intensified among the remaining inhabitants and the number of local species rapidly declined.[31] Acidification-driven changes in populations of keystone species could have strong domino effects on local ecosystems. Sea stars, urchins, and salmon are among Washington's keystone marine species.

Understanding how the relationships and interactions among seawater chemistry, microbes, algae, plants, animals, and people are changing over time is also important. Complex interactions can be difficult to discern, and feedbacks can exist. In addition to the chemistry of the atmosphere and ocean influencing marine life, marine life has a reciprocal influence on the chemistry of ocean and atmosphere. Notably, photosynthesis and respiration are not merely responsive to seawater pH; their daily cycles can

31 Wagner, S. C. (2012) Keystone Species. *Nature Education Knowledge, 3*(10):51 ; see also Paine, R.T. (1966) Food web complexity and species diversity. *The American Naturalist, 100* (910): 65-75.

also drive large pH fluctuations. Similarly, deposition and dissolution of shells influence water chemistry both in the water column and in the water held by sediments, where adding shell material has been shown to improve aragonite saturation levels.

For insight into what a future high-carbon dioxide ocean might look like, scientists have recently begun studying "natural laboratories"—places naturally high in carbon dioxide, such as underwater volcanic systems (Figure 6). Their observations indicate that the pH considered likely by about the year 2100 could result in lower biodiversity, reduced reproductive success among calcifiers and some non-calcifying species, and an overall community-wide shift toward non-calcifying seaweeds and seagrasses.

Additional insights can be gained from the fossils and chemicals in ancient rocks. Paleontological studies tell us that past acidification events (due, for example, to large volcanic eruptions) have been accompanied by major marine extinctions. Many previously important species disappeared while others gained new prominence.

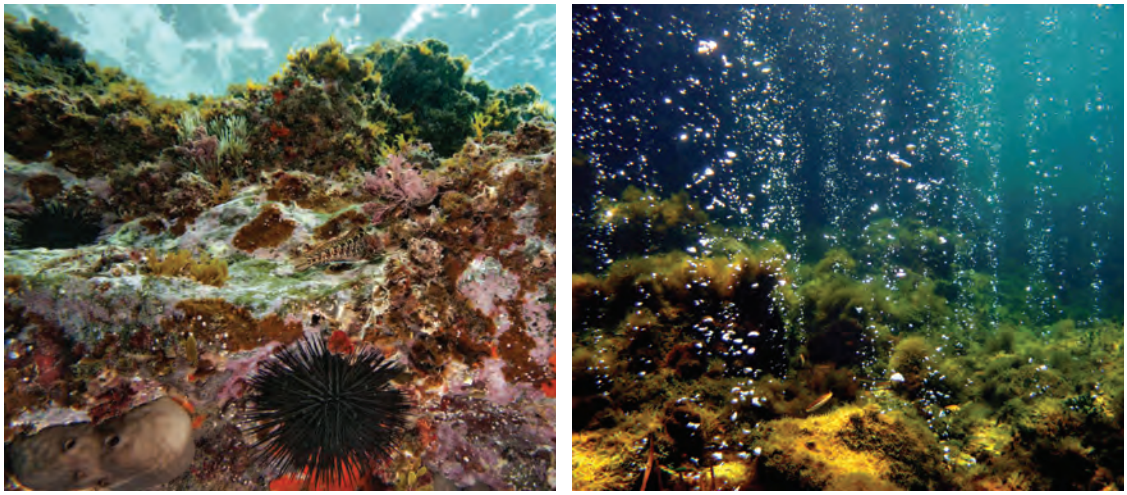


Figure 6. Low and high carbon dioxide communities. The figure on the left shows a diverse marine environment in normal (low) carbon dioxide conditions (mean pH 8.2). The photo on the right shows the impact of high carbon dioxide conditions found near naturally occurring carbon dioxide vents near Ischia Island in Italy (pH 7.8). *Photos by (left) David Littswager and (right) Luca Tiberti, Associazone Nemo, used with permission. For more information, see Hall-Spencer et al. 2008.*[33]

32 Hall-Spencer, J. M., Rodolfo-Metalpa, R., Martin, S., Ransome, E., Fine, M., Turner, S. M., Rowley, S. J., Tedesco, D., & Buia, M.-C. (2008). Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature, 454*(7200), 96–99. doi: **http://dx.doi.org/10.1038/nature07051**

2.5 Summary

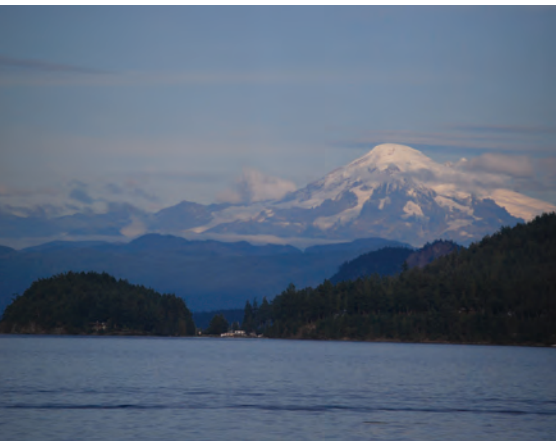
Global ocean acidification is well-documented from observations and its impacts are being felt in the Northwest. The transfer of carbon dioxide from the atmosphere to the oceans is rapidly and measurably lowering seawater pH. Local land-based sources of nutrients and organic carbon can add additional carbon dioxide to the water after microbial decomposition and further exacerbate acidification, especially in areas where human activities increase the flow of nutrients and organic carbon from land to marine waters.

Acidification is lowering the amount of carbonate ion in seawater, thereby reducing the stability of calcium carbonate—an important mineral used by calcifying organisms to build and maintain shells and other hard body parts. Many other life processes, including photosynthesis, growth, respiration, recruitment, reproduction, and behavior are also sensitive to increases in carbon dioxide and reductions in pH. As a result, acidification has the potential to affect a wide range of organisms both directly and indirectly. These impacts are expected to have significant biological, economic, and social consequences.

For more information about ocean acidification in Washington's marine waters, see *Scientific Summary of Ocean Acidification in Washington State Marine Waters*. This technical summary, written for the Panel by Pacific Northwest scientists (many of whom are Panel members), describes in detail what is known about local conditions and how various species, communities, and ecosystems will likely respond to ocean acidification. The summary also discusses current scientific work in the region and identifies significant knowledge gaps. The summary is available at: http://www.ecy.wa.gov/bilio/1201016.html.

3

Responding to Ocean Acidification



THE STRATEGIES AND ACTIONS RECOMMENDED by the Panel recognize the need for action across a range of areas. A critical starting point is slowing the pace of ocean acidification by reducing the drivers of acidification in Washington's marine waters. These include carbon dioxide emissions and runoff of nutrients and organic carbon from local land-based sources.

Adaptation and remediation will also be necessary given the increasing acidity of seawater upwelling along the Washington coast in the coming decades. When combined with local source reduction, adaptation and remediation efforts will in effect "buy time" for native and commercial shellfish species and marine ecosystems while society collectively works on reducing global carbon dioxide emissions.

Other key focal points for the Panel's recommendations include research and monitoring investments to fill key knowledge gaps, and engaging with the public, policymakers, and others to build awareness about ocean acidification. A final focal point is ensuring a sustained and coordinated focus on ocean acidification. This requires having the appropriate mechanisms for supporting and facilitating implementation of the Panel's recommendations; engaging governmental and non-governmental entities, industry, and the public on issues related to ocean acidification; and promoting scientific collaboration.

The recommended strategies and actions included in this report each have a role in reducing the impacts of ocean acidification, and therefore should be implemented. The Panel recognizes, however, that it is not possible to implement all of the recommendations immediately. Consequently, it has designated a subset of actions as "Key Early Actions" (KEAs).

The Panel considers the KEAs to be essential next steps for reducing the risks associated with ocean acidification. KEAs were determined primarily on the basis of urgency and relative importance. In some cases, the need to sequence actions in a particular order may have also influenced their designation. Assumptions about the availability of funding or political feasibility were not factors in designating the KEAs, nor are they considered "low-hanging fruit." Most importantly, the absence of a KEA designation does not mean an action is optional. The Panel strongly urges implementing each of the recommended actions, particularly if there are unique "windows of opportunity" or other factors that facilitate implementation. A list of KEAs is provided in Table S-1. A complete list of the Panel's strategies and actions is found in Table 1.

The cost of responding to ocean acidification may be substantial, but still far less than the costs of inaction. Many of these actions will be expensive and difficult to implement. They will require political will, intense multi-year efforts, and new funding sources. Implementing agencies should leverage existing federal and state funding as well as seek new sources of funding to implement the KEAs. Although Washington is well situated to respond to ocean acidification, the Panel calls on Congress, the White House, NOAA, and other federal agencies to support Washington's efforts to address acidification and, in particular, to take a leading role in the recommended research agenda so the nature of the problem facing Washington and the majority of other coastal states can be better understood and more effectively addressed.

Table 1. Blue Ribbon Panel Recommended Strategies and Actions

KEAs ("Key Early Actions") are actions the Panel has designated as essential next steps for reducing the risks associated with ocean acidification. Action on all of the Panel's recommendations is strongly urged, however.

Reduce Emissions of Carbon Dioxide (Chapter 4)	
Take action to reduce global, national, and local emissions of carbon dioxide. (Strategy 4.1)	Work with international, national, and regional partners to advocate for a comprehensive strategy to reduce carbon dioxide emissions. *(Action 4.1.1)* **[KEA]**
	Implement additional actions recommended by the Climate Action Team where such actions would reduce acidification of Washington's marine waters. *(Action 4.1.2)*
	Review data to determine if there is a causal relationship between local air emissions and local marine water acidity. If the data confirms such a relationship, take actions to reduce local air emissions that contribute to acidification. *(Action 4.1.3)*
	Enlist key leaders and policymakers to act as ambassadors advocating for carbon dioxide emissions reductions and protection of Washington's marine resources from acidification. *(Action 4.1.4)* **[KEA]**

Table 1: Blue Ribbon Panel Recommended Strategies and Actions, continued

Reduce Local Land-Based Contributions to Ocean Acidification (Chapter 5)	
Strengthen and augment existing pollutant reduction actions to reduce nutrients and organic carbon (Strategy 5.1)	Implement effective nutrient and organic carbon reduction programs in locations where these pollutants are causing or contributing to multiple water quality problems. *(Action 5.1.1)* **[KEA]**
	Support and reinforce current planning efforts and programs that address the impacts of nutrients and organic carbon. *(Action 5.1.2)* **[KEA]**
	Assess the need for water quality criteria relevant to ocean acidification. *(Action 5.1.3)*
	Adopt legislation that will allow sewer connections in rural areas to limit nutrients entering marine waters where it is determined to be necessary based on water quality impacts. *(Action 5.1.4)*
Impose stringent controls to reduce and limit nutrients and organic carbon from sources that are contributing significantly to acidification of Washington's marine waters (Strategy 5.2)	If it is scientifically determined that nutrients from small and large on-site sewage systems are contributing to local acidification, require the installation of advanced treatment technologies. *(Action 5.2.1)*
	If determined necessary based on scientific data, reduce nutrient loading and organic carbon from point source discharges. *(Action 5.2.2)*

Table 1: Blue Ribbon Panel Recommended Strategies and Actions, continued

Increase Our Ability to Adapt to and Remediate the Impacts of Ocean Acidification (Chapter 6)	
Remediate seawater chemistry (Strategy 6.1)	Develop vegetation-based systems of remediation for use in upland habitats and in shellfish areas. *(Action 6.1.1)* **[KEA]**
	Maintain and expand shellfish production to support healthy marine waters. *(Action 6.1.2)*
	Use shells in targeted marine areas to remediate impacts of local acidification on shellfish. *(Action 6.1.3)*
Increase the capacity of resource managers and the shellfish industry to adapt to ocean acidification (Strategy 6.2)	Ensure continued water quality monitoring at the six existing shellfish hatcheries and rearing areas to enable real-time management of hatcheries under changing pH conditions. *(Action 6.2.1)* **[KEA]**
	Expand the deployment of instruments and chemical monitoring to post-hatchery shellfish facilities and farms. *(Action 6.2.2)*
	Investigate and develop commercial-scale water treatment methods or hatchery designs to protect larvae from corrosive seawater. *(Action 6.2.3)* **[KEA]**
	Develop and incorporate acidification indicators and thresholds to guide adaptive action for species and places. *(Action 6.2.4)*
Enhance resilience of native and cultivated shellfish populations and ecosystems on which they depend (Strategy 6.3)	Preserve Washington's existing native seagrass and kelp populations and where possible restore these populations. *(Action 6.3.1)*
	Identify, protect, and manage refuges for organisms vulnerable to ocean acidification and other stressors. *(Action 6.3.2)* **[KEA]**
	Support restoration and conservation of native oysters. *(Action 6.3.3)*
	Use conservation hatchery techniques to maintain the genetic diversity of native shellfish species. *(Action 6.3.4)*
	Investigate genetic mechanisms and selective breeding approaches for acidification tolerance in shellfish and other vulnerable marine species. *(Action 6.3.5)*

Table 1: Blue Ribbon Panel Recommended Strategies and Actions, continued

Invest in Washington's Ability to Monitor and Investigate the Effects of Ocean Acidification (Chapter 7)	
Understand the status and trends of ocean acidification in Washington's marine waters (Strategy 7.1)	Establish an expanded and sustained ocean acidification monitoring network to measure trends in local acidification conditions and related biological responses. *(Action 7.1.1)* **[KEA]**
	Develop predictive relationships for indicators of ocean acidification (pH and aragonite saturation state). *(Action 7.1.2)*
	Support development of new technologies for monitoring ocean acidification. *(Action 7.1.3)*
Identify factors that contribute to ocean acidification in Washington's marine waters, and estimate the relative contribution of each (Strategy 7.2)	Quantify key natural and human-influenced processes that contribute to acidification based on estimates of sources, sinks, and transfer rates for carbon and nitrogen. *(Action 7.2.1)* **[KEA]**
	Develop new models or refine existing models to include biogeochemical processes of importance to ocean acidification. *(Action 7.2.2)*
Characterize biological responses of local species to ocean acidification and associated stressors (Strategy 7.3)	Determine the association between water and sediment chemistry and shellfish production in hatcheries and in the natural environment. *(Action 7.3.1)* **[KEA]**
	Conduct laboratory studies to assess the direct effects of ocean acidification, alone and in combination with other stressors, on local species and ecosystems. *(Action 7.3.2)* **[KEA]**
	Conduct field studies to characterize the effects of ocean acidification, alone and in combination with other stressors, on local species. *(Action 7.3.3)*
Build capabilities for short-term forecasting and long-term prediction of ocean acidification (Strategy 7.4)	Establish the ability to make short-term forecasts of corrosive conditions for application to shellfish hatcheries, growing areas, and other areas of concern. *(Action 7.4.1)* **[KEA]**
	Enhance the ability to predict the long-term future status of carbon chemistry and pH in Washington's waters and create models to project ecological responses to predicted ocean acidification conditions. *(Action 7.4.2)*
	Enhance the ability to model the response of organisms and populations to ocean acidification to improve our understanding of biological responses. *(Action 7.4.3)*

Table 1: Blue Ribbon Panel Recommended Strategies and Actions, continued

Inform, Educate, and Engage Stakeholders, the Public, and Decision Makers in Addressing Ocean Acidification (Chapter 8)	
Share information showing that ocean acidification is a real and recognized problem in Washington State (Strategy 8.1)	Identify key findings for use by the Governor, Panel members, and others who will act as ambassadors on ocean acidification. *(Action 8.1.1)* **[KEA]**
	Increase understanding of ocean acidification among key stakeholders, targeted audiences, and local communities to help implement the Panel's recommendations. *(Action 8.1.2)* **[KEA]**
	Build a network of engaged shellfish growers, tribes, and fishermen to share information on ocean acidification with key groups. *(Action 8.1.3)*
	Provide a forum for agricultural, business, and other stakeholders to engage with coastal resource users and managers in developing and implementing solutions. *(Action 8.1.4)* **[KEA]**
Increase ocean acidification literacy (Strategy 8.2)	Develop, adapt, and use curricula on ocean acidification in K-12 schools and higher education. *(Action 8.2.1)*
	Leverage existing education and outreach networks to disseminate key information and build support for priority actions. *(Action 8.2.2)*
	Share knowledge on ocean acidification causes, consequences, and responses at state and regional symposiums, conferences, workshops, and other events. *(Action 8.2.3)*
Maintain a Sustainable and Coordinated Focus on Ocean Acidification (Chapter 9)	
Ensure effective and efficient multi-agency coordination and collaboration (Strategy 9.1)	Charge, by gubernatorial action, a person in the Governor's Office or an existing or new organization to coordinate implementation of the Panel's recommendations with other ocean and coastal actions. *(Action 9.1.1)* **[KEA]**
	Create an ocean acidification science coordination team to promote scientific collaboration across agencies and organizations and connect ocean acidification science to adaptation and policy needs *(Action 9.1.2)* **[KEA]**

4

Reduce Emissions of Carbon Dioxide

Emissions of carbon dioxide must be significantly reduced to prevent irreversible harm to marine organisms and coastal ecosystems. Meanwhile the real and present consequences of acidification require that we act now to reduce, manage, and adapt to impacts of acidification.

OCEAN ACIDIFICATION IS AN URGENT global and local problem. The deposition of carbon dioxide from the atmosphere into the world's oceans is the largest source of acidifying pollution. Local emissions of carbon dioxide, nitrous oxides, and sulfur oxides may also be enhancing acidification in local waters, especially in urbanized areas around Puget Sound. Costly, adverse impacts to shellfish have already occurred, and predicted increases in acidity caused by increasing emissions of carbon dioxide could have devastating impacts on marine ecosystems as well as tribal and commercial shellfish resources.

If we are to counter the very real and urgent threat of ocean acidification, global emissions of carbon dioxide must be drastically and quickly reduced. The concentration of carbon dioxide in the atmosphere is rapidly approaching 400 parts per million (ppm)—a level not seen in at least 800,000 years—and current emissions trends could put us well above 700 ppm by 2100. Recent models indicate that when atmospheric carbon dioxide concentrations reach 460 ppm (currently expected by 2050), more than half the marine waters in our region will be corrosive to oyster larvae and other calcifying species.

Box 5. Washington's Climate Leadership.

In 2008, Washington State's Climate Action Team produced a comprehensive set of greenhouse gas reduction recommendations. Many of these recommendations have been either fully or partially implemented. Examples of actions already working to reduce greenhouse gases include:

- Adoption of mandatory greenhouse gas reduction requirements;
- Adoption of clean cars and alternative fuel standards;
- Establishing a minimum standard for renewable energy in Washington, which has resulted in developing 2,300 megawatts of wind capacity (making Washington fourth in the nation in wind production);
- Adopting changes in the energy code to achieve a 70 percent reduction in building energy by 2030 compared to 2006;
- Investing in green building and energy efficiency projects for public buildings and low-income properties; and
- Providing efficient transportation options.

Washington cannot accomplish global emission reductions alone, however. Washington—like the rest of the world—should be part of a comprehensive emission reduction effort designed to reduce atmospheric carbon dioxide levels, stabilize global temperatures, and maintain ocean pH at a level that protects shellfish, other organisms, and marine ecosystems. Washington can be a leader in these efforts through its work with federal and regional partners to reduce emissions of carbon dioxide and other greenhouse gases, by continuing its own carbon dioxide emissions reduction efforts, and by being a prominent voice in the national and global arena on the need to reduce the causes and consequences of ocean acidification.

In fact, Washington has already shown itself to be a global and national leader by enacting policies that reduce emissions of greenhouse gases, including carbon dioxide. Washington has adopted greenhouse gas reduction targets, a renewable energy portfolio standard, clean car standards, green building and energy efficiency standards, a greenhouse gas performance standard for new power plants and a scheduled transition to natural gas for the state's only coal plant (Box 5).

The Panel recommends that Washington continue to lead in the adoption of policies and practices that address the multiple risks posed by carbon dioxide accumulation in the atmosphere. Indeed, the creation of this Panel is an example of Washington's leadership. Other actions by which Washington can continue to demonstrate its leadership are described here.

Strategy 4.1 – Take action to reduce global, national, and local emissions of carbon dioxide.

Action 4.1.1: Work with international, national, and regional partners to advocate for a comprehensive strategy to reduce carbon dioxide emissions. **[KEA]**

Significant and timely progress in reducing acidifying pollutants at both the global and local levels is critical to protecting Washington from the potentially devastating impacts of ocean acidification. Washington should actively work with the federal government, other coastal states, Canadian provinces and territories, and other national jurisdictions within the Pacific Rim and around the globe to share knowledge, data, scientific expertise, and potential policy initiatives, including policies that reduce emissions of carbon dioxide, and to take joint actions to protect oceans and other marine waters from the threat of ocean acidification.

Actions could include pursuing agreements with other states, provinces, and nations to cooperate in scientific initiatives to define the impacts of rising carbon dioxide emissions on marine fisheries and seafood supplies; intergovernmental compacts and agreements to reduce acidifying pollution; and joint outreach to build public awareness and promote strong action at regional, national, and international levels.

Washington State has already implemented many actions to reduce carbon dioxide emissions

Action 4.1.2: Implement additional actions recommended by the Climate Action Team where such actions would reduce acidification of Washington's marine waters.

The Washington Climate Action Team was convened in 2008 by Governor Gregoire to develop actions for reducing greenhouse gas emissions in Washington. The Team represented policymakers from many sectors of the state's economy; state, local, and tribal governments; environmental and conservation organizations; and citizens. Legislators also sat on this Team.

Several of the policy actions recommended by the Climate Action Team have not yet been implemented. The 2012 State Energy Strategy, submitted

to the Governor and the State Legislature, includes many actions that would reduce emissions of carbon dioxide and other greenhouse gases. These actions include large-scale deployment of plug-in vehicles; investment in an integrated network of charging stations, car sharing, and mileage-based insurance; low-carbon fuel standards; transportation pricing; smart growth and transportation planning; expansion of programs to reduce commuter trips; efficiency standards for certain appliances; expanded investment in low-income weatherization programs; and expansion of distributed energy systems (i.e., on-site electricity generation from many small energy sources).

It is important to review our progress in reducing emissions of greenhouse gases under those recommendations of the Climate Action Team that have been or are being implemented. The state should also review the unimplemented recommendations of the Climate Action Team and the State Energy Strategy to identify which actions should be taken to further reduce in-state emissions of carbon dioxide and other greenhouse gases. These policy actions, if implemented, can significantly reduce the state's carbon dioxide emissions. Implementation will require the engagement of stakeholders and, in many cases, additional funding. It is important that policymakers and stakeholders begin to work soon on the near-term emissions reductions actions.

Action 4.1.3: Review data to determine if there is a causal relationship between local air emissions and local marine water acidity. If the data confirms such a relationship, take actions to reduce local air emissions that contribute to acidification.

Local air emissions may have an impact on local marine water quality.

Local air pollutants—specifically carbon dioxide, nitrogen oxides, and sulfur oxides—deposited in urban corridors can accumulate in surface waters, potentially contributing to acidification. Preliminary research shows a connection between local air pollution and the absorption of carbon dioxide into Puget Sound waters. The quantitative effect on the acidity of local waters is unknown, however. The Panel's research, modeling, and monitoring recommendations include measures to estimate how much these individual processes contribute to the acidification of Washington's waters. If that research shows that local air pollution is a significant driver of local acidification, additional steps beyond the implementation of strategies and actions identified in Action 4.1.2 may be required to reduce local emissions of carbon dioxide and other acidifying gases.

Action 4.1.4: Enlist key leaders and policymakers to act as ambassadors advocating for carbon dioxide emissions reductions and protection of Washington's marine resources from acidification. **[KEA]**

The Governor, members of the State Legislature, our Congressional delegation, and other leaders (including Panel members) are in a position to serve as ambassadors for reducing the causes and consequences of ocean acidification. State delegations and missions to promote trade, development, and cooperation can and should carry the message about the importance of reducing carbon emissions to leaders of other states and nations. Other forums may also provide important vehicles for this message, including the Pacific Coast Collaborative, the West Coast Governors Alliance on Ocean Health, the West Coast Governors' Global Warming Initiative, the Western Climate Initiative, interstate educational conferences of state legislators, and multi-tribal climate change forums.

Communications materials designed to support the ocean acidification "ambassadors" should be developed as described in Action 8.1.1. Elected officials and other key leaders should be periodically briefed on the issue and associated communications materials to stay current on carbon emissions trends, ocean acidification science, and impacts relevant to Washington.

Capitol Building, Olympia, Washington

5

Reduce Local Land-Based Contributions to Ocean Acidification

Reducing inputs of nutrients and organic carbon from local sources will decrease acidity in Washington's marine waters that are impacted by these local sources and thereby decrease the effects of ocean acidification on local marine species.

ACIDIFICATION NEAR THE COASTS, AND particularly in highly populated and developed areas, is often exacerbated by locally derived human and natural inputs that generate additional carbon dioxide in marine waters. Two important local contributions are nutrients and organic carbon.

Nutrients enter the marine environment from single (point) or diffused (nonpoint) sources. Point sources include discharges from municipal and industrial wastewater treatment facilities, large stormwater outfalls, and concentrated animal feedlots. Nonpoint sources include runoff from on-site septic systems; improperly managed farms, grazing lands, and dairy lagoons; urban runoff; excessive fertilizers from residential lawns and gardens; and wastes from recreational and commercial vessels. Runoff can also add nutrients derived from decomposing plants and animals.

Excessive nutrients can cause problems through their effect on dissolved oxygen and through their influence on ocean acidification. Nutrients can stimulate algal and plant growth, sometimes excessively. These algae and plants ultimately die and decompose. This decomposition reduces dissolved oxygen in the water column, which is critical to large numbers of marine species. The decomposition process that reduces oxygen levels also releases carbon dioxide directly into marine waters and thus lowers pH. Decomposition from excessive algal blooms has increased acidification in other states' coastal systems, underscoring the role that local nutrients can play in local and regional acidification.

Organic carbon enters the marine environment in the form of living or decaying organic matter such as plants, freshwater algae, plant and animal materials, and some types of sewage effluent. Sources of organic carbon include stormwater runoff and freshwater flows from rivers and streams, which carry organic carbon to marine waters and estuaries, such as Willapa Bay. Like nutrients, the decomposition of organic matter releases carbon dioxide into marine waters, thus lowering pH.

The adverse effects of nutrients on dissolved oxygen levels in Washington have been a concern for many years. Sophisticated water quality programs are in place around the state to reduce nutrient loading. Hood Canal, South Puget Sound, and other shallow, enclosed bays and estuaries are particularly susceptible to periodic, sometimes catastrophic low oxygen levels that can lead to fish kills and other biological impacts. Despite these existing programs, marine nutrient levels continue to be a significant problem and are worsening in some locations.

It is critically important that we gather more data on the relative importance of local sources of acidifying pollutants and atmospheric carbon dioxide. While current scientific information tells us that local land-based sources of nutrients and organic carbon exacerbate local acidity, we need more information about the significance of these sources in Washington waters. It is probable that the science will tell us that the answers will vary by geography and time. For example, it is likely that local sources will be more significant in Hood Canal and South Puget Sound than in the Strait of Juan de Fuca, where the global signal will likely predominate. Similarly, the answer will likely vary seasonally and over the longer term as atmospheric concentrations of carbon dioxide continue to increase.

Nisqually National Wildlife Refuge, in Puget Sound.

Developing pollutant budgets and models that can accurately determine current contributions and reliably predict future contributions are important tools for increasing our understanding of the role that local land-based inputs play in acidifying local waters (see Action 7.2.1). The Panel urges that these tools be developed quickly and that government and nongovernmental entities invest in the research and monitoring that will provide needed answers.

We should not put nutrient control efforts on hold while this scientific work is done, however. On the contrary, the Panel recommends that existing nutrient and organic carbon reduction programs be enhanced and strengthened; these pollutants are already lowering dissolved oxygen levels and causing a variety of significant ecosystem impacts in some areas. Additionally, local sources of nutrients and organic carbon often contain dangerous

bacteria, pathogens, toxic metals, and other harmful pollutants. Finally, the decomposition of organic material and nutrient-stimulated algae can eventually release carbon dioxide into the water, thereby lowering pH and causing acidification.

Given the impacts of ocean acidification and the multiple benefits of nutrient and carbon source reduction, the Panel recommends enhanced actions to control and reduce local sources. Acidification presents an additional reason to accelerate and strengthen these existing programs.

Approach to Reducing Local Contributions

As discussed in the previous section, we know that nutrients and organic carbon exacerbate local ocean acidification but we do not yet know the specific magnitude of that impact. The relative contribution of local sources has not been quantified in Washington, and doing the research and monitoring necessary to provide that quantification is a critically important aspect of the recommendations made by the Panel.

Recognizing this, the Panel recommends a two-tiered approach for moving forward on nutrient and organic carbon input reduction. The first tier (Strategy 5.1) constitutes a set of actions that builds on existing programs to reduce nutrient and organic carbon inputs in ways that provide near-term economic and environmental benefits.

The second tier of actions (Strategy 5.2) recognizes that more stringent controls of nutrients and organic carbon pollutants will be required if additional data confirm that these inputs are contributing significantly to acidification. Many of the actions in Strategy 5.2 will require substantial additional technical work, cost, and time. Consistent with a commitment to science-based policy, the actions in Strategy 5.2 should be implemented only if research finds that more substantial reductions in nutrients and organic carbon are necessary to address ocean acidification.

Strategy 5.1 – Strengthen and augment existing pollutant reduction actions to reduce nutrients and organic carbon.

In Washington, we have made substantial investment—and progress—in reducing the pollutants that affect water quality and human health, including nutrients and organic carbon. These gains have been achieved through the concerted effort of farmers, landowners, watershed groups, and non-governmental organizations, who have worked in partnership with state and federal agencies over many years to improve water quality. Yet many challenges remain, especially in managing nutrients. To reduce nutrients and organic carbon we need to strengthen and augment existing programs that reduce the harmful effects of runoff; increase multi-agency coordination and collaboration; involve farmers, landowners, communities and local organizations; and provide and ensure reliable sources of funding for efforts aimed at reducing nutrients and organic carbon.

Action 5.1.1: Implement effective nutrient and organic carbon reduction programs in locations where these pollutants are causing or contributing to multiple water quality problems. **[KEA]**

The LOTT sewage treatment plant in Olympia, Washington.

Because of adverse impacts from largely uncontrolled sources of pollutants, including bacterial pollutants from septic tanks, agricultural and urban run-off, and other sources, over 4,000 acres of prime commercial shellfish beds were downgraded in Samish Bay in 2011. As a result of these impacts, an array of government and private landowners is working hard to reduce sources of pollutants draining to the Bay, including nutrients and organic carbon.

Similarly, in South Puget Sound, efforts to reduce nutrient loading, primarily by addressing low dissolved oxygen levels, have been in place for years. The LOTT (Lacey, Olympia, Tumwater and Thurston) sewage treatment plant has been removing nitrogen from its effluent for several years, with significant benefits to Budd Inlet, where the plant's discharge is located.

These are two examples of serious efforts to reduce nutrient loading. They are not perfect, but significant progress is being made in both locations. The Panel strongly recommends that these programs be strengthened and augmented with increased resources and visible political support. The Panel also recommends that nutrient and organic carbon reduction efforts be brought to bear in other locations where these inputs contribute to acidification.

Nutrient and organic carbon reduction programs provide multiple benefits. They protect people and shellfish from bacterial contamination. They remove pollutants that lower dissolved oxygen levels. And they remove pollutants that reduce pH. The following are examples of existing or emerging tools that remove or reduce nutrients and organic carbon.

- **Best management practices**: Best management practices include structural or engineered control devices and systems (e.g., retention ponds) to treat polluted runoff, as well as operational or procedural practices (e.g., minimizing use of chemical fertilizers and pesticides). There is a need to ensure consistent application of best management practices in different watersheds across the state. This will require coordination among federal, state, and local agencies and organizations, and active involvement of farmers, local resource management officials, and implementing agencies.

  Coordinated approaches to implementing best management practices include using existing and newly emerging cross-organizational teams with local knowledge and implementation experience, such as Pollution Control Action Teams and Pollution Identification and Correction programs. These teams function best when they include representatives of local, state, tribal, and federal agencies working closely with landowners and other interested parties.

  This approach requires augmenting technical assistance, inspection, and compliance capacity; developing an understanding of new technologies; and monitoring performance to ensure that practices are installed and effective with demonstrated reductions in nutrient loading. Landowners should be provided with opportunities to participate in monitoring practices and water quality improvements.
- **Improved Technologies**: There is a critical need for better technologies to address nutrient loading, especially from nonpoint sources. New septic system technologies that more effectively treat nutrients are one example. The state should seek private partnerships to identify, promote, and support new and improved technologies that remove or reduce nitrogen and organic carbon from point and nonpoint sources.
- **Innovative Approaches:** Nutrient trading is an approach that has been recently adopted in Ohio, Indiana, and Kentucky. It is also being used to help restore

Chesapeake Bay. In a nutrient trading market, individuals (for example, farmers) that reduce their nutrient runoff or discharges below allowable levels can sell their surplus reductions or "credits" to other individuals (for example, wastewater treatment facilities). This approach allows those that can reduce nutrients at low cost to sell credits to those facing higher-cost nutrient reduction options. The "sellers" need to go beyond their baseline target. The state of Connecticut established a nitrogen trading program in 2001. The program is projected to reduce the cost for 79 wastewater treatment facilities to meet their waste allocation under the nitrogen TMDL by approximately 33 percent (CT DEP, 2009).

Washington has the legal authority to establish a water quality trading program and is interested in working with stakeholders to do so. The Panel recommends that Ecology and other appropriate agencies initiate a stakeholder process to evaluate and, if appropriate, assist in designing such a trading program.

Action 5.1.2: Support and reinforce current planning efforts and programs that address the impacts of nutrients and organic carbon. **[KEA]**

Several local, state, and federal planning efforts and programs are aimed at reducing pollution and improving water quality. They advance the goals of economic vitality, environmental protection, resource conservation, and future sustainable development. The Growth Management Act, the newly created Washington State Voluntary Stewardship Program, the Shoreline Management Act, and the Puget Sound Partnership Action Agenda, for example, can be extremely effective in reducing nutrients and organic carbon originating from nonpoint sources.

In addition, these programs and others can be used to conserve forest and agricultural lands, which can function as natural filters to remove nutrients and sequester carbon. For example, state and local governments could advance the use of incentives and regulatory tools to promote and conserve forest and agricultural land uses, promote reduction in impervious surfaces, and encourage use of green infrastructure and other sustainable practices, all of which help reduce the nutrients and organic carbon entering marine waters.

In addition, groups on the ground (for example, watershed groups, conservation districts, shellfish protection districts, and other qualified organizations) could use existing planning and technical and financial assistance programs to help farmers, rural and urban landowners, and others properly manage nutrients and reduce organic carbon. Regulatory and voluntary programs should be vigorously pursued and their effects monitored to see what works under what circumstances.

Action 5.1.3: Assess the need for water quality criteria relevant to ocean acidification.

Currently, pH is the only water quality criteria that can be readily associated with ocean acidification. But dissolved-oxygen impacts are also associated with acidification, and recent scientific research suggests that other ocean chemistry parameters and biological indicators may be relevant to local acidification.

Scientists from NOAA's Pacific Marine Environmental Laboratory and the Pacific Shellfish Institute sample water in Puget Sound's Totten Inlet.

EPA should convene a technical group with representation from the Washington Department of Ecology, NOAA, interested tribes, and academic institutions to determine the relevance of existing standards to ocean acidification. If the group determines that these standards are insufficient to control the impacts of local sources, it should evaluate the applicability of other water quality criteria identified by recent research or recommended by scientific experts in the fields of ocean acidification and water quality.

Many rural communities do not have access to sewer systems.

Action 5.1.4: Adopt legislation that will allow sewer connections in rural areas to limit nutrients entering marine waters where it is determined to be necessary based on water quality impacts.

In 2002, the state Supreme Court ruled that the Growth Management Act (GMA) does not allow extending sewer lines into rural areas. This does not change the fact that connecting rural residences' septic systems to an existing or new sewage treatment plant could be effective in reducing nutrients.

The Panel recommends that the Washington Departments of Commerce, Health, and Ecology and the Puget Sound Partnership convene a legislative workgroup charged with developing an effective approach to removing this legal barrier, while still accomplishing the GMA's laudable goal of preventing urban growth in rural areas. This workgroup should also identify and evaluate potential funding options for sewer line extensions, residential and small business hook-ups, and other costs associated with reducing nutrient loading from septic systems.

Strategy 5.2 – Impose stringent controls to reduce and limit nutrients and organic carbon from sources that are contributing significantly to acidification of Washington's marine waters.

The actions recommended as part of Strategy 5.2 would impose stringent new controls on nutrients and organic carbon pollutants. They could be quite costly, would involve significant additional technical work, and would likely take a long time to implement. The Panel recommends that these actions be implemented to address ocean acidification *only if additional scientific data and information confirm that nutrients and organic carbon from certain sources significantly contribute to ocean acidification*.

It is important to understand that some of these actions are already being taken at some locations due to existing water quality problems other than ocean acidification. For example, the LOTT sewage treatment plant is already removing nitrogen from its effluent due to extremely low dissolved oxygen levels in Budd Inlet. The Panel's recommendation that stringent controls be imposed only after further scientific analysis of the relationship between local nutrient and organic carbon loading and local acidity relates to combating acidification per se. It does not bear on the use of these controls to address other water quality problems.

Action 5.2.1: If it is scientifically determined that nutrients from small and large on-site sewage systems are contributing to local acidification, require the installation of advanced treatment technologies.

When properly designed and installed, on-site sewage systems provide a high level of treatment for bacteria and other pollutants. However, nutrients are not removed unless nitrogen-reducing technologies are used. The Washington Department of Health is field testing such technologies. If they prove effective and reliable, appropriate steps should be taken to require these nitrogen-removal technologies in areas where it is determined that nutrients from on-site sewage systems are contributing significantly to ocean acidification.

The cost of the advanced treatment of nutrients will generally fall on individuals—not utility rate payers—with little subsidy. The Panel recommends that funding (for example, a self-sustained, low-interest loan program) for upgrades of small and large on-site systems be identified to assist system owners.

Action 5.2.2: If determined necessary based on scientific data, reduce nutrient loading and organic carbon from point source discharges.

Nutrient and organic carbon originating from point sources (including municipal wastewater treatment facilities, large stormwater discharges, some industrial discharges, and concentrated animal feedlots) account for the majority of local nutrient inputs into Washington's marine waters. Discharges from these large point sources are comprehensively regulated by individual or general permits issued under the National Pollutant Discharge Elimination System program. These permits impose specific effluent limits, monitoring and reporting requirements, and other conditions on permitted discharges.

A crew installs a stormwater runoff system in downtown Seattle.

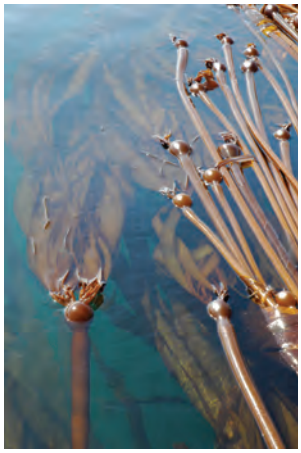
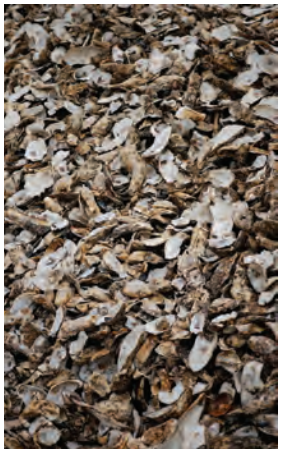
Wastewater facilities are permanent infrastructure, which is costly to construct, maintain, and operate. Reducing nutrients from wastewater point-source discharges often requires technologies that must be tailored to local conditions and facilities. As a result, these technologies can be costly.

The Panel recommends additional research and monitoring to determine the extent to which point sources of nutrients and organic carbon are significant causes of acidification. Sources that are determined to be significant should be required to reduce their contribution of nutrients and/or organic carbon.

Washington State's Legal and Policy Options for Combating Ocean Acidification in State Waters. Stanford University's Center for Ocean Solutions prepared *Washington State's Legal and Policy Options for Combating Ocean Acidification in State Waters* to help Panel members understand the scope of regulatory and non-regulatory tools that can be used to address nutrients and other acidifying pollutants. The review also suggests where new tools might be developed. To access the paper, please go to: http://www.ecy.wa.gov/water/marine/oceanacidification.html.

6

Increase Our Ability to Adapt to and Remediate the Impacts of Ocean Acidification

We need to use a wide range of approaches to adapt to and remediate the impacts of ocean acidification in order to limit future losses of shellfish resources.

IT WILL TAKE TIME TO achieve deep reductions in carbon dioxide emissions, and the resulting ocean acidification and related changes are expected to persist for decades or longer. Since some changes in water chemistry are now inevitable, Washington must act to reduce the harm likely to occur. Shellfish growers are already starting to adapt through changes in their own practices. However, these efforts may be insufficient given the projected pace of ocean acidification. Further investigation of, and investment in, adaptation and remediation strategies is necessary to overcome the deteriorating conditions predicted for the coming decades.

The strategies and actions recommended in this Chapter call for preserving and enhancing the resilience of native shellfish and the ecosystems they depend on, and implementing a mix of innovative approaches and technologies to maintain and enhance cultivated shellfish production. The effectiveness of the recommendations will depend on collaboration between the private sector, nongovernmental organizations, academia, and state and tribal governments.

Private and public investment will be needed to fund robust approaches and technologies for protecting shellfish and marine ecosystems. A formal process for soliciting, evaluating, and recommending adaptation and remediation proposals should be established by the coordinating entity described in Chapter 9. This responsibility can be given to the science coordination team recommended in Chapter 9, working with shellfish growers, tribes, and others.

Strategy 6.1 – Remediate seawater chemistry.

Ocean acidification stresses shellfish and other species both by lowering pH and by decreasing the availability of shell-building materials. Several methods of remediating local seawater conditions show promise for protecting species from changes in water chemistry, especially during their most vulnerable life stages. Remediation options should be field tested to verify their efficacy and suitability for practical use in shellfish culture and conservation.

Action 6.1.1: Develop vegetation-based systems of remediation for use in upland habitats and in shellfish areas. **[KEA]**

Seaweed growing on oyster longlines at a Samish Bay, Washington shellfish farm.

Plants absorb carbon dioxide from the atmosphere and/or the water column and store it as carbon in foliage and roots. In addition, most plants ingest nutrients directly from the soil through their roots or from the atmosphere, reducing nitrogen input into marine waters. Using vegetation in upland areas to reduce nutrient-laden runoff and in cultivated shellfish beds to remove carbon dioxide from seawater can help protect vulnerable young shellfish from acidification and hypoxia. These techniques, known as phytoremediation, include maintaining or planting vegetation in buffer zones, using seaweeds or seagrasses within shellfish hatcheries for better larval survival and growth, co-culturing eelgrass and shellfish, using seaweed farming to capture and remove carbon, and harvesting algae from shellfish-growing gear for use onshore as a fertilizer. Developing these and other phytoremediation techniques will require sustained experiments and field trials, a better understanding of the mitigation potential provided by upland and marine vegetation, monitoring, and a sustained commitment to refining phytoremediation protocols as new information is gained.

Action 6.1.2: Maintain and expand shellfish production to support healthy marine waters.

Sustaining shellfish production in Washington is a component of a sound plan to protect healthy seawater chemistry and marine ecosystems from acidification. Productive shellfish beds provide natural treatment of some water quality conditions. By the very act of feeding, shellfish organisms filter nutrients out of the water, cleaning and clarifying it. Clearer water allows more sunlight to penetrate, which aids in the growth of crucial seagrasses, including eelgrass. Seagrasses, in turn, take up carbon dioxide and sequester it deep in their root systems, reducing carbon dioxide levels in the water. Different mechanisms exist for maintaining and expanding shellfish beds, including monetary incentives. For example, the state of Maryland offers a $500 tax credit ($1,000 per household) to residents who raise oysters because of the ecosystem services they provide.

Action 6.1.3: Use shells in targeted marine areas to remediate impacts of local acidification on shellfish.

Spreading shell material in shallow waters can increase the survival of newly settling bivalve larvae, both native and cultured, by buffering corrosive conditions. This occurs when the calcium carbonate in the deposited shell material dissolves, increasing seawater alkalinity. The increased alkalinity counters the corrosive conditions within and close to the seafloor that are created by the byproducts of normal respiration processes and other contributions. Intact shells also have other well-documented ecological benefits. For example, they provide firm structure for the larvae to attach to and can protect against predators.

Shells from millions of oysters consumed at restaurants throughout Washington currently go to landfills. With appropriate handling protocols, a shell collection and deposition program could help protect cultivated and native oysters and clams from acidification, expand native oyster restoration efforts, and engage citizens and businesses in mitigating local impacts of acidification.

Oyster shell stockpiled at a shucking plant in Willapa Bay, Washington.

Centralized stockpiling locations would need to be identified, likely in association with shellfish growing operations, to season the shell sufficiently to meet state standards for prevention of disease and exotic organisms. Many growers already maintain large shell piles and deploy shells to catch new oyster seed, so much of the infrastructure to scale up this activity is already in place.

Strategy 6.2 – Increase the capacity of resource managers and the shellfish industry to adapt to ocean acidification.

As acidification worsens, shellfish hatcheries may become refuges where larvae can be raised in a controlled environment. Monitoring and maintaining hatchery water quality will be essential. Similar adaptive measures should also be expanded to shellfish farms to support remote setting and production of oyster seed. Better information about the ability of species to tolerate acidification can help the tribes, shellfish industry, and conservation programs adapt to changing conditions.

Action 6.2.1: Ensure continued water quality monitoring at the six existing shellfish hatcheries and rearing areas to enable real-time management of hatcheries under changing pH conditions. **[KEA]**

Beginning in 2010, the Pacific Coast Shellfish Growers Association began real-time monitoring of pH, pCO_2, salinity, temperature, and dissolved oxygen in intake water at the Whiskey Creek, Taylor, and Lummi hatcheries and at three Willapa Bay sites. The real-time data provided by this monitoring have enabled hatchery operators to draw water at times and from depths with lower carbon dioxide and higher pH levels. As a result, shellfish growers have restored much of the production lost in the preceding three years.

Federal and foundation funding for this monitoring will end in December 2012. While the growers operating the six hatcheries financially support operation and maintenance of the monitoring equipment, they need assistance to keep the equipment calibrated and functioning properly, to interpret the data, and to coordinate results with other facilities.

This recommendation calls for securing the funding necessary to maintain and improve the six monitoring sites. The scientific information obtained at these sites is also essential for increasing our scientific understanding of the impacts of acidified water on marine resources. See Action 7.1.1 for details on how these six stations are part of the ocean acidification monitoring network.

Action 6.2.2: Expand the deployment of instruments and chemical monitoring to post-hatchery shellfish facilities and farms.

While much attention has been given to the impacts of ocean acidification on shellfish larvae, post-larval stages of shellfish growth may also need protection. Most remote setting stations (where larvae are "set" on solid substrate to form spat) and nurseries (where spat develop into oyster seed) currently lack the capacity to detect and avoid corrosive seawater. Expanding high-quality chemical monitoring programs similar to the one described in Action 6.2.1 to setting stations and broodstock culture locations (where adult oysters are prepared for spawning) would allow growers to avoid drawing corrosive seawater into their tanks. In nurseries, where oysters are raised in ambient seawater, better information about the local chemistry would enable growers to select and evaluate appropriate mitigation strategies for a given location. This post-hatchery monitoring should be included as part of the ocean acidification monitoring network recommended in Action 7.1.1.

Monitoring pH and carbonate chemistry can be accomplished either by installing new instruments in field locations for direct measurements or by extrapolating from routinely collected hydrographic data. This latter method would have lower operating costs but would require that site-specific empirical relationships be developed for each location. Coupled biological monitoring in all these settings is essential to understanding how fluctuations in seawater chemistry affect shellfish health. Potential locations to deploy instruments and collect data include Gray's Harbor, Willapa Bay, and additional sites in Puget Sound. In addition, Humboldt Bay, California, and Kona, Hawaii, are important seed sources for the Washington shellfish industry, and monitoring water chemistry in these locations could contribute significantly to increased shellfish production throughout the state.

Commercial growers monitoring water quality at a shellfish farm in Totten Inlet, Washington.

Action 6.2.3: Investigate and develop commercial-scale water treatment methods or hatchery designs to protect larvae from corrosive seawater. **[KEA]**

Improving control of (or buffering) seawater chemistry in shellfish hatcheries is an urgent challenge due to rapid encroachment of increasingly acidified seawater along the West Coast. The central adaptation strategy that currently sustains the Northwest's shellfish industry depends on hatcheries to protect larvae. Hatcheries shelter larvae from corrosive water during their most vulnerable early stages, and increasingly, they must mitigate seawater chemistry (for example, via out-gassing or chemical additives) to correct corrosive conditions that cannot always be avoided. Buffering systems are still in early stages of development and as corrosive waters become more widespread and severe, shellfish producers and native shellfish restoration managers will need reliable commercial-scale methods to ensure that hatcheries and nurseries can continue to provide an adequate refuge for vulnerable larvae.

This action recommends two approaches to improve control of water chemistry within the hatcheries and nurseries. The first is to optimize methods of mitigating the water pumped in from the sea by, for example, using natural photosynthetic pathways to remove carbon dioxide or improving design of automated control systems that can trigger release of alkaline agents precisely when needed for larval survival. The second approach is to develop closed-loop, re-circulating aquaculture systems to shield larvae from inhospitable water chemistry. For both approaches, fundamental system design criteria must be identified and scaled for commercial use to alleviate the impact of acidified seawater. Significant engineering, design, and research hurdles remain before implementation of these approaches can occur on a commercial scale.

Action 6.2.4: Develop and incorporate acidification indicators and thresholds to guide adaptive action for species and places.

Research will likely identify tolerance limits and forecast future "tipping points" for shellfish populations and marine ecosystems. It will be important to develop and incorporate ocean acidification-related indicators and thresholds into monitoring, resource management, and conservation plans to guide responses to ocean acidification.

This early-warning system will require drawing on the results of research and monitoring to identify key environmental factors, establish appropriate indicators and thresholds, and incorporate those indicators and thresholds into management and monitoring plans. Where possible, these indicators and thresholds should be tuned to the species and places being managed. For example, when water chemistry approaches a known limit

for successful reproduction of native mussels in a particular bay, plans might call for site-specific phytoremediation strategies, adding shell to buffer shellfish beds, or even introducing strains of native shellfish that are more tolerant of acidifying conditions.

Similar thresholds are used for decisions related to the impacts of climate change but not yet for ocean acidification. Developing indicators and thresholds will help managers and resource users monitor changing conditions and evaluate if and when certain adaptation and remediation actions need to be implemented. Thus interventions that are initially unnecessary (or even incompatible with other conservation goals) can be used only when required. The indicators and thresholds can also be used to measure progress toward addressing ocean acidification.

Strategy 6.3 – Enhance resilience of native and cultivated shellfish populations and ecosystems on which they depend.

Some Washington estuarine and marine sites have vegetation and other features that can provide significant local protection against acidification, or could do so in the future. These sites will become increasingly valuable as acidification worsens and should be managed to provide shelter to vulnerable organisms. The resilience of local shellfish populations, including native oysters, should be enhanced though conservation and restoration of marine ecosystems.

Action 6.3.1: Preserve Washington's existing native seagrass and kelp populations and, where possible, restore these populations.

Growing evidence indicates that aquatic plants and algae, including seagrasses and kelp, can effectively draw down carbon dioxide from the surrounding seawater, thereby increasing seawater pH. This is especially the case in semi-enclosed areas and those with slower water circulation. Additional evidence

Native eelgrass (left) and bull kelp beds (right) in Puget Sound.

indicates that seagrasses and kelp can effectively sequester carbon from the water in underlying sediments following their decomposition, removing this carbon from the system. Preserving, and where possible restoring, Washington's abundance of native seagrasses and kelp offers an important means of remediating acidification and hypoxia in local waters.

Action 6.3.2: Identify, protect, and manage refuges for organisms vulnerable to ocean acidification and other stressors. **[KEA]**

Native marine ecosystems and shellfish production can be protected by: (1) identifying areas that provide refuge to affected species (areas where acidification is likely to occur more slowly or to a lesser extent than in others, due to physical features); (2) enhancing natural marine ecosystems where possible through habitat restoration, conservation, phytoremediation, and other measures; and (3) actively managing these ecosystems to reduce impacts from existing and future stressors (e.g., higher sea level, higher temperatures, altered hydrologic conditions).

We can begin by assessing bays and nearshore resources as well as low-lying areas that are likely to be submerged in the future for potential changes in chemical and physical conditions and the ability of these ecosystems to protect marine organisms they host. Areas ranked highly in the assessment should be conserved, managed for future uses, and/or used as experimental areas for testing shellfish adaptation and remediation strategies. Parameters and criteria that could be used to identify refuges and recognize significant ecological changes need to be developed.

A community group engaged in oyster restoration.

Action 6.3.3: Support the restoration and conservation of native oysters.

Research on mature native oyster beds suggests that the local environment is governed partly through the oysters' interactions with surrounding sediments and microorganisms. In Washington, our native Olympia oysters have been exposed to ocean upwelling for a long time, and the ecological communities they create may have evolved to tolerate some of the effects of acidified water. Mature Olympia oyster beds, intact or restored, could shelter naturally tolerant strains and provide information that may be applicable to managing other farmed and native shellfish.

Restoring Olympia oysters to regain the ecological characteristics of a mature, self-sustaining population is a priority under the Washington Shellfish Initiative. The Washington Department of Fish and Wildlife's new restoration plan for Olympia oysters would re-establish dense populations in 19 of their historic strongholds. This action supports the funding and implementation of the restoration plan.

Action 6.3.4: Use conservation hatchery techniques to maintain the genetic diversity of native shellfish species.

Ocean acidification accelerates the need to protect native Olympia oyster and pinto abalone resources through use of conservation hatchery methods, which should be done in conjunction with research to understand their wild population dynamics, life cycles, genetic diversity, and response to environmental disturbances. Additionally, a scientific evaluation should be conducted to determine whether and when other native shellfish resources may require similar interventions.

Without conservation hatchery techniques, changing water chemistry would likely reduce the genetic diversity of sensitive populations, raising the risk of extinction.Maintaining reference stocks in conservation hatcheries can reduce this risk. At least two conservation hatchery facilities are already planned or operating. NOAA's Manchester Research Station is building a new hatchery that initially will produce native oyster seed for restoration projects and the Mukilteo field station operates a small pinto abalone hatchery. These projects are primarily aimed at protecting genetic diversity in natural populations using strict guidelines being developed now. These operations explicitly focus on conservation and restoration, not artificial selection or commercial production. As acidification and other stressors alter natural population structures, the two facilities will seek to maintain the full range of genetic variability in these imperiled wild stocks. These research and production efforts should be supported.

Hatchery-raised juvenile pinto abalone.

Action 6.3.5: Investigate genetic mechanisms and selective breeding approaches for acidification tolerance in shellfish and other vulnerable marine species.

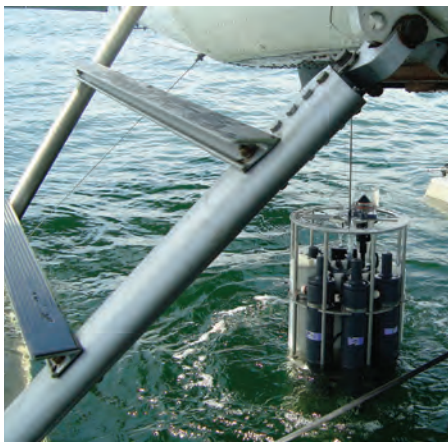
Northwest native and cultivated shellfish may be able to adapt to some changes in ocean chemistry. This potential comes from three mechanisms, which may vary across species and populations: (a) some species may already be able to tolerate acidified conditions by, for example, producing a wide range of physical and behavioral types, some of which will be better suited to higher acidity than others; (b) existing genetic variation may include traits conferring acidification tolerance in some individuals, which would be favored by natural selection under acidified conditions; and (c) some species may respond to selective breeding under acidified laboratory conditions, resulting in new genotypes that perform well under future acidified conditions.

To address these potential mechanisms, it is vital to understand existing variation within species and the genetic underpinnings of sensitivity to, or tolerance of, acidification-related changes in water chemistry. Acidification-resistant strains of commercial shellfish could be developed and the approach could then be applied to aid conservation of key wild species or strains.

For more information about measures to counter ocean acidification in Washington's marine waters, see *Sweetening the Waters: The Feasibility and Efficacy of Strategies to Protect Washington's Marine Resources from Ocean Acidification*. This report, prepared by the Sustainable Fisheries Partnership, examines a wide range of strategies for addressing acidification. Potential feasibility, efficacy, benefits, and other consequences are considered. The report is available at: http://www.ecy.wa.gov/water/marine/oceanacidification.html.

7

Invest in Washington's Ability to Monitor and Investigate the Causes and Effects of Ocean Acidification



Investing in ocean acidification research and monitoring will provide the necessary scientific support for developing, implementing, and evaluating effective responses to ocean acidification.

SCIENTIFICALLY BASED ACTIONS ARE REQUIRED to reduce the risk of ocean acidification to Washington's shellfish, other organisms, and marine ecosystems, and to sustain the ecological, economic, and cultural benefits they provide. Investing in the capacity to monitor and investigate the effects of ocean acidification is central to providing—and building on—that necessary scientific foundation.

Our knowledge about the causes and consequences of ocean acidification is rapidly advancing, but important gaps remain, especially as we move from knowledge to action. Critical information needs addressed by the Panel's research and monitoring recommendations include the following:

- **Understanding the status of and trends in ocean acidification in Washington's marine waters.** At present the general chemical processes of ocean acidification are well understood. However, the status of acidification in local waters is not well characterized, nor are many of the complex physical, chemical, and biological interactions that influence the progression and extent of ocean acidification in Washington's marine waters.
- **Quantifying the relative contribution of different acidifying factors to ocean acidification in Washington's marine waters.** A combination of global and local factors contributes to ocean acidification, but the degree to which each factor contributes to the problem will vary by location and season. We need to quantify the various natural and human-caused acidifying influences so we can understand their relative significance at different locations and time scales. This knowledge will help managers identify where particular response strategies are likely to be most effective. For example, those places where nutrients are found to have a significant influence on acidification may respond better to efforts that reduce nutrient inputs, while other actions may be more effective in sites less affected by nutrients.

- **Understanding the biological responses of local species to ocean acidification and associated stressors.** Changes in Washington's marine environments will have implications for the organisms that live within them. Understanding these implications requires knowing how local marine species and ecosystems are likely to respond to ocean acidification. However, because biological responses to ocean acidification are highly variable, those responses cannot be reliably predicted without experimental studies. Laboratory and field investigations of local marine species will be needed to build scientific understanding and guide effective responses to changing water chemistry. Scientists worldwide are rapidly building a database of experimental observations, but relatively few studies have been performed on Washington's species.
- **Developing capabilities to identify real-time corrosive seawater conditions, as well as short-term forecasts and long-term predictions of global and local acidification effects.** The real-time and short-term forecasts systems can, for example, alert hatchery managers to the approach of threatening waters.

While the Panel recognizes the importance of shellfish in Washington, research on ocean acidification must extend beyond shellfish resources to the broader ecosystem. The ability to model ocean chemistry, species and ecosystem responses, and socioeconomic impacts will serve a variety of functions ranging from helping to guide effective management, restoration, and protection of natural resources to estimating the costs and benefits of response vis-à-vis economic, cultural, and ecological values. Establishing the ocean acidification science coordination team called for in Action 9.1.2 will accelerate our scientific efforts in these areas. The ultimate goal is to provide sound guidance for making important societal choices.

Strategy 7.1 – Understand the status and trends of ocean acidification in Washington's marine waters.

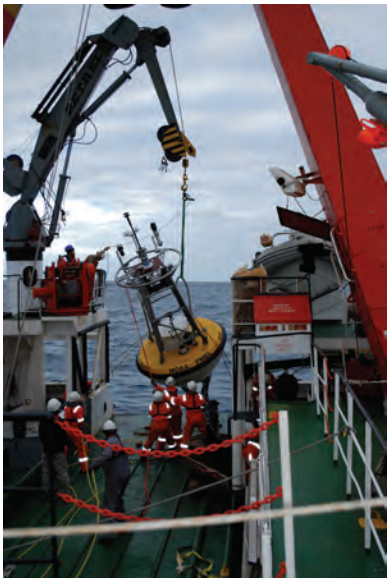
Washington's coast encompasses a great variety of environments, including high-energy sandy shores; rocky bluffs and sea stacks; deep, dark fjords; and sunlit, shallow bays. Some sites are relatively remote from human influence, while others support intensive use by humans. Strategic surveys of these diverse waters and selection of a few sites for a sustained closer look will help identify controlling processes and important linkages, which will differ from place to place and season to season. This information can then be used to develop the capability to predict how the ecosystem will respond to the large-scale chemical and physical changes associated with ocean acidification.

The West Coast is expected to experience increasingly corrosive conditions.

Action 7.1.1: Establish an expanded and sustained ocean acidification monitoring network to measure trends in local ocean acidification conditions and related biological responses. **[KEA]**

We need sustained, expanded monitoring to provide data at a spatial and temporal resolution sufficient to understand the current status of ocean acidification in Washington waters and to discern trends across space and over time. Failure to measure these effects through appropriate monitoring would effectively "blindfold" Washington's marine-based industries, coastal communities, and resource managers. Establishing an ocean acidification monitoring network will improve adaptation options for business and industry, and provide information essential for adaptive management of marine ecosystems and the living resources they support.

Despite this need, no sustained ocean acidification monitoring network for Washington's coastal waters currently exists. It is essential that the improved network provide data at high enough resolution to reveal the current status of acidification in Washington waters and to discern trends across space and over time. Additionally, a subset of monitoring stations must be established to simultaneously collect the physical, chemical, and biological data required to evaluate the relationships between changing chemical conditions and biological responses among organisms living in the water and on the sea-bed. The stations should be chosen strategically to include existing sites at shellfish hatcheries and other shellfish growing areas, sites with existing biological time series, and areas representative of ecological and oceanographic processes within Washington waters.



NOAA scientists deploy a monitoring buoy.

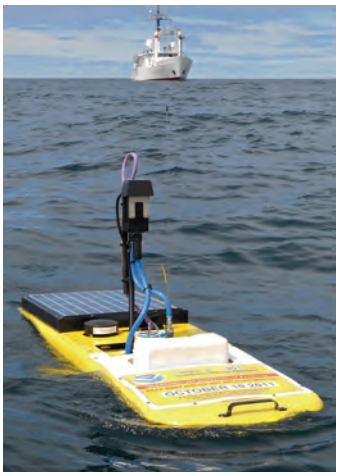
Shellfish growers, under the aegis of the Pacific Coast Shellfish Growers Association, have established several sites for collecting such data. The scientific information obtained at these sites is essential not only for shellfish growing operations, but also to increase our scientific understanding of biological responses to marine chemistry. These sites need to be sustained and expanded. See Action 6.2.1 for details on how maintaining these stations as part of the ocean acidification monitoring network supports adaptation.

Data collection. The expanded network proposed here would allow for collecting measurements at appropriately high spatial and temporal resolution to detect trends in local conditions and to characterize:

- The pH and carbon chemistry of marine waters in Washington;
- The variation in chemistry over space and time;
- How the watershed, ocean, and atmosphere affect status and trends;
- How biological processes affect chemical conditions; and
- How biological responses to water chemistry vary over space and time.

The expanded network should use a variety of platforms, including ship surveys, moorings, fixed stations, and gliders that build upon existing assets and capabilities. Maps of existing assets and proposed sites are shown in Chapter 7 of *Scientific Summary of Ocean Acidification in Washington State Marine Waters*.[33] These assets include:

- Cruises, moorings, fixed stations, and gliders on the Washington coast;
- Cruises, moorings, and fixed stations in Puget Sound and the Strait of Juan de Fuca;
- Cruises and fixed stations in the Columbia River Estuary; and
- Cruises, moorings, and fixed stations in shallow estuaries.



NOAA's autonomous Wave Glider harnesses wave energy to propel itself across the ocean surface. Solar-powered monitoring equipment collects information about pH and carbon chemistry

Data quality provisions and training. Ensuring reliable data quality is critical. All chemical monitoring should be conducted according to the European Program on Ocean Acidification (EPOCA)'s *Guide to Best Practices for Ocean Acidification Research and Data Reporting*[34] and *Guide to Best Practices for Ocean CO_2 Measurements*.[35] New best-practice standards should be developed as needed for specific applications. Training programs for accuracy and repeatability in data collection will need to be developed and implemented for scientific and technical personnel participating in the monitoring network.

33 Available at **https://fortress.wa.gov/ecy/publications/SummaryPages/1201016.html**

34 Riebesell, U., Fabry, V. J., Hansson, L., & Gattuso, J.-P. (Eds.). (2010). *Guide to Best Practices for Ocean Acidification Research and Data Reporting*. Luxembourg: Publications Office of the European Union.

35 Dickson, A. G., C.L. Sabine, and J.R. Christian (eds.) (2007): Guide to Best Practices for Ocean CO_2 Measurements. *PICES Special Publication 3*, 191 pp.

Preserving data and public access to data. Once obtained, data must be archived and made accessible to the public, and the quality of the data must be defined. This need can be met in part by leveraging the existing data delivery system of NANOOS (Northwest Association of Networked Ocean Observing Systems; **http://www.nanoos.org**), which currently delivers ocean acidification data streams from NOAA, the University of Washington, the Pacific Coast Shellfish Growers Association, tribes, and others. Further investment is required to provide all of the capabilities listed above.

Action 7.1.2: Develop predictive relationships for indicators of ocean acidification (pH and aragonite saturation state).

Carbon system parameters (dissolved inorganic carbon or DIC; total alkalinity or TA; CO_2 partial pressure or pCO_2) and pH in estuarine and coastal waters are influenced by water properties such as temperature, salinity, and dissolved oxygen. These latter parameters are relatively easy to measure, whereas carbon system parameters and pH are relatively difficult and expensive to measure. Developing and refining predictive relationships between these parameters will allow us to use mooring and glider data to provide high-resolution time series data on carbon system parameters, pH, and aragonite saturation state. These will also provide an independent test of the accuracy of the pCO_2 and pH sensors.

Action 7.1.3: Support development of new technologies for monitoring ocean acidification.

Advances are needed in the monitoring of both ocean acidification and biological response to acidification. Current technologies for monitoring acidification are limited and best used when large volumes of seawater are available for immediate analysis. Sensors with high precision and accuracy are available for only two carbon parameters, pCO_2 and pH, and are expensive. Developing new or improved technologies for measuring pH, dissolved inorganic carbon, total alkalinity, and pCO_2 will improve capability to monitor ocean acidification.

For example, developing of a new technique for carbon system parameter analysis that can use small volumes of seawater would allow the Washington Department of Ecology's seaplane sampling protocol to include monitoring for ocean acidification, and development of an improved pH sensor with better accuracy and precision would improve data collection from moorings and gliders.

The need to develop new technologies was recently highlighted when the X Prize Foundation announced sponsorship of an Ocean Health X Prize. The competition seeks improvements in the speed, depth tolerance, and lifespan of autonomous pH sensors used to measure the global effects of carbon dioxide on the world's oceans.

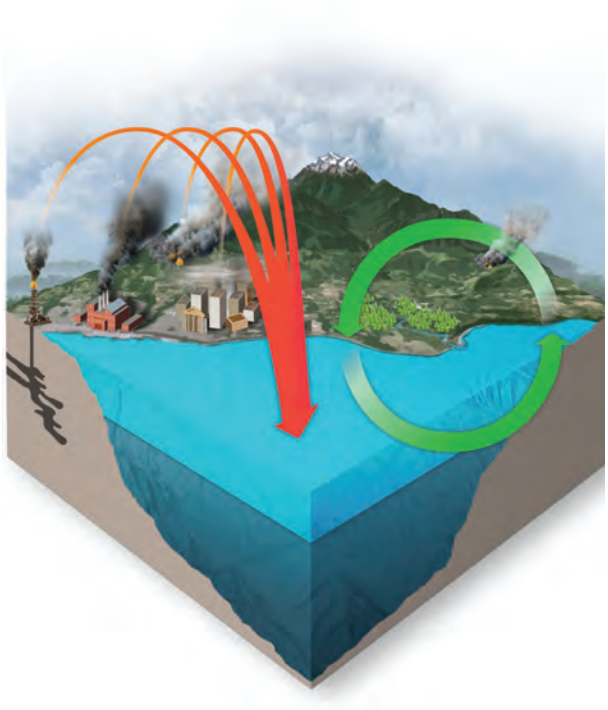
Monitoring plankton in conjunction with chemical parameters can reveal correlations between changing ocean chemistry and changes in plankton communities, a primary impact of ocean acidification. The current monitoring method—collecting plankton with nets for manual identification—is costly, inefficient, and unsuitable for continuous biological monitoring. Computer image recognition systems developed for facial recognition and medical research could be applied to this task

Strategy 7.2 - Identify factors that contribute to ocean acidification in Washington waters, and estimate the relative contribution of each.

In addition to atmospheric carbon dioxide, other processes that generate carbon dioxide in the water column can contribute significantly to acidification in coastal waters. The combined effects of various processes (nutrient inputs, respiration, nitrogen oxide and sulfur oxide inputs, local atmospheric sources of carbon dioxide, and dissolved and particulate carbon loadings) are now acknowledged to be important drivers of ocean acidification, particularly when the land nearby is highly populated or agriculturally developed. We need to develop quantitative estimates of how much these individual processes contribute to ocean acidification in Washington waters.

Action 7.2.1: Quantify key natural and human-influenced processes that contribute to acidification based on estimates of sources, sinks, and transfer rates for carbon and nitrogen. **[KEA]**

Inorganic dissolved and particulate forms of carbon can directly affect the pH and carbonate chemistry of marine waters. Nitrogen can indirectly affect pH through enhancement of primary production followed by sinking, decomposition, and respiration of organic material. We need to develop a quantitative understanding of how the various forms of carbon and nitrogen enter and flow through the marine system (i.e., a budget) in order to describe and rank regional acidification drivers and develop strategies for mitigation.



Schematic depicting how carbon enters and flows through the marine system.

To accomplish this, data from observations and numerical models should first be used to construct budgets for carbon and nitrogen in coastal and inland waters that capture physical and biological processes significant to the area of application. Second, we need to quantify key processes, including the human contribution, to acidification in Washington waters. Specific attention should be given to quantifying the role of nutrient loading from human sources, nitrogen oxide and sulfur oxide from atmospheric and riverine sources, local atmospheric inputs of carbon dioxide, and dissolved and particulate carbon loadings. These processes should be investigated on a spatial scale that is relevant to regulation and should cover seasonal variation.

This is a major undertaking that will benefit from sequencing activities. Data are needed to construct budgets for carbon and nitrogen. Some data already exist, but new data will be required for input to models. Existing models will require further development and refinement, and new models may be needed, as noted in Action 7.2.2. Funding will be required to fully implement this research, and the time frame for implementation depends on the level of funding.

Action 7.2.2: Develop new models or refine existing models to include biogeochemical processes of importance to ocean acidification.

Modeling is a powerful tool that can be used to understand areas of sensitivity and to evaluate the strength of underlying mechanisms. Regionally, existing modeling capacity exists for circulation, conventional water quality, and plankton processes. None of these models incorporates carbon chemistry parameters and pH, limiting their utility for evaluating ocean acidification impacts.

Strategy 7.3 - Characterize biological responses of local species to ocean acidification and associated stressors.

Forage fish, which feed on zooplankton and are preyed upon by larger fish, are an important link in marine food webs.

Washington's shellfish resources—both wild and commercial—rely on and are embedded in productive marine ecosystems. To sustain shellfish resources and the aggregate services and values provided by Washington's marine ecosystems, diverse elements of the ecosystem must be investigated for their response to ocean acidification. These include groups such as zooplankton and forage fish that maintain critical linkages in marine food webs, benthic species that create important structural habitat, and seagrasses and seaweeds that provide both structural habitat and potential mitigating effects.

Action 7.3.1: Determine the associations between water and sediment chemistry and shellfish production in hatcheries and in the natural environment. **[KEA]**

A more complete understanding of the effects of seawater chemistry on the survival and growth of shellfish in hatcheries will assist growers in making modifications to culture practices to sustain productivity. Outside of hatcheries, on shellfish farms and in natural settings, both seawater chemistry and sediment chemistry will influence shellfish viability, and the effects of both need investigation. Field studies that document the status of and trends in farmed and natural shellfish populations and pair these data with chemistry measurements are required to detect changes in productivity, population size, and status over time. Determining species- and strain-specific responses to ocean acidification will help guide management strategies for wild populations and culture practices in hatcheries and on farms. Identification of robust populations, stocks, or strains and favorable local environments can guide efforts to promote sustainability.

Oyster larvae, like the hatchery-raised specimens pictured here, are extremely sensitive to fluctuations in seawater chemistry.

Action 7.3.2: Conduct laboratory studies to assess the direct effects of ocean acidification, alone and in combination with other stressors, on local species and ecosystems. [KEA]

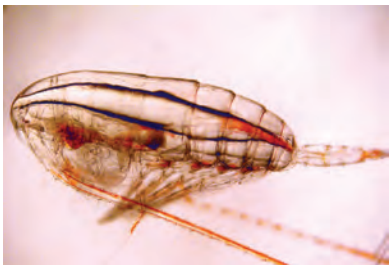
Laboratory studies to assess the direct effects of pH and carbon system parameters on survival, growth, and reproduction of species living in Washington waters will improve our understanding of species-specific responses to ocean acidification and the capacity of species to adapt. This information, in turn, will help guide management strategies, policy actions, and human adaptation.

It is also important to understand how interacting stressors affect how organisms respond to ocean acidification. Acidification co-occurs with other environmental changes, and organisms will respond to the full suite of stressors to which they are exposed. Laboratory studies can be used to determine biological responses of multiple species to ocean acidification in combination with other factors, such as temperature, nutritional status, and oxygen stress. Research priorities include species of ecological, economic, or cultural significance, species of conservation concern, and species that can influence human health and well-being (for example, species that cause harmful algal blooms). Variation in response to ocean acidification *within* species will help estimate the genetic potential of that species to adapt to ocean acidification.

Action 7.3.3: Conduct field studies to characterize the effects of ocean acidification, alone and in combination with other stressors, on local species.

Field studies conducted in natural environments allow organisms to be studied in the context of their natural habitats, building on and refining insights gained from laboratory studies. A practical approach to field studies could initially focus on species that, based on laboratory studies, are sensitive to pH, those that are expected to be affected strongly via indirect effects of ocean acidification, and those (such as zooplankton) that form critical linkages in food webs.

Experimental and observational field studies can identify ecological processes affected by pH and carbon chemistry, including indirect effects of ocean acidification that are mediated through food web interactions, other ecological interactions, or habitat transformation. Field-based research conducted across the diversity of Washington's marine habitat types will help determine habitat-specific responses and estimate habitat-specific risk and vulnerability



Many important marine species, such as copepods (pictured here) will likely be directly or indirectly affected by ocean acidification

Strategy 7.4 – Build capabilities for short-term forecasting and long-term prediction of ocean acidification.

Operational models are required to understand hourly, weekly, and seasonal changes in seawater carbon chemistry. These models will provide information on timescales that are useful to hatchery managers for directing operations and to scientists for determining longer-term trends. The long-term prediction of ocean acidification status and biological response will help guide planning, restoration decisions, and adaptation strategies.

Action 7.4.1: Establish the ability to make short-term forecasts of corrosive conditions for application to shellfish hatcheries, growing areas, and other areas of concern. **[KEA]**

Better forecasting of corrosive conditions on the scale of days to weeks will help hatcheries and growers minimize the effects of ocean acidification on shellfish production. Forecasts could also be of use to managers of wild shellfish populations. A first step to improving forecasting capability is developing and using real-time monitoring and model-based values of atmospheric and oceanographic variables to forecast risk of corrosive conditions. A second step is providing online access to a suite of variables that forecast corrosive conditions, so that shellfish growers and managers can track conditions in real time.

Action 7.4.2: Enhance the ability to predict the long-term future status of carbon chemistry and pH in Washington waters and create models to project ecological responses to predicted ocean acidification conditions.

Numerical modeling allows for the development of future scenarios over time-scales of decades to centuries, which will help inform human response and adaptation to ocean acidification, including decisions regarding protection and restoration of resources and habitats. Numerical models can be developed to predict long-term changes in carbon chemistry and pH in Washington's marine waters. These models can be refined, and predictive skill can be improved as new data become available. A longer-term goal is to apply our understanding of biological responses to ocean acidification to coupled physical-biological models to project ecological responses to future ocean conditions.

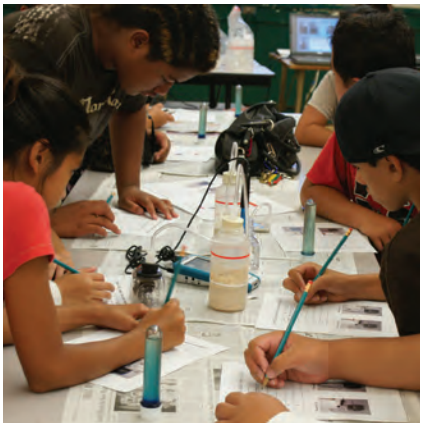
Action 7.4.3: Enhance the ability to model the response of organisms and populations to ocean acidification to improve our understanding of biological responses.

It is not feasible to perform empirical studies on all species, life stages, and biological processes. Models allow scientists to better understand and characterize the mechanisms that determine how species and populations respond to carbon chemistry and pH, thereby improving the ability to generalize across species, life history stages, and processes. Model outputs can save time and expense by informing the design of second-generation manipulative experiments and field studies.

A first step is to build models that characterize the mechanisms behind biological responses to ocean acidification at the individual- and population-levels. These models then can be refined as new data from experimental studies become available. Ultimately, model outputs can be used to inform the design of laboratory and field studies, detect critically vulnerable biological processes and organisms, and guide human response and adaptation.

8

Inform, Educate and Engage Stakeholders, the Public, and Decision Makers in Addressing Ocean Acidification



Increasing understanding of ocean acidification and its consequences among policy leaders, interested organizations, and the public is essential to implementing appropriate response measures.

RECENT NATIONAL SURVEYS SHOW LOW public awareness of ocean acidification; only seven percent of Americans say they have heard of it. Educating elected officials, resource managers, business and industry leaders, and the general public (including youth) is a key prerequisite to action.

To improve understanding of ocean acidification and engage stakeholders in solutions, information needs to emphasize four key points. First, information must communicate that ocean acidification is affecting jobs and resources here in Washington State. Second, materials must emphasize the importance of the ocean to our health, coastal economies, and well-being. Third, the information must explain the rapid change in ocean chemistry, the consequences of this change for marine life in Washington, and what it means for individuals and Washingtonians collectively. Finally, the information needs to show the value of early action and highlight the role that Washingtonians can play in developing and implementing solutions.

Strategy 8.1 – Share information showing that ocean acidification is a real and recognized problem in Washington State.

Action 8.1.1: Identify key findings for use by the Governor, Panel members, and others who will act as ambassadors on ocean acidification. **[KEA]**

The Governor, members of the State Legislature, our Congressional delegation, and others (including Panel members) will need to work for change at regional, national, and international levels to address the effects of ocean acidification. This will require clear and ongoing communication about the problem of ocean acidification, what is at stake, and what needs to be done to reduce the scale and severity of the problem.

Washington State is the country's top provider of farmed shellfish.

Communication materials designed for elected officials, decision-makers, business leaders, and the public should: 1) make a clear connection between ocean acidification and human activities that contribute to it, 2) emphasize the importance of Washington's shellfish and marine resources to the regional and national economy and to the environment, and 3) share examples of local people who are being affected by ocean acidification. These materials should be developed in a variety of formats, distributed widely through digital and mainstream public media, and updated as needed to reflect new research.

Action 8.1.2: Increase understanding of ocean acidification among key stakeholders, target audiences, and local communities to help implement the Panel's recommendations. **[KEA]**

Two early actions to help identify the current level of understanding of ocean acidification include conducting a public opinion survey and conducting outreach with key stakeholders (e.g., representatives from businesses, agriculture, utilities, cities, and counties) who are either affected by or in a strong position to help implement the Panel's recommendations.

Materials on ocean acidification should be gathered, developed, and disseminated based on the findings of both the survey and the outreach meetings. A variety of communication channels (e.g., website, videos, newsletter, FAQs, Facebook, and Twitter) should be targeted to various audiences, building on existing education and outreach networks. Specific media tools should highlight resources that are at risk and showcase local people who are taking positive action to protect marine resources that they value or depend on. Toolkits will identify tangible actions we can take at individual and community levels to make a difference. Where needed, customized communication tools or campaigns for specific actions should be developed for different audiences or geographic areas.

Action 8.1.3: Build a network of engaged shellfish growers, tribes, and fishermen to share information on ocean acidification with key groups.

The goal of this action is to ensure the effectiveness of outreach efforts by developing a network of speakers who can speak personally about the current and potential impacts of ocean acidification and the actions needed to address it. Outreach to target audiences would be conducted by trained and knowledgeable speakers drawn from groups affected by acidification, such as shellfish growers and fisherman, with the goal of moving the conversation about ocean acidification from an abstract problem to a more solution-oriented dialogue about a real issue affecting people and industries today. Specific examples of outreach could include: 1) sharing adaptation practices that allow the production of shellfish in acidifying waters; 2) educating major seafood buyers and retailers about how they can help tackle acidification; 3) engaging seafood restaurants and vendors in outreach efforts to consumers and other interested groups; and 4) informing local communities and business groups about the resources likely to be affected by ocean acidification and how they can help reduce its impacts.

Fishermen are an example of a stakeholder group that can help raise awareness about ocean acidification.

Action 8.1.4: Provide a forum for agricultural, business, and other stakeholders to engage with coastal resource users and managers in developing and implementing solutions. **[KEA]**

Landowners discuss shoreline processes with geologist Jim Johannessen in Snohomish County.

Agriculture, businesses, and coastal communities play an important role in helping to maintain shellfish production by reducing nutrient pollution to the marine system. Early and ongoing communication between the stakeholders and state and local government, natural resource managers, and resource users is essential to supporting this role and reducing nutrient inputs from agriculture to Puget Sound

and the Pacific Coast. Roundtable discussions should be organized to discuss the ramifications of ocean acidification and to allow for regular dialogue and problem solving. This dialogue could be initiated as part of the Puget Sound Partnership's agriculture strategy workshops or other Partnership activities.

Strategy 8.2 – Increase ocean acidification literacy.

Learning about ocean acidification can occur in formal and informal educational settings. Interest in environmental teaching and learning has increased dramatically in the past decade. Environmental issues are complex and multidisciplinary, involving knowledge from many fields. Similarly, teaching and learning about ocean acidification will need to connect traditional disciplines (for example, chemistry, biology, and social studies) with emerging scientific issues (for example, increased carbon dioxide emissions, climate change, and projected environmental and ecological threats).

Action 8.2.1: Develop, adapt, and use curricula on ocean acidification in K-12 schools and higher education.

Introducing ocean acidification in a curriculum must be done in an innovative and engaging manner to be effective. For example, a curriculum should allow for hands-on experimentation and exploration activities to make the topic understandable and engaging.

The Center for Microbial Oceanography in Hawaii has developed science kits for teaching ocean acidification

Existing ocean acidification materials for K-12 schools need to be reviewed, adapted if necessary, and/or developed from other sources and disseminated to educators. Materials need to be closely aligned with the *National Next Generation Science and Common Core Standards* for each subject and grade so they can be used as supplements to the required curriculum. An online ocean acidification database should be created to help teachers select

materials specifically suited to their subject and grade level. Use in private schools and home school networks should also be encouraged. At the university level, ocean acidification should be integrated into existing programs.

To facilitate the incorporation of ocean acidification into curricula, networking events and summits for educators should be hosted by various educational and non-profit organizations to share and exchange information, experiences, and best practices. Fostering school and community partnerships would be a major step toward advancing this action. A small grant program administered through Washington Sea Grant or the Northwest Aquatic and Marine Educators could provide funding to support low-cost, big-impact school and community partnerships ($100,000 per year).

Action 8.2.2: Leverage existing education and outreach networks to disseminate key information and build support for priority actions.

Leveraging existing outreach networks across Washington to educate people about ocean acidification is an efficient way to raise broader awareness and literacy. These groups are already active at the community level and have untapped expertise and knowledge of local conditions, which can be used to support implementation of local actions. Existing networks should be provided with information to connect ocean acidification to local issues, showcase solutions that are available locally, and demonstrate how members of the public can participate by collecting and recording data and helping to implement actions.

Action 8.2.3: Share knowledge on ocean acidification causes, consequences, and responses at state and regional symposiums, conferences, workshops, and other events.

Special effort should be made to bring the issue of ocean acidification to a range of venues and stakeholders. Washington ocean acidification issues should be included in conferences, workshops, and other related events to inform participants about the state of ocean acidification science and adaptation efforts in Washington. Existing opportunities include the biannual Salish Sea Ecosystem Conference, the annual Pacific Northwest Climate Science Conference, and annual meetings of cities, counties, and business associations.

A periodic conference or symposium on ocean acidification science and adaptation in Washington should also be organized to continue the state's leadership role on this issue. This conference should bring together a range of constituencies, including elected officials, scientists, tribes, resource managers, educators, the seafood industry, farmers, non-profit organizations, restaurant and food service groups, senior citizens, and others from within and beyond Washington. Conference report(s) should be produced and distributed.

9

Maintain a Sustainable and Coordinated Focus on Ocean Acidification

The state's effectiveness in addressing the impacts of changing ocean chemistry on our marine ecosystems and coastal communities requires sustained leadership and support by the Governor and other state officials and a coordinating mechanism to facilitate implementation of the Panel's recommendations.

EFFECTIVE RESPONSES TO THE RISK of ocean acidification require ongoing collaboration, well-coordinated strategies and actions, and efficient implementation of the recommended actions. The problem should not be divorced from other ocean and coastal actions and priorities, however. The Panel's recommendations touch on a wide range of ocean and coastal activities involving multiple entities. Coordinating actions related to ocean health and coastal resources should reduce redundancies and inefficiencies. Also, coordination and collaboration among scientists, decision makers, and various interests should help the state address the problem.

Strategy 9.1 - Ensure effective and efficient multi-agency coordination and collaboration.

Action 9.1.1: Charge, by gubernatorial action, a person in the Governor's Office or an existing or new organization to coordinate implementation of the Panel's recommendations with other ocean and coastal actions. **[KEA]**

The Governor's endorsement of the Panel's recommendations and designation of a person or entity (new or existing) to function as a central coordinator are critical to advancing the efforts by state, tribal, federal, and local agencies to strategically study and monitor the status of ocean health, including impacts from acidification; managing and protecting marine waters, coastal communities and local economies; and engaging the public and various stakeholders in developing and supporting ocean and coastal solutions. A coordinating person or entity should:

- Have the full support of the Governor;
- clearly be seen as supporting the Governor's ocean policies;

- have the full support of and partnership with existing state agencies that have ocean responsibilities; and
- have adequate resources to carry out the responsibilities outlined below.

The coordinating person or entity must be responsible for:

1. Advancing the Panel's recommendations; seeking and leveraging funding at the state, national, and regional levels; and leading future refinement and updates of the recommendations. This will require coordinating numerous activities aimed at protecting and restoring marine waters among state agencies, federal agencies, tribal governments, and the private sector (including businesses and nongovernmental organizations).
2. Working with the treaty tribes of Washington, the National Ocean Council, the West Coast Governors Alliance on Ocean Health, the Pacific Coast Collaborative, and other organizations at the national and regional levels to advance several of the Panel's recommendations where relevant.
3. Helping bridge ocean-acidification-related science and policy needs by supporting continued productive interaction between scientists and policymakers. The person or entity should support the creation of a science coordination team as suggested in Action 9.1.2.
4. Coordinating with key federal agencies, including NOAA, EPA, and the Department of the Interior. This can be done by developing memoranda of understanding or other mechanisms among partners to support data sharing, collaboration, and leveraging and prioritizing of funds.
5. Providing and ensuring accountability in implementing the Panel's recommendations and ensuring effective expenditure of funds necessary to achieve the desired outcome.
6. Building public awareness, support, and engagement to advance public understanding of the importance of a healthy ocean and of the most pressing challenges facing the ocean, and to engage citizens and various stakeholders in the development of and support for actions and solutions needed to address those challenges.

As previously stated, the responsibilities outlined above can be accomplished by a person in the Governor's Office, an existing entity, or a new entity. We have reviewed two governance structures that could be seen as models for Washington, the National Ocean Council and the California Ocean Protection Council. The functions of both councils are carried out within a comprehensive and collaborative framework to facilitate cohesive actions across multiple agencies and ensure broad participation by stakeholders and other

interests that can provide local perspectives and solutions. The two examples provided are summarized in Appendix 3. In addition, we have described current activities at the state, local, regional, and national levels that need to be coordinated by the new entity.

Action 9.1.2: Create an ocean acidification science coordination team to promote scientific collaboration across agencies and organizations and connect ocean acidification science to adaptation and policy needs. **[KEA]**

The recent Pacific Northwest oyster seed crisis and the effective science-driven response to boost hatchery production offer a good illustration of a well-coordinated collaboration among scientists, managers, and shellfish growers. This collaboration has also produced significant scientific discoveries. The Panel strongly encourages establishing a science coordination team for acidification-related research in Washington. This team could promote collaboration across agencies and organizations, reduce redundancies, and improve efficiencies in implementing the recommended actions. It can also help connect science to adaptation and policy needs by, among other services, evaluating and field testing new management approaches. The team should consist of diverse entities, including representatives from federal, state, tribal, and local governments, universities, industries, non-governmental organizations, and others.

10

Conclusions

Ocean acidification presents a significant challenge to Washington's marine environment and economy but it is a challenge that can—and must—be met.

THE WASHINGTON STATE BLUE RIBBON Panel on Ocean Acidification brought together many of the region's top scientists, industry representatives, public opinion leaders, conservation community representatives, and state, local, federal, and tribal policymakers to address the causes and consequences of ocean acidification. *Ocean Acidification: From Knowledge to Action – Washington State's Strategic Response* identifies 42 actions, including 18 "Key Early Actions," that will increase Washington's capacity to understand, reduce, remediate, and where possible adapt to the consequences of ocean acidification. Actions include the following broad categories of activity

1. Reduce carbon dioxide emissions, the most significant driver of ocean acidification. Emissions of carbon dioxide must be significantly reduced or the actions recommended here will be far less effective in addressing the risk of ocean acidification.
2. Reduce local land-based contributions to ocean acidification. Reducing inputs of nutrients and organic carbon from local sources will decrease acidity in marine waters impacted by these local sources, thereby decreasing the effects of ocean acidification on local marine species in those areas.
3. Increase our ability to adapt to and remediate the impacts of ocean acidification. We must implement a wide range of measures to adapt to and remediate the impacts of ocean acidification in order to limit future losses of shellfish production, jobs, local businesses, and natural resources.
4. Invest in Washington's ability to monitor ocean acidification and investigate its effects. Investing in ocean acidification research and monitoring will provide the necessary scientific support for developing, implementing, and evaluating effective responses to ocean acidification.

5. Inform, educate, and engage stakeholders, decision makers, and the public in addressing ocean acidification. Public engagement and dialogue on ocean acidification and how to address it are essential to building support for effective implementation of the recommended actions.

6. Maintain a sustainable and coordinated focus on ocean acidification. Addressing the impacts of changing ocean chemistry on marine ecosystems and coastal communities requires sustained leadership and support from the Governor and other state officials, and a coordinating mechanism to facilitate the implementation of the Panel's recommendations.

Washington has many resources to leverage in implementing the Panel's recommended actions. We have world-class scientists in our region who are already working in a variety of applicable fields. Additionally, we have an important source of understanding in the traditional and historical knowledge of tribes. State agencies, businesses, and tribes are taking the lead in developing innovative approaches that reduce carbon dioxide and nutrient runoff in Washington, and state and tribal leaders are actively engaging with our federal partners to find solutions to ocean acidification. We also have a shellfish industry committed to protecting native ecosystems as well as farmed resources, and a diverse nonprofit community ready to work with the public on understanding the problem of ocean acidification and how we might solve it. Finally, we have citizens who value the rich and diverse ecosystems in Washington's marine waters.

Public investment by the state is needed, as are public-private partnerships that promote innovative solutions to acidification. However, the state also needs the support of our federal partners in these efforts. Just as Washington's shellfish industry is the canary in the coal mine for a broader range of species in Washington's marine waters, so too is Washington state's experience the canary in the coal mine for our collective ability to address this problem where the impacts are being felt most acutely.

It is time to harness these resources and start tackling the many challenges to come. It is time to act.

Appendices

The following appendices are included in this report:

Appendix 1. *Summary Table of Panel Recommendations*

Appendix 2. *Blue Ribbon Panel Recommendation Workgroups*

Appendix 3. *Examples of Ocean Governance Structures*

Appendix 4. *Acronyms and Glossary*

Appendix 5. *Photo Credits*

Appendix 6. *Representative Norma Smith Letter to the Co-chairs*

The following additional appendices are available at **http://www.ecy.wa.gov/water/marine/oceanacidification.html**

Appendix 7. *Scientific Summary of Ocean Acidification in Washington State Marine Waters*

Appendix 8. *Washington State's Legal and Policy Options for Combating Ocean Acidification in State Waters*

Appendix 9. *Sweetening the Waters: The Feasibility and Efficacy of Strategies to Protect Washington's Marine Resources from Ocean Acidification*

Appendix 1. Summary Table of Panel Recommendations

The following table provides general estimates of the implementation timeframe and costs for each recommendation as well as suggested implementation leads and partners. Please note the following:

- Implementation timeframe is a qualitative indicator of how soon the action can be implemented. It does not mean the action will necessarily be completed in that timeframe. The timeframe categories used by the Panel are: near term (< 5 years), medium term (5-10 years), and long term (10+ years).
- Estimated cost ranges are: low (less than $250,000), moderate (between $250,000 and $1 million), and high (greater than $1 million)
- Proposed implementation leads and partners are provisional and subject to change. Identification as implementation lead or co-lead implies the necessary expertise to perform the specified function exists but does not imply that funding for the activity exists.

Action No.	Action Title *[KEA = Key Early Action]*	Implementation Timeframe	Estimated Cost	Implementation Lead(s)	Implementation Partner(s)
Chapter 4 - Reduce Emissions of Carbon Dioxide					
Strategy 4.1 – Take action to reduce global, national, and local emissions of carbon dioxide.					
Action 4.1.1	Work with international, national, and regional partners to advocate for a comprehensive strategy to reduce carbon dioxide emissions. ***[KEA]***	Near term to Medium term	Low	Governor's Office, in coordination with Washington Department of Ecology	Washington state agencies, federal agencies, Congressional delegation, state legislature, Tribes, and west coast states
Action 4.1.2	Implement additional actions recommended by the Climate Action Team where such actions would reduce acidification of Washington's marine waters.	Near term for the review. Medium term for implementation	Low (for review); implementation cost will vary	Washington State Department of Ecology (for the review)	Governor's office, Washington state agencies, local governments, and public and private entities
Action 4.1.3	Review data to determine if there is a causal relationship between local air emissions and local marine water acidity. If the data confirms such a relationship, take actions to reduce local air emissions that contribute to acidification.	Near term to Medium term	Moderate to High	Washington State Department of Ecology	Other state agencies, local governments, and public and private interests
Action 4.1.4	Enlist key leaders and policymakers to act as ambassadors advocating for carbon dioxide emissions reductions and protection of Washington's marine resources from acidification. ***[KEA]***	Near term	Low	Governor's Office	Members of the Panel, Washington state agencies, federal agencies, Tribes, universities, Congressional delegation, and State Legislature

Action No.	Action Title *[KEA = Key Early Action]*	Implementation Timeframe	Estimated Cost	Implementation Lead(s)	Implementation Partner(s)
Chapter 5 - Reduce Local Land-Based Contributions to Ocean Acidification					
Strategy 5.1 – Strengthen and augment existing pollutant reduction actions to reduce nutrients and organic carbon.					
Action 5.1.1	Implement effective nutrient and organic carbon reduction programs in locations where these pollutants are causing or contributing to multiple water quality problems. ***[KEA]***	Near term to Medium term	High	Washington State Department of Ecology in collaboration with the Washington Departments of Agriculture and Health, Puget Sound Partnership, and the Washington State Conservation Commission	U.S. EPA, USDA Natural Resources Conservation Service, conservation districts, Tribes, cities, counties and land owners
Action 5.1.2	Support and reinforce current planning efforts and programs that address the impacts of nutrients and organic carbon. ***[KEA]***	Near term	Unknown	Washington State Departments of Commerce and Ecology, and coastal counties	Washington State Conservation Commission, Washington State Departments of Agriculture and Health, landowners and operators; watershed groups, conservation districts; and other public and private organizations
Action 5.1.3	Assess the need for water quality criteria relevant to ocean acidification.	Near term to Medium term	Unknown	U.S. EPA	NOAA, University of Washington, Washington State Department of Ecology, and interested Tribes, with input from industry, environmental groups, and the public

Action No.	Action Title *[KEA = Key Early Action]*	Implementation Timeframe	Estimated Cost	Implementation Lead(s)	Implementation Partner(s)
Action 5.1.4	Adopt legislation that will allow sewer connections in rural areas to limit nutrients entering marine waters where it is determined to be necessary based on water quality impacts.	Near term	Low	Washington State Legislature	Legislative workgroup: representatives from Washington State Departments of Health, Commerce, and Ecology, Puget Sound Partnership, and coastal county health departments
Strategy 5.2 – Impose stringent controls to reduce and limit nutrients and organic carbon from sources that are contributing significantly to acidification of Washington's marine waters.					
Action 5.2.1	If it is scientifically determined that nutrients from small and large on-site sewage systems are contributing to local acidification, require the installation of advanced treatment technologies.	Near term to Medium term	High	Washington State Department of Health	U.S. EPA, Washington State Departments of Ecology and Commerce, Puget Sound Partnership, coastal counties and wastewater utilities
Action 5.2.2	If determined necessary based on scientific data, reduce nutrient loading and organic carbon from point source discharges.	Medium term	High	Point source dischargers	Washington State Departments of Health, Commerce and Ecology; coastal county health departments; public and private utilities; industrial dischargers, and local interests
Chapter 6 – Increase Our Ability to Adapt to and Remediate the Impacts of Ocean Acidification					
Strategy 6.1 – Remediate seawater chemistry.					
Action 6.1.1	Develop vegetation-based systems of remediation for us in uplands and in shellfish areas. ***[KEA]***	Near term	High	Washington State Department of Natural Resources	Pacific Coast Shellfish Growers Association, Pacific Shellfish Institute, interested Tribes, Commercial shellfish farmers, University of Washington, and Puget Sound Restoration Fund

Action No.	Action Title *[KEA = Key Early Action]*	Implementation Timeframe	Estimated Cost	Implementation Lead(s)	Implementation Partner(s)
Action 6.1.2	Maintain and expand shellfish production to support healthy marine waters.	Near term	Low	Pacific Shellfish Institute and Puget Sound Restoration Fund	Shellfish growers, and Washington Department of Fish and Wildlife
Action 6.1.3	Use shells in targeted marine areas to remediate impacts of local acidification on shellfish.	Near term	low	Pacific Shellfish Institute and Puget Sound Restoration Fund	Shellfish growers, restaurants serving shellfish, shellfish processing facilities, and trucking/recycling companies
Strategy 6.2 – Increase the capacity of resource managers and the shellfish industry to adapt to ocean acidification.					
Action 6.2.1	Ensure continued water quality monitoring at the six existing shellfish hatcheries and rearing areas to enable real-time management of hatcheries under changing pH conditions. ***[KEA]***	Near term	Moderate	University of Washington	Oregon State University, Tribes, California Current Acidification Network (C-CAN), Pacific Shellfish Institute, and Pacific Coast Shellfish Growers Association and hatchery owners and operators
Action 6.2.2	Expand the deployment of instruments and chemical monitoring to post-hatchery shellfish facilities and farms.	Near term	Moderate	Pacific Shellfish Institute, University of Washington and Pacific Coast Shellfish Growers Association	Washington State Departments of Natural Resources and Ecology, Washington Department of Fish and Wildlife, shellfish growers and others
Action 6.2.3	Investigate and develop commercial-scale water treatment methods or hatchery designs to protect larvae from corrosive seawater. ***[KEA]***	Near term	Moderate	University of Washington in collaboration with the NOAA Northwest Fisheries Science Center and the Washington State Department of Ecology	HatcheryOregon State University (COAS, Hatfield Marine Science Center), Whiskey Creek Shellfish Hatchery, Taylor Shellfish Hatchery, Pacific Shellfish Institute, and Lummi Indian Nation Hatchery
Action 6.2.4	Develop and incorporate acidification indicators and thresholds to guide adaptive action for species and places.	Medium term	Low	University of Washington	Many scientific, agencies, Nongovernmental organizations, and industry experts would be helpful, both in developing thresholds and incorporating them into planning processes

Action No.	Action Title *[KEA = Key Early Action]*	Implementation Timeframe	Estimated Cost	Implementation Lead(s)	Implementation Partner(s)
Strategy 6.3 – Enhance resilience of native and cultivated shellfish populations and ecosystems on which they depend.					
Action 6.3.1	Preserve Washington's existing native seagrass and kelp populations and where possible restore these populations.	Near term to Long term	Medium	Washington State Department of Natural Resources	Washington Department of Fish and Wildlife, Puget Sound Partnership, Recreation and Conservation Office, Northwest Indian Fisheries Commission, conservation NGOs and the Pacific Shellfish Institute
Action 6.3.2	Identify, protect and manage refuges for organisms vulnerable to ocean acidification and other stressors. ***[KEA]***	Near term to Medium term	High	Washington Department of Natural Resources in collaboration with the Washington Department of Fish and Wildlife	Individual Tribes, Puget Sound Restoration Fund, Washington State Department of Natural Resources, Washington State Recreation and Conservation Office, Northwest Straits Commission, Marine Resource Committees, Pacific Shellfish Institute, commercial shellfish growers, The Nature Conservancy, National Fish & Wildlife Foundation, USDA Natural Resource Conservation Service, U.S. Navy, and private tideland owners
Action 6.3.3	Support restoration and conservation of native oysters.	Medium term	High	Washington Department of Fish and Wildlife	Puget Sound Partnership, Puget Sound Restoration Fund, Tribes, shellfish growers
Action 6.3.4	Use conservation hatchery techniques to maintain the genetic diversity of native shellfish species.	Near term	Moderate	NOAA's Research Stations	Oregon State University Molluscan Broodstock Program, USDA Agricultural Research Service, Washington Department of Fish and Wildlife, Washington State Department of Natural Resources and Tribes
Action 6.3.5	Investigate genetic mechanisms and selective breeding approaches for acidification tolerance in shellfish and other vulnerable marine species.			University of Washington	NOAA, Washington State Department of Natural Resources, and shellfish growers

Action No.	Action Title *[KEA = Key Early Action]*	Implementation Timeframe	Estimated Cost	Implementation Lead(s)	Implementation Partner(s)
Chapter 7 – Invest in Washington's Ability to Monitor and Investigate the Causes and Effects of Ocean Acidification					
Strategy 7.1 – Understand the status and trends of ocean acidification in Washington's marine waters.					
Action 7.1.1	Establish an expanded and sustained ocean acidification monitoring network to measure trends in local acidification conditions and related biological responses. ***[KEA]***	Many parts of this action can be operational within one year; some parts are operational currently but need sustained support, other parts can be enhanced to include ocean acidification monitoring.	Depends upon scale. Moderate to High	University of Washington in collaboration with NOAA	NANOOS, Washington Department of Ecology, Tribes, Pacific Coast Shellfish Growers Association, Taylor Shellfish Farms, Lummi Hatchery, Puget Sound Ecosystem Monitoring Program, California Current Ocean Acidification Network, Inter-governmental Policy Council, Center for Coastal Margin Observation and Prediction, Olympic Coast National Marine Sanctuary, Washington Sea Grant, Puget Sound Partnership, Marine Science Centers (including Seattle Aquarium), Olympic Regional Harmful Algal Blooms Partnership and others
Action 7.1.2	Develop predictive relationships for indicators of ocean acidification (pH and aragonite saturation state).	Near term	Low	University of Washington and NOAA	Pacific Coast Shellfish Growers Association, Pacific Shellfish Institute, Washington Department of Ecology, Tribes and others
Action 7.1.3	Support development of new technologies for monitoring ocean acidification.	Near term	Low	University of Washington and NOAA	Washington Department of Ecology, Scripps Institution of Oceanography, X Prize Foundation, Suquamish Tribe, and others

Action No.	Action Title *[KEA = Key Early Action]*	Implementation Timeframe	Estimated Cost	Implementation Lead(s)	Implementation Partner(s)
Strategy 7.2 – Identify factors that contribute to ocean acidification in Washington's marine waters, and estimate the relative contribution of each.					
Action 7.2.1	Quantify key natural and human-influenced processes that contribute to acidification based on estimates of sources, sinks, and transfer rates for carbon and nitrogen. ***[KEA]***	Medium term	Moderate to High	Washington Department of Ecology and University of Washington	EPA, NOAA, Joint Institute for the Study of the Atmosphere and Ocean, and Pacific Northwest National Laboratory
Action 7.2.2	Develop new models or refine existing models to include biogeochemical processes of importance to ocean acidification.	Near term	Moderate	University of Washington and Washington Department of Ecology	NOAA, U.S. EPA, Joint Institute for the Study of the Atmosphere and Ocean, and Pacific Northwest National Laboratory
Strategy 7.3 – Characterize biological responses of local species to ocean acidification and associated stressors.					
Action 7.3.1	Determine the association between water and sediment chemistry and shellfish production in hatcheries and in the natural environment. ***[KEA]***	Near term	Dependent on number of species and environments studied.	Washington Department of Natural Resources in collaboration with the University of Washington and Washington Department of Ecology	Pacific Shellfish Institute, Taylor Shellfish Farms, Lummi Nation Shellfish Hatchery, Whiskey Creek Shellfish Hatchery, Puget Sound Restoration Fund, Tribes, Intergovernmental Policy Council, Puget Sound Ecosystem Monitoring, Washington Department of Fish and Wildlife, NOAA Ocean Acidification Program and Washington Sea Grant
Action 7.3.2	Conduct laboratory studies to assess the direct effects of ocean acidification, alone and in combination with other stressors, on local species and ecosystems. ***[KEA]***	Near term	Will scale with the number of species tested.	University of Washington	NOAA, Pacific Coast Shellfish Growers Association, Tribes, Inter-governmental Policy Council, Washington Department of Fish and Wildlife, and others
Action 7.3.3	Conduct field studies to characterize the effects of ocean acidification, alone and in combination with other stressors, on local species.	Near term	Dependent on number of species tested	University of Washington	NOAA, Pacific Coast Shellfish Growers Association, Tribes, Washington Department of Fish and Wildlife, and and others

Action No.	Action Title *[KEA = Key Early Action]*	Implementation Timeframe	Estimated Cost	Implementation Lead(s)	Implementation Partner(s)
Strategy 7.4 – Build capabilities for short-term forecasting and long-term prediction of ocean acidification.					
Action 7.4.1	Establish the ability to make short-term forecasts of corrosive conditions for application to shellfish hatcheries, growing areas, and other areas of concern. ***[KEA]***	Near term	Moderate	University of Washington	Washington Department of Ecology, Pacific Northwest National Laboratory, shellfish growers, Pacific Coast Shellfish Growers Association, Tribes, and Joint Institute for the Study of the Atmosphere, and NOAA
Action 7.4.2	Enhance the ability to predict the long-term future status of carbon chemistry and pH in Washington's waters and create models to project ecological responses to predicted ocean acidification conditions.	Near term	Moderate	University of Washington and NOAA	Joint Institute for the Study of the Atmosphere, Washington Department of Ecology, Pacific Northwest National Laboratory, shellfish growers, Pacific Shellfish Institute, Tribes, Washington Sea Grant, and others
Action 7.4.3	Enhance the ability to model the response of organisms and populations to ocean acidification to improve our understanding of biological responses.	Near term	Moderate	University of Washington and NOAA	Washington Department of Ecology, Pacific Northwest National Laboratory, Tribes, and Washington Sea Grant
Chapter 8 – Inform, Educate and Engage Stakeholders, the Public, and Decision Makers in Addressing Ocean Acidification					
Strategy 8.1 – Share information showing that ocean acidification is a real and recognized problem in Washington State.					
Action 8.1.1	Identify key findings for use by the Governor, Panel members, and others who will act as ambassadors on ocean acidification. ***[KEA]***	Near term	Low	Washington Department of Ecology	Blue Ribbon Panel members, NOAA, University of Washington, Ocean Conservancy, Washington Sea Grant, Puget Sound Partnership, Washington State Department of Natural Resources, Washington Department of Fish and Wildlife, and Health, and others
Action 8.1.2	Increase understanding of ocean acidification among key stakeholders, target audiences, and local communities to help implement the Panel's recommendations. ***[KEA]***	Near term	Low	Washington Department of Ecology in collaboration with the University of Washington and Washington Sea Grant	Washington Department of Fish and Wildlife, NOAA, Pacific Coast Shellfish Growers Association, Sustainable Fisheries Partnership, and Northwest Straits Commission

Action No.	Action Title *[KEA = Key Early Action]*	Implementation Timeframe	Estimated Cost	Implementation Lead(s)	Implementation Partner(s)
Action 8.1.3	Build a network of engaged shellfish growers, Tribes, and fishermen to share information on ocean acidification with key groups.	Near term	Low	Washington Sea Grant	Northwest Straits Commission, shellfish growers, Tribes, and fishermen
Action 8.1.4	Provide a forum for agricultural, business, and other stakeholders to engage with coastal resource users and managers in developing and implementing solutions. ***[KEA]***	Near term	Low	Puget Sound Partnership	U.S. Natural Resource Conservation Service, agricultural community, Washington State Departments of Ecology and Agriculture, Washington Department Fish and Wildlife, Washington State Conservation Commission, local governments and Tribes
Strategy 8.2 – Increase ocean acidification literacy.					
Action 8.2.1	Develop, adapt and use curricula on ocean acidification in K-12 schools and higher education.	Near term	Low to Moderate	Washington Office of Superintendent of Public Instruction, universities and colleges	Local school districts, aquariums, Marine Science Centers, agencies, teachers' associations, green school advocacy organizations, and other organizations
Action 8.2.2	Leverage existing education and outreach networks to disseminate key information and build support for priority actions.	Near term	Low	Washington State Department of Ecology	Washington Sea Grant, Northwest Straits Commission, Puget Sound ECONet members, Marine Resource Committees, tribal education networks, business-based educational networks, and others
Action 8.2.3	Share knowledge on ocean acidification causes, consequences, and responses at state and regional symposiums, conferences, workshops, and other events.	Near term	Low	University of Washington	NOAA, Washington State agencies, Tribes, shellfish industry, members of the Blue Ribbon Panel, and other interested parties

Action No.	Action Title *[KEA = Key Early Action]*	Implementation Timeframe	Estimated Cost	Implementation Lead(s)	Implementation Partner(s)
Chapter 9 – Maintain a Sustainable and Coordinated Focus on Ocean Acidification					
Strategy 9.1 – Ensure effective and efficient multi-agency coordination and collaboration.					
Action 9.1.1	Charge, by gubernatorial action, a person in the Governor's Office or an existing or new organization to coordinate implementation of the Panel's recommendations with other ocean and coastal actions. ***[KEA]***	Near term	Low	Governor's Office	Washington state agencies, Commissioner of Public Lands, and University of Washington
Action 9.1.2	Create an ocean acidification science coordination team to promote scientific collaboration across agencies and organizations and connect ocean acidification science to policy and program needs. ***[KEA]***	Near term	Low	Washington Department of Ecology and the University of Washington College of the Environment	NOAA, U.S. EPA, Washington Department of Fish and Wildlife, Washington State Department of Natural Resources, Puget Sound Partnership, Tribes and others

Appendix 2. Blue Ribbon Panel Workgroup

The recommendations included in this report were developed by workgroups consisting primarily of Blue Ribbon Panel members. In some cases, individuals with subject matter expertise were asked to participate in the workgroups. All recommendations were submitted for review by the Panel as a whole.

Research and Monitoring

Co-Leads: Richard Feely, NOAA Pacific Marine Environmental Laboratory and Jan Newton, Univ. of Washington Applied Physics Laboratory; Staff support: Meg Chadsey, Washington Sea Grant

Members:

- Simone Alin, NOAA Pacific Marine Environmental Laboratory
- Shallin Busch, NOAA Northwest Fisheries Science Center
- Benoit Eudeline, Taylor Shellfish
- Carolyn Friedman, Univ. of Washington School of Aquatic and Fishery Sciences
- Jennifer Hagen, Quileute Tribe
- Terrie Klinger, Univ. of Washington School of Marine and Environmental Affairs
- Christopher Krembs, Washington Department of Ecology
- Mindy Roberts, Washington Department of Ecology
- Jennifer Ruesink, Univ. of Washington, Department of Biology
- George Waldbusser, Oregon State University College of Ocean and Atmospheric Sciences
- Paul Williams, Suquamish Tribe

Reducing Local Sources

Lead: Ted Sturdevant, Washington Department of Ecology; Staff support: Hedia Adelsman, Washington Department of Ecology

Members:

- Jackie Ford, Washington Dept. of Agriculture
- Melissa Gildersleeve, Washington Department of Ecology
- Kate Kelly, US EPA Region 10
- Ryan Kelly, Stanford University Center for Ocean Solutions
- Sara Kendall, Weyerhaeuser Company
- Kevin Morse, The Nature Conservancy
- Jan Newton, Univ. of Washington Applied Physics Laboratory
- Mindy Roberts, Washington Department of Ecology
- Eric Scigliano, Journalist and Researcher
- Brad Warren, Sustainable Fisheries Partnership

Adaptation and Remediation

Co-Leads: Brad Warren, Sustainable Fisheries Partnership, and Bill Dewey, Taylor Shellfish; Staff support: Meg Chadsey, Washington Sea Grant

Members:

- Alan Barton, Whiskey Creek Hatchery
- Sue Cudd, Whiskey Creek Hatchery
- Joth Davis, Taylor Shellfish
- Paul Dye, The Nature Conservancy
- Benoit Eudeline, Taylor Shellfish
- Carolyn Friedman, Univ. of Washington School of Aquatic and Fishery Sciences
- Peter Goldmark, Washington Department of Natural Resources
- Betsy Peabody, Pacific Shellfish Institute and the Puget Sound Restoration Fund
- George Waldbusser, Oregon State University, College of Ocean and Atmospheric Sciences

Public Education and Outreach

Lead: Betsy Peabody, Puget Sound Restoration Fund and Pacific Shellfish Institute; Staff Support: Meg Chadsey, Washington Sea Grant

Members:

- Hedia Adelsman, Washington Department of Ecology
- Bill Dewey, Taylor Shellfish
- Lisa Dropkin, Edge Research
- Richard A. Feely, NOAA Pacific Marine Environmental Laboratory
- Sandy Howard, Washington Department of Ecology
- Teri King, Washington Sea Grant
- Tony Myer, Northwest Indian Fisheries Commission
- Marco Pinchot, Taylor Shellfish
- Julia Roberson, Ocean Conservancy
- Bill Ruckelshaus, Madrona Venture Group and Panel Co-chair
- Jennifer Ruesink, University of Washington Department of Biology
- Amy Sprenger, NANOOS Education/ Outreach Coordinator
- Eric Swenson, Sustainable Fisheries Partnership
- Paul Williams, Suquamish Tribe

Post-Panel Institutional Needs to Support Implementation

Lead: Bill Ruckelshaus, Madrona Venture Group and Panel Co-chair; Staff support: Hedia Adelsman, Washington Department of Ecology

Members:

- Chris Davis, The Nature Conservancy
- Bill Dewey, Taylor Shellfish
- Richard A. Feely, NOAA Pacific Marine Environmental Laboratory
- Jay Manning, Cascadia Law Group and Panel Co-Chair
- Jan Newton, Univ. of Washington Applied Physics Laboratory
- Keith Phillips, Washington Department of Ecology
- Ted Sturdevant, Washington Department of Ecology
- Brad Warren, Sustainable Fisheries Partnership
- Terry Williams, The Tulalip Tribes of Washington

Appendix 3: Examples of Ocean Governance Structures

There are two governance structures that could be viewed as models for the post-Panel coordinating entity recommended for Washington State in Chapter 9. Both structures promote the need for a comprehensive and collaborative framework to facilitate cohesive actions across multiple agencies, and ensure broad participation by stakeholders and various interests to provide local perspectives and solutions to marine issues.

National Ocean Council. President Obama, on July 10, 2010, issued an Executive Order adopting a national policy to ensure that the ocean, coasts and Great Lakes are healthy and resilient. The Executive Order adopted the recommendations of the Interagency Ocean Policy Task Force. The national policy promotes a comprehensive and collaborative framework that facilitates cohesive actions across the federal governments, as well as participation of state, tribal and local authorities, regional governance structures, nongovernmental organizations, the public, and the private sector.

The Executive Order also directed executive agencies to implement the recommendations under the guidance of a National Ocean Council. The National Ocean Council consists of senior members of executive departments, agencies and offices. Independent agencies are invited to participate. The Chair of the Council for the Environment and the Director of the Office of Science and Technologies co-chairs the national Ocean Council.

The functions of the National Ocean Council include: providing appropriate direction to ensure the executive departments', and agencies' decisions and actions affecting the ocean and coasts will be guided by the principles and priority objectives set forth in the recommendations. The agencies represented on the national Ocean Council are required to take action as necessary to implement the policy, participate in the process for coastal and marine spatial planning. Each executive agency is required to prepare and make publicly available an annual report describing the actions taken by the agency in the previous year.

The National Ocean Council created a Governance Coordinating Committee that consists of officials from state, tribal and local governments. The committee can establish subcommittees to provide for greater collaboration and diversity. Regional Advisory Committees are also established to provide regional information and advice to promote the national policy.

California Ocean Protection Council. The Council was created pursuant to the **California Ocean Protection Act** (COPA), which was signed into law in 2004. The Council is responsible for:

- Coordinating activities of ocean-related state agencies to improve the effectiveness of state efforts to protect ocean resources within existing fiscal limitations
- Establishing policies to coordinate the collection and sharing of scientific data related to coast and ocean resources between agencies
- Identifying and recommending to the Legislature changes in law
- Identifying and recommending changes in federal law and policy to the Governor and Legislature

The Council consists of the Secretary of the Resources Agency, the Secretary for Environmental Protection, the Chair of the State Lands Commission, and two members of the public appointed by the Governor. One Member of the Senate, appointed by the Senate Committee on Rules, and one Member of the Assembly, appointed by the Speaker of the Assembly, meets with the council as nonvoting, ex officio members.

A steering committee composed of senior representatives of state departments, boards, and commissions with ocean and coastal protection responsibilities plays an essential role in advancing multi-agency approaches to addressing key ocean and coastal resource management issues that span California state agencies. These include: climate change adaptation, marine spatial planning, implementing marine protected areas, and improving coastal water quality.

The Council established a Scientific Advisory Board to identify, develop, and prioritize subjects and questions for research or investigation, and review and evaluate results of research or investigations to provide information for the council's activities. The OPC works jointly with government agencies responsible for ocean and coastal resource management, and is supported by several federal and state partner organizations (e.g., NOAA, EPA, USGS, etc.) The Council has an active ocean awareness program. The Council evaluation of its leadership and accomplishments is done by an independent entity.

Key Organizations and Activities Related to Ocean Acidification

A governance structure in Washington State must not be redundant. It must, instead, focus on coordinating activities and improving the effectiveness of efforts of numerous agencies and organizations at the state, regional and national levels focused on protection and conservation of coastal and ocean ecosystems and the economies they support.

At the state and local levels:

- Departments of Ecology, Fish and Wildlife, Natural resources, Agriculture, and Health, Conservation Commission, counties and cities and several other local organizations have responsibilities for the use and protection of our coastal and marine resources. Several of the agencies and organizations are involved in activities listed below.
- Puget Sound Partnership – It has three basic charges: define an Action Agenda that identifies work needed to protect and restore Puget Sound to health by 2020; determine accountability for achieving results; and promote public awareness and communication.
- State Ocean Caucus – An interagency team convened by the Governor to assess existing marine resources and to focus on marine spatial planning and associated activities within the outer coast. The Caucus formed a multi-stakeholder group —Washington Coast Marine Advisory Council—to advice on ocean policy and provide local perspectives and solutions to marine resource issues and projects.
- Coastal Marine Resource Committees – county-based, volunteer groups composed of tribal co-managers, fishermen, citizens, scientists, recreational, economic, and conservation interests, and government agencies—that promote local marine resource management and stewardship in five southern Puget Sound counties and five coastal counties.
- Northwest Straits Commission – Its members represent each of the Marine Resources Committees, tribes, the Puget Sound Partnership and additional appointments by the Governor. It provides guidance and offers resources to the marine resources committees (MRCs), with the goal of mobilizing science to focus on key priorities and coordinating regional priorities for the ecosystem.

At the regional level:

- West Coast Governors Alliance on Ocean Health – formed by Governors' offices of Schwarzenegger, Kulongoski, and Gregoire to advance effort of regional collaboration on ocean health, and in part as a response to national recommendations for the formation of regional partnership written in the US Ocean Commission and the Pew Ocean Commission. Many of the action recommendations from WCGA align with the National Ocean Policy. The West Coast Governors' Alliance is the Regional Ocean Partnership for the West Coast as such it has access to a NOAA annual funding source.
- NANOOS – Northwest Association of Networked Ocean Observing Systems overarching purpose is to address needs for ocean data and information for the Pacific Northwest.

At the federal level:

- National Ocean Council (Micah McCarty and Senator Kevin Ranker participate in Governance Coordination Committee). The Council released a draft national ocean policy implementation plan in early 2012 that includes nine priority actions, including one to strengthen resiliency and adaptation to climate change and ocean acidification.
- Ocean Acidification Interagency Working Group (Dick Feely a member) - The interagency was created pursuant to the Federal Ocean Acidification Research and Monitoring Act of 2009. The group meets regularly to coordinate ocean acidification activities across the Federal government to fulfill the goals of the FOARAM Act. NOAA chairs the group which includes representatives from the National Oceanic and Atmospheric Administration (NOAA), National Science Foundation (NSF), Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE), Department of State (DOS), Environmental Protection Agency (EPA), National Aeronautics and Space Administration (NASA), U.S. Fish and Wildlife Service (USFWS), U.S. Geological Survey (USGS), and the U.S. Navy.

Appendix 4. Acronyms and Glossary

Acronyms

CO_2	Carbon Dioxide
COAS	The College of Oceanic and Atmospheric Sciences (at Oregon State Univ.)
EPA	U.S. Environmental Protection Agency
EPOCA	European Program on Ocean Acidification
KEA	Key Early Actions
LOTT	Lacey, Olympia, Tumwater, and Thurston County
NANOOS	Northwest Association of Networked Ocean Observing Systems
NGO	Non-governmental organization
NOAA	National Oceanic Atmospheric Administration
USDA	U.S. Dept. of Agriculture

Glossary of Terms

(terms in italics are defined in the glossary)

Term	*Definition*
Acidity	The concentration of hydrogen ion in a solution
Acidification drivers	Processes, such as atmospheric emission of carbon dioxide, respiration, or upwelling, which favor the expression of ocean acidification.
Algae	Photosynthetic organisms that occur in a diversity of habitats, including coastal and marine habitats. Algae vary from small, single-celled forms to complex multicellular forms and include *phytoplankton* and seaweeds.

Algal blooms	A rapid increase or accumulation in the population of algae (typically microalgae) in an aquatic system, stimulated by an excess of nutrients.
Alkalinity	A measure of the maximum capacity of an aqueous solution to neutralize acids. See also *Total Alkalinity*.
Aragonite	A specific crystalline form of the mineral *calcium carbonate*, found in mollusc shells (particularly the *larval* & juvenile forms) and coral skeletons. It dissolves more readily than *calcite*.
Benthic	In contact with the ocean bottom.
Bivalves	Belong to the taxonomic class Bivalvia; they are bivalved (two shells) molluscs that include mussels, clams, scallops, and oysters.
Budget (for carbon & nitrogen)	A quantitative understanding of how the various forms of carbon and nitrogen enter and flow through the marine system
Calcifier	An organism that uses *calcium carbonate* to form shells, skeletons, carapaces, and other stiff structures. Calcifiers include organisms such as molluscs, corals, *foraminifera*, echinoderms (e.g. sea stars, sea urchins), *crustaceans* and some *algae*.
Calcite	A specific crystalline form of the mineral *calcium carbonate*, found in the shells of many marine organisms, including adult oysters; it dissolves less readily than *aragonite*.
Calcium carbonate	A mineral composed of calcium (Ca^{2+}) and *carbonate ions* (CO_3^{2}). Marine *calcifiers* incorporate specific crystalline forms of $CaCO_3$ (e.g., calcite and aragonite) into their shells, skeletons, and other hard body parts.

Carbonate ion

An essential building block used (in combination with calcium ions) by many marine animals and some plants to form *calcium carbonate*, which the organisms then use to build their shells, skeletons, or other hard parts.

Carbonate chemistry

The inorganic dissolved chemical species of the carbon system in a solution, including dissolved carbon dioxide ($CO_{2(aqueous)}$), carbonic acid (HCO_3^-), bicarbonate (H_2CO_3), and *carbonate ion* (CO_3^{2-}).

Carbonate saturation state

A metric used to provide an estimate of how readily *calcite* and *aragonite* dissolve in seawater.

Carbon system parameters

The individual inorganic carbon species that are dissolved in seawater, including dissolved carbon dioxide ($CO_{2(aqueous)}$), carbonic acid (HCO_3^-), bicarbonate (H_2CO_3), and *carbonate ion* (CO_3^{2-}).

Copepod

A term from the Greek meaning "oar-feet", applied to a group of small aquatic *crustaceans*, which include both *planktonic* and *benthic* species.

Crustaceans

A large subgroup of arthropods, which includes animals as crabs, shrimp, copepods, krill and barnacles. Some crustaceans incorporate amorphous calcium carbonate into their exoskeletons.

Dissolved inorganic carbon

The sum of the concentrations inorganic carbon species in a solution. These include carbon dioxide (CO_2), carbonic acid (HCO_3^-), bicarbonate ion (H_2CO_3), and *carbonate ion* (CO_3^{2-}).

Dissolved oxygen

The concentration of molecular oxygen (O_2) dissolved in water. Measured as a concentration using a variety of units, including mg/L and µmol/kg (micromoles/kg).

Dissolved organic carbon A broad classification organic molecules, smaller 0.45 micrometers, resulting from the decomposition of dead *organic material*. Dissolved organic carbon in marine and freshwater systems is one of the greatest cycled reservoirs of organic matter on Earth.

Estuary A partially enclosed coastal body of water with one or more rivers or streams flowing into it, and with a free connection to the open sea.

Forage fish Small fishes that are preyed upon by larger predators.

Food web A food web describes feeding connections in an ecological community.

Foraminifera A large phylum of amoeboid *protists* that are among the most common marine *plankton* species. Foraminifera typically produce a test, or shell, made of *calcium carbonate*.

Genetic diversity Refers to the total number of genetic characteristics in the genetic makeup of a species.

Gliders Tools for collecting data on the internal structure of the ocean for assimilation into ocean models. A glider is a long-endurance autonomous underwater vehicle (AUV) used to collect ocean data; it surfaces periodically to transmit data via satellite. Gliders are capable of collecting numerous types of data, including currents, temperature, salinity, pressure, and optics.

Hypoxia Depletion of *dissolved oxygen* to a point that is detrimental to aquatic organisms. Hypoxia is typically defined as 2 mg/L or 65 µmol/kg oxygen concentration.

Keystone species A species upon which other species of a community depend, whose removal leads to reduced species diversity within the community.

Larvae	An immature stage that is quite different from the adult form.
Macroalgae	Macroscopic, multicellular *algae*; commonly referred to as seaweeds.
Microbes	Microscopic organisms that can exist as single cells or form multicellular assemblages. Microbes (or microorganisms) are very diverse; they include bacteria, fungi, *algae* and protozoa.
Nitrogen/Sulfur Oxides (NO_X/SO_X)	Generic terms for nitric oxide (NO), nitrogen dioxide (NO_2), and sulfur oxides, such as SO_2. NO_X and SO_X are produced by the processing and burning of fossil fuels, and are major contributors to acid deposition (rain).
Nonpoint sources	Refers to both water and air pollution from diffuse sources, such as stormwater runoff and car exhaust.
Numerical model	A computational (mathematical) model used to describe the behavior of a system over time.
Ocean acidification	Reductions in the pH of seawater due primarily to the uptake of carbon dioxide from the atmosphere by the ocean but can also be caused by other chemical additions or subtractions from the ocean.
Operational model	A model that assimilates real-time data to continuously calculate current conditions.
Organic material	Materials derived from living organisms.
Oxidation	Oxidation is the loss of electrons by a molecule, atom, or ion, through transfer to another molecule, atom or ion. It is an important part of many biological processes, including cellular *respiration*. For example, microbes obtain metabolic energy by oxidizing *organic carbon*, such as glucose ($C_6H_{12}O_6$), to CO_2.
Particulate carbon	Organic material that is too large to pass through a 0.45 micrometer filter, derived from dead organic matter such as plants.

pCO_2	The partial pressure of CO_2. Quantitative units used to describe pCO_2 are microatmospheres (µatm), which are a unit of atmospheric pressure equal to one millionth of 1 atmosphere (atm).
pH	The term used to describe *acidity*; pH is the negative log of the hydrogen ion (H^+) concentration in an aqueous solution. Neutral pH is 7.0. Solutions with pH values less than 7.0 are "acidic," and those with pH values greater than 7.0 are "basic."
Phenotypic plasticity	The capacity of organisms with the same genetic make-up to exhibit different traits (behavior, morphology, physiology) across environmental conditions.
Photosynthesis	The process used by plants and other organisms to capture the sun's energy to split water into hydrogen and oxygen. The hydrogen is combined with carbon dioxide (absorbed from air or water) to form sugar (glucose); oxygen is produced as a waste product.
Phytoplankton	*Photosynthesizing* microorganisms that inhabit the upper sunlit layer of the ocean. In terms of numbers, the most important groups of phytoplankton include the diatoms, cyanobacteria and dinoflagellates.
Phytoremediation	Using vegetation to reduce nutrient-laden runoff or remove carbon dioxide from seawater. Phytoremediation can help protect vulnerable young shellfish from acidification and *hypoxia*.
Plankton	Organisms that drift in the ocean.
Point source	A single, identifiable source of pollution, such as a wastewater treatment plant.
ppm	"Parts per million"; often used to describe the relative abundance of dissolved chemical species or gases in water.

Primary productivity The production of organic compounds from atmospheric or aqueous CO_2 though *photosynthesis*. Primary productivity sustains the *food web*. In marine ecosystems, *phytoplankton* are the major primary producers.

Protists A diverse group of eukaryotic (nucleus-containing) microorganisms, characterized by relatively simple organization (unicellular, or unspecialized multicellular).

Pteropod A term from the Greek meaning "wing-foot", applied to two separate *taxonomic* groups of small free-swimming sea snails.

Recruitment Recruitment occurs when juvenile organisms survive to be added to a population (e.g., the dispersal, settlement to the bottom, and metamorphosis of planktonic larvae into new adult organisms).

Remediation The removal of pollution from the environment. See also *phytoremediation*.

Resilience The ability of a population or system to bounce back to a condition similar to its previous state following disturbance or change, with core functions and processes intact.

Respiration The metabolic conversion by organisms of nutrients into biochemical energy. Biological respiration consumes oxygen and generates CO_2 as a waste product.

Saturation state The saturation state (Ω) of a mineral is a measure of the thermodynamic potential of that mineral to form or to dissolve. At Ω values greater than 1.0, precipitation of the mineral is thermodynamically stable.

Total alkalinity	The amount of alkali, or base, in a solution, often expressed in terms of pH. In seawater, most of the *alkalinity* is contributed by carbonate species, but other common basic components such as borate, nitrate, and dissolved ammonia contribute.
Time series data	A sequence of observations that are ordered in time.
Tolerance	The ability of an organism to survive in certain physical conditions.
Upwelling	A process whereby winds push surface ocean waters away from shore, causing an upward movement of deeper waters to replace the surface water. The upwelled water is typically colder, saltier, and nutrient- and CO_2-rich but oxygen poor. Along the U.S. west coast, the upwelling season is during summer months.
Zooplankton	Heterotrophic plankton, which feed on bacterioplankton, *phytoplankton*, and other zooplankton. Individual zooplankton are usually too small to be seen with the naked eye, but some, such as jellyfish, are large.

Appendix 5. Photo Credits

Photo credits listed in the order in which images appear in the report chapters

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Olympia oyster seed (6 months old)—Benjamin Drummond / bdsjs.com

Seastar and seaweed—Minette Layne

Summary

Cover page (left to right): shucked Pacific oyster—Dan Bennett; Goose Point oyster harvest—Benjamin Drummond / bdsjs.com ; starfish—Bern Harrison

Box S-1: geoducks—U.S. Dept. of Agriculture; sea urchin—Chris Wilson

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Lummi family digging clams—Northwest Indian Fisheries Commission

Chapter 1

Cover page (left to right): Pacific oysters—Pacific Coast Shellfish Growers Association; historic image of tribal shellfishers, and Upper Skagit Tribe oyster longlines—Northwest Indian Fisheries Commission

Nisbet Oyster Company— Benjamin Drummond / bdsjs.com

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Chapter 2

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Calcifiers: blue mussels—WA Dept. of Fish and Wildlife; juvenile king crab on pink calcifying algae, and Dungeness crab—Vlad Karpinkskiy

Pteropod—Russ Hopcroft, University of Alaska Fairbanks, NOAA

Figure 4: Elizabeth Brunner and George Waldbusser, Oregon State University

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Chapter 3

Cover page (left to right): Mount Baker—Northwest Straits Initiative; eelgrass—WA Dept. of Natural Resources; Seattle skyline—NOAA Pacific Marine Environmental Laboratory

Chapter 4

Cover page (left to right): cyclist boarding light rail, and DC fast charging station—WA State Dept. of Transportation; Seattle traffic—Oran Viriyincy

2012 Washington State Energy Strategy—WA Dept. of Commerce (http://www.commerce.wa.gov/Programs/Energy/Office/Topics/Pages/EnergyStrategy.aspx)

Smokestack—http://www.TheEnvironmentalBlog.org/

Capitol Building—WA Dept. of Ecology

Chapter 5

Cover page (left to right): shellfish bed—Benjamin Drummond / bdsjs.com ; Wastewater treatment plant—Suvi Geary; sewer outlet— Kate Boicourt; algae bloom—WA Dept. of Ecology

Nisqually National Wildlife Refuge—Russ McMillan

Beach community—Hugh Shipman

Wastewater treatment plant—Suvi Geary

Assessing water quality, Totten Inlet—Pacific Coast Shellfish Growers Assn.

Aerial image Vashon Island, WA—John Brew

Installing stormwater runoff system—WA State Dept. of Transportation

Chapter 6

Cover page (left to right): Olympia oysters and bull kelp—Puget Sound Restoration Fund; oyster shells—Bryan Penttila and Richard Wilson; hatchery algae tanks—Benjamin Drummond / bdsjs.com

Oyster longlines with seaweed—Bill Dewey

Oyster shucking plant—Jon Rowley

Monitoring at shellfish farm—Pacific Coast Shellfish Growers Assn.

Eelgrass—WA Dept. of Natural Resources

Bull Kelp bed—Hugh Shipman

Olympia oyster restoration project—Puget Sound Restoration Fund

Juvenile pinto abalone—Puget Sound Restoration Fund

Chapter 7

Cover page (left to right): Puget Sound cast (water sampling)—NOAA Pacific Marine Environmental Laboratory; Hoodsport mooring—Wendi Reuf; monitoring coastal biodiversity (NaGISA Project)—Northwest Indian Fisheries Commission; seaplane water sampling—WA Dept. of Ecology

Washington coastline—Russ McMillan

ARC buoy deployment—NOAA Pacific Marine Environmental Laboratory

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Oyster larvae—Benjamin Drummond / bdsjs.com

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Chapter 8

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Market-ready oysters—Benjamin Drummond / bdsjs.com

Crab fisherman and managers—Northwest Indian Fisheries Commission

Landowners with geologist—Tracie Johannessen, Northwest Straits Foundation

Ocean acidification in the classroom—Center for Microbial Oceanography: Research and Education

Chapter 9

Cover page (left to right): Capitol Building—WA Dept. of Ecology; aerial view of NOAA—NOAA Pacific Marine Environmental Laboratory; Nisqually National Wildlife Refuge—Russ McMillan; 'Clara Ann' oyster dredge—Jon Rowley

Chapter 10

Cover page (left to right): orca pod—Center for Whale Research (Friday Harbor, WA 98250); shucked Olympia oyster—Benjamin Drummond / bdsjs.com; salmon catch—Brian Hoffman

Wild oysters—Terrie Klinger

Mount Baker over Puget Sound—Northwest Straits Initiative

Appendix 6. Representative Norma Smith Letter to the Co-chairs

Washington State Legislature

November 19, 2012

To:
William D. Ruckelshaus
Madrona Venture Group
1000 2nd AV, Suite 3700
Seattle, WA 98014

Jay Manning
Cascadia Law Group
606 Columbia Street NW, Suite 212
Olympia, WA 98501

RE: Ocean Acidification Blue Ribbon Panel to Governor Christine Gregoire

As a member of the Washington State Blue Ribbon Panel on Ocean Acidification, please accept this letter as my vote of "support with concerns" for the final recommendations of the panel. Addressing ocean acidification is vital to our shellfish industry, and their story compels all of us to advance our scientific understanding of the processes involved and to make wise decisions in shaping our response. A solid case has been made for the significant implications to our economy, culture and cherished resources. I appreciate the serious work accomplished by the panel members and the willingness demonstrated to make significant changes due to concerns raised. However, my qualified support of the recommendations is based primarily upon:

1. The limited involvement of key stakeholders. While the report and recommendations include specific focus on agricultural practices, the Department of Agriculture, the agricultural science and business communities, Washington State Conservation Commission and Conservation Districts were not invited to the table, and have had almost no input in this process. They play a key role in nutrient management in our state and have expertise in the area of achieving water quality standards through voluntary practices, as acknowledged in the report. The panel did not have the benefit of their meaningful participation, and was left without a thorough understanding of current practices and reforms and a thoughtful review of the potential consequences to farmers and landowners that could impair agricultural viability in Washington state. While I appreciate the late effort to convene a meeting on November 7 with four representatives of agri-business in response to this ongoing expressed concern, it cannot be considered a substitute for full inclusion. The input of agriculture must be given considerable weight in policies directly impacting them. It is not enough to allow farmers and agriculture to comment at the end of the process, without having their involvement in forming recommendations.

2. Recommendations focused on increasing regulations prior to the collection of sound data for determining the role of local source contributions to ocean acidification. (See Action 5) Action Seven recognizes "important gaps remain" and that "the status of acidification in local waters are not well characterized, or are many of the complex physical, chemical and biological interactions that influence the progression and extent of ocean acidification in Washington's marine waters." (See Action 7) Panel scientists stated early in the process time was needed to build reliable models from sound data to determine local source contributions. Importantly, a NOAA presentation to the panel of best science available (Alin 3/30/12) indicated that worldwide CO2

Appendix 6. Representative Norma Smith Letter to the Co-chairs

emissions are responsible for 8-17 percent of Puget Sound acidification, (14 percent on the Washington coast) and estimated decomposition between 17-26 percent. Ocean upwelling sources are the primary contributor at 66 percent. These numbers certainly dictate careful evaluation of what is occurring, thoughtful recognition of the differences in sensitivity around the Puget Sound in various locales, and measured action to insure the greatest probability of effective results. Language that states "Regulatory and voluntary programs should be vigorously pursued and their effects monitored to see what works under what circumstances" (See 5.1.2) most certainly raises questions about Washington state's commitment to efficacy. Quantifiable data is essential to building public awareness, support and action.

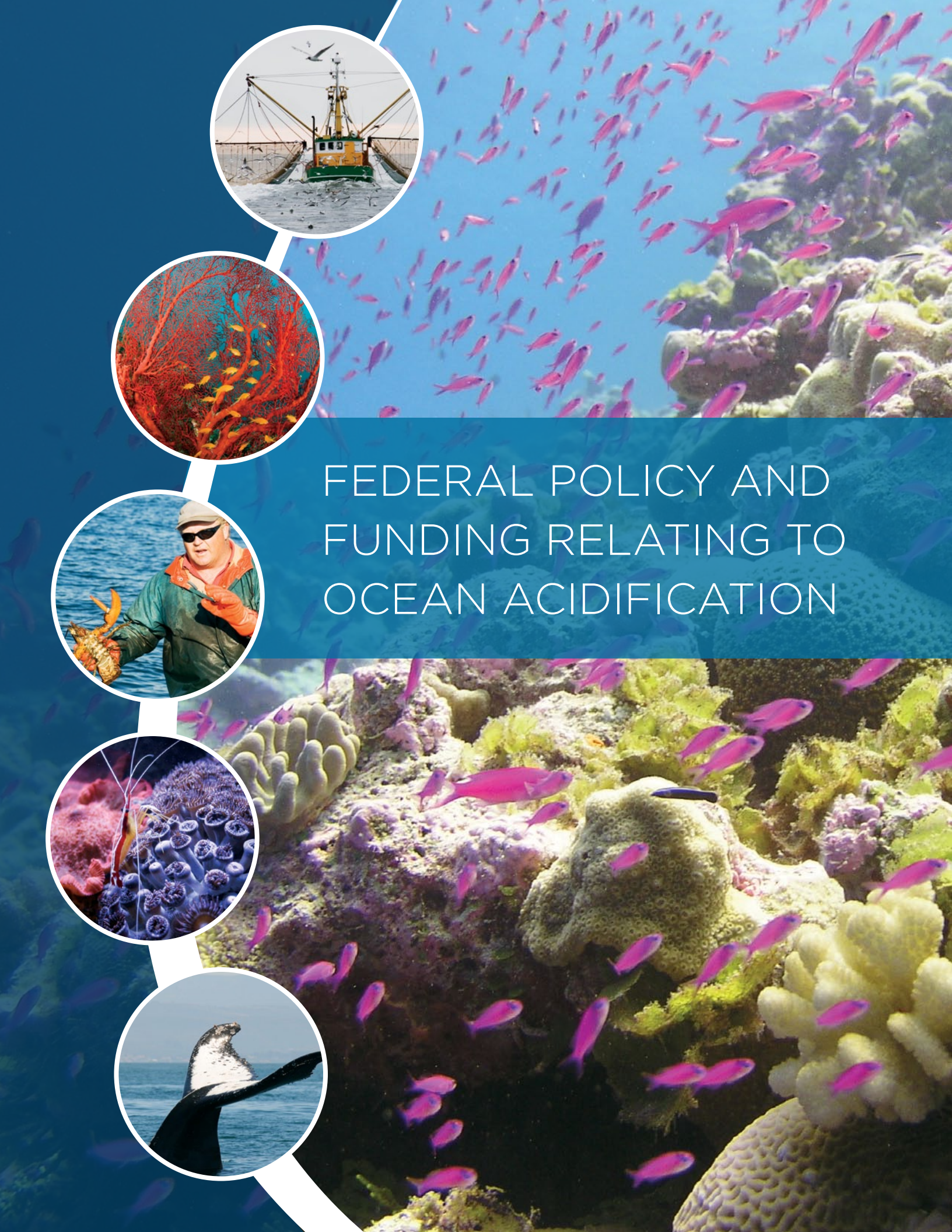
3. The lack of context with regard to the enormous economic challenges we face in a fragile economic recovery and the costs to our communities, employers and landowners of implementation. Significant strain resulting from hurried, un-informed actions could have serious long-term consequences, particularly in our advanced manufacturing, agriculture and production sectors. We must balance our efforts with sound policies that promote job creation, stability and opportunity. Many farmers and small business owners are struggling to survive, working within our state's nationally recognized costly and complex regulatory climate. A holistic perspective will most effectively serve all Washingtonians.

As our charter states, "If consensus cannot be reached, opinions of individual members will be respected and reflected in the final report." Thank you for allowing me to express my opinion on this important work, and for the honor of having served on a panel with such distinguished colleagues.

Sincerely,

Norma Smith

Norma Smith
Washington State Representative
10 Legislative District



FEDERAL POLICY AND FUNDING RELATING TO OCEAN ACIDIFICATION

FEDERAL POLICY AND FUNDING RELATING TO OCEAN ACIDIFICATION

AUTHOR: Lara Levison

Research assistance provided by Corey Ridings

This publication is produced by the National Marine Sanctuary Foundation, and funded by the Gordon and Betty Moore Foundation.

March 2012

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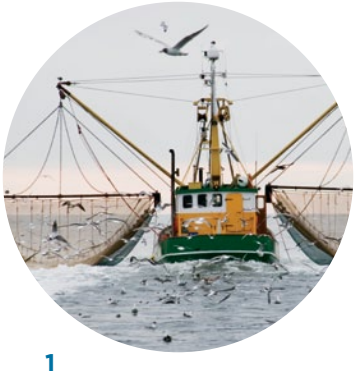

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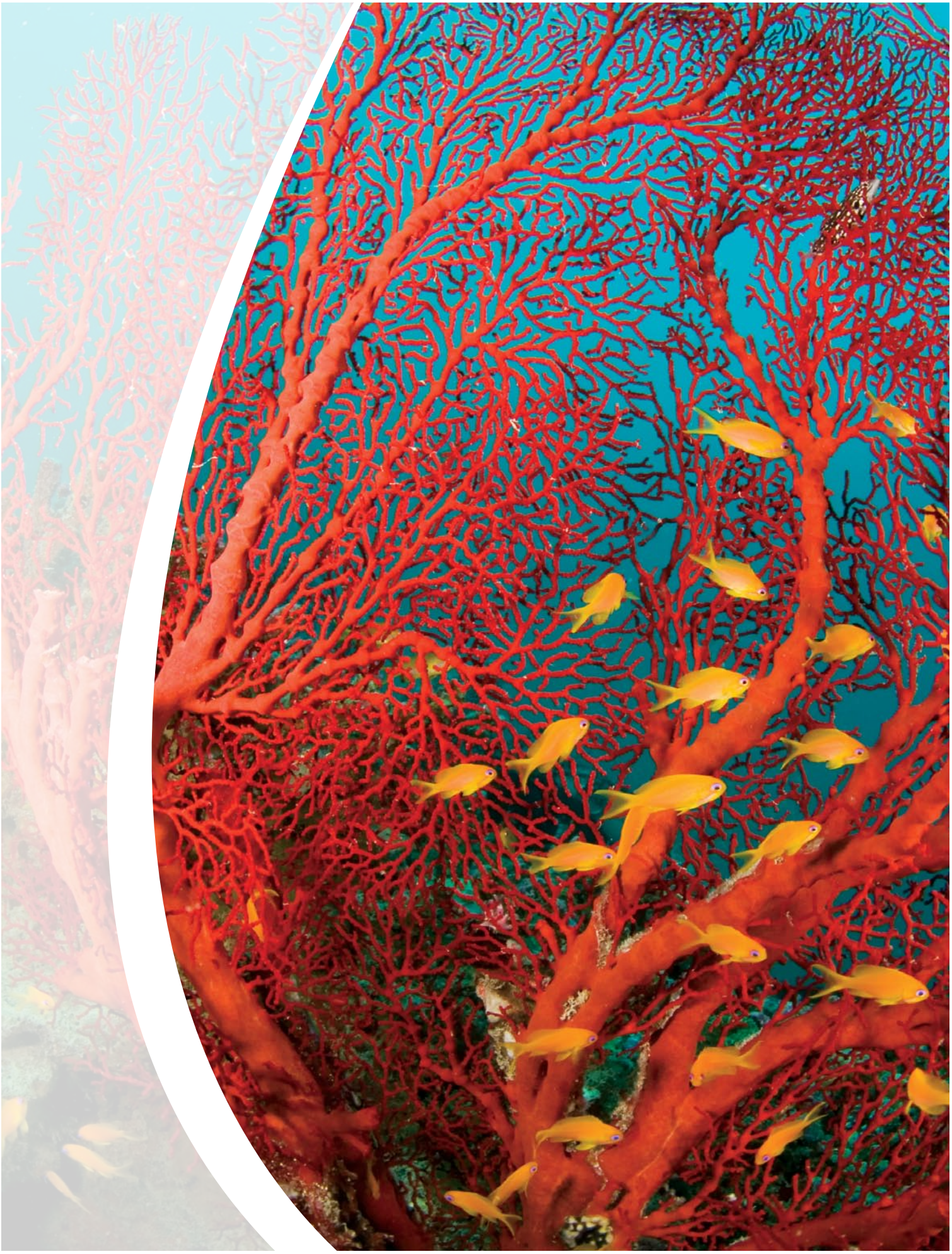

1. Introduction

In recent decades, we have become increasingly aware of changes to our global climate resulting from human-made emissions of carbon dioxide and other greenhouse gases. It is common knowledge that increasing levels of these gases in the atmosphere are changing earth's climate, resulting in changes in temperature, sea level, weather patterns, agricultural production, distribution of species, and so on. Rising levels of carbon dioxide, however, also have profound effects on the world's oceans. The chemistry of the oceans is changing rapidly, with significant consequences for individual species, food webs in the ocean, and humanity's reliance on these natural resources.

About a third of the carbon dioxide produced by human activities since the beginning of the industrial revolution has been absorbed by the oceans,[1] causing significant changes in ocean chemistry. Carbon dioxide dissolved in water increases the number of hydrogen ions, reducing the pH of seawater in a process known as ocean acidification.[2] This shift reduces the amount of the mineral calcium carbonate available in the water, making it more difficult for marine life such as corals, shellfish, plankton, and algae to build their shells and other hard structures. These "calcifiers"—organisms with shells or skeletons made from calcium carbonate—are among the most abundant forms of life in the ocean,[3] playing essential roles in ocean food chains. For example, coral reefs, the most diverse of all marine ecosystems, provide habitat for a quarter of all marine species.[4]

The pH scale measures how acidic or basic a substance is, as determined by the concentration of hydrogen ions (H+). The scale ranges from 0 to 14, with 0 being highly acidic, 7 neutral (pure water is neutral), and 14 highly basic/alkaline. The pH scale is logarithmic, meaning that every unit in the scale represents a ten-fold change in the concentration of hydrogen ions. For example, the concentration of hydrogen ions at pH 4 is ten times greater than at pH 5. The average pH of the ocean, which is 8.1, is still basic, but because the pH is decreasing, the ocean is characterized as undergoing acidification.[5]

It is likely that carbon dioxide dissolved in the surface ocean will rise to double the pre-industrial levels by the middle of this century.[6] Based on reviews of

1. C. L. Sabine, R.A. Feely et al., "The Oceanic Sink for Anthropogenic CO_2," *Science* 305 (2004), 367–371. Also cited on Coral Reef Watch website: http://coralreefwatch.noaa.gov/satellite/oa/description/oaps_intro_oa.html.

2. National Research Council, *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean,* (Washington, DC: The National Academies Press, 2010), p. 15.

3. National Research Council pamphlet, "Ocean Acidification: Starting with the Science," (Washington, DC: The National Academies Press, 2011), pp. 6–7.

4. A. Fishchlin et al., "Chapter 4: Ecosystems, their properties, goods, and services," in "Climate Change 2007: Impacts, Adaptation and Vulnerability," contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, (Cambridge: Cambridge University Press, 2007), p. 235.

5. National Research Council, *National Strategy*, p. 15.

6. R. A. Feely, C. L. Sabine et al., "Impact of Anthropogenic CO_2 on the $CaCO_3$ System in the Oceans," *Science* 305 (2004), 362–366. Also cited on Coral Reef Watch website: http://coralreefwatch.noaa.gov/satellite/oa/description/oaps_intro_oa.html.

earth's geological record, the current rate of acidification is more rapid than at any time in the past 300 million years, including periods when many corals and other calcifiers became extinct.[7] It is essential that we learn as much as we can, as quickly as we can, about the implications of ocean acidification.

Looking solely at the economic value of U.S. commercial fisheries, U.S. fishermen in 2010 landed 8.2 billion pounds of finfish and shellfish valued at $4.5 billion at ports in the 50 states. The value of domestic production in 2010 of edible and non-edible fishery products is estimated at $9 billion.[8] By weight, more finfish than shellfish are landed (84 percent vs. 16 percent in 2009), but shellfish—which are more vulnerable to ocean acidification—are considerably more valuable in the marketplace than finfish (52 percent of landed value versus 48 percent).[9] Processing, wholesale, and retail activities increase the economic value of the shellfish harvest significantly.[10]

In a 2010 report, the National Research Council concluded, "Ocean acidification has demonstrated impacts on many marine organisms. While the ultimate consequences are still unknown, there is a risk of ecosystem changes that threaten coral reefs, fisheries, protected species, and other natural resources of value to society."[11]

With this report, we provide an overview of federal government activities relating to the pressing issue of ocean acidification, including monitoring, research, and regulatory activities. Specifically:

- We discuss the statutory and regulatory authorities that compel and guide the involvement of federal agencies.
- We summarize the research agenda and the investment needs for research, monitoring, and mitigation, as identified within the scientific community, to compare to actual funding levels maintained by federal agencies.
- We examine, to the extent available, funding figures for these activities on an agency-by-agency basis for fiscal years (FY) 2008 through 2011. In particular, this report uses funding figures contained in the Initial Report by the Interagency Working Group on Ocean Acidification, which are provided along themes, and restructures them along agency/office funding lines, in keeping with budgetary and appropriations convention. This allows ready comparison with other appropriations line items. Our report also includes figures through FY11, whereas the interagency report contains figures only for FY08–FY09.
- We contrast likely funding over the next several years with the compelling need for increased investment in monitoring, research, education, and mitigation regarding ocean acidification.
- We call attention to the regulatory and budgetary implications for federal agencies with respect to their mandates to protect natural resources on which ocean acidification will have adverse impacts.

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7. B. Hönisch, Andy Ridgwell, et al., "The Geological Record of Ocean Acidification," *Science* 335, no. 6072 (2012): 1058–1063.

8. National Marine Fisheries Service, Office of Science and Technology, "Fisheries of the United States 2010," Silver Spring, Maryland: National Oceanic and Atmospheric Administration, 2010.

9. Finfish vs. shellfish figures are for 2009. Charles S. Cogan, "The Economics of Ocean Acidification," panelist for "NCSE: Hanging in the pH Balance? Ocean Acidification Impacts on Food Security," January 18, 2012, Washington, DC, pp. 7–8, http://www.compassonline.org/node/487.

10. NOAA Ocean Acidification Steering Committee, "NOAA Ocean and Great Lakes Acidification Research Plan," April 2010, p. 23, http://www.oar.noaa.gov/oceans/ocean-acidification/feel3500_without_budget_rfs.pdf.

11. National Research Council, *National Strategy*, p. 5.

II. Summary of the Report

Responding to a rapid escalation of concern in the scientific community regarding the impacts of ocean acidification, federal agencies have significantly increased their investment in research and monitoring related to the issue in recent years. Federal agencies have relied on their existing legal authorities, as well as on new legislative mandates from the U.S. Congress, to establish and expand their programs.

Table 1 shows total federal funding for FY08–FY11 for research and monitoring conducted by the following agencies: the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), the U.S. Department of the Interior's Bureau of Ocean Energy Management (BOEM), the U.S. Department of the Interior's U.S. Geological Survey (USGS), and the U.S. Environmental Protection Agency (EPA). The figures for fiscal years 2010–2011 should be regarded as approximate.

TABLE 1. FEDERAL OCEAN ACIDIFICATION FUNDING (in thousands of dollars)

FY08	FY09	FY10	FY11
29,492	32,196	32,849*	23,192

* FY10 reflects a one-year increase in NSF funding due to NSF's FY2010 solicitation for research proposals on ocean acidifcation.

We sought to determine whether these investments, while significant, are robust enough to fund a research and monitoring program commensurate with the urgency of the challenges to ocean ecosystems and human society posed by increasing acidification of the ocean. We sought estimates of needed funding levels to which we could compare current funding.

One estimate is available from the scientific community, as represented by the Ocean Carbon and Biochemistry (OCB) program, which supports study of the evolving role of the ocean in the global carbon cycle.[12] In March 2009, the OCB's Ocean Acidification Subcommittee issued a white paper estimating that a U.S. national research program on ocean acidification would need around $50 million per year to provide timely information for managers and decision-makers, starting at a level of $30 million in the first several years and ramping up to $50–$100 million per year.[13] The white paper proposed a ten-

12. OCB is supported by the NSF, NASA, and NOAA and serves an important convening function. OCB website, http://www.us-ocb.org/, accessed fall 2011.

13. OCB Ocean Acidification Subcommittee White Paper, "Ocean Acidification: Recommended Strategy for a U.S. National Research Program," May 25, 2009, p. 8, http://www.us-ocb.org/publications/OCB_OA_Whitepaper.pdf.

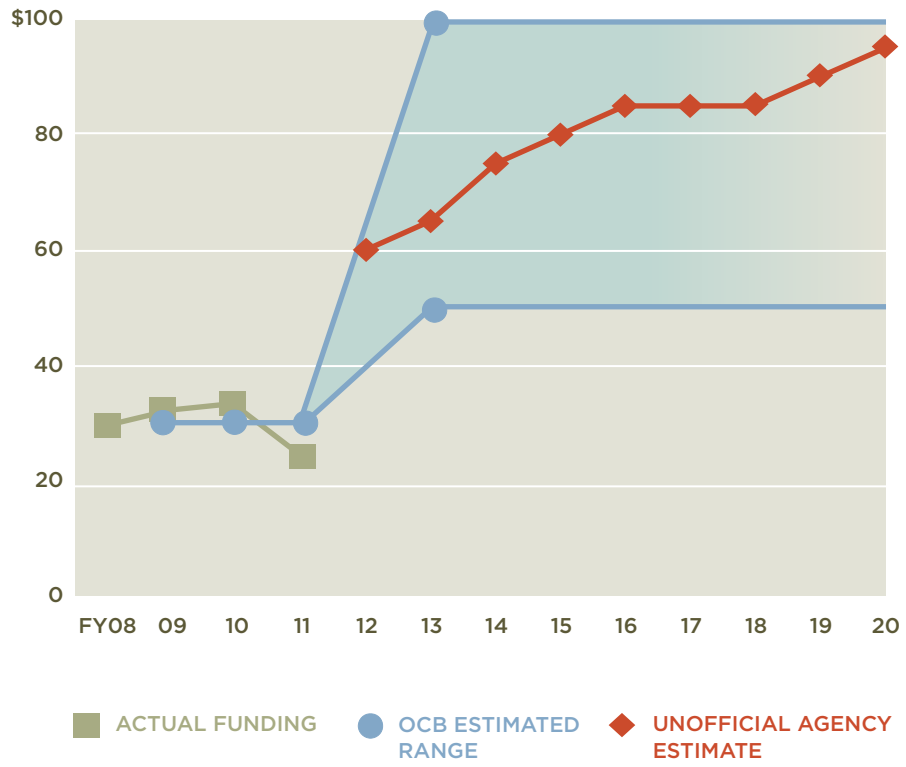
year research plan.[14] The graph below includes a visual representation approximating the OCB's estimate of funding needs.

The Federal Ocean Acidification Research and Monitoring (FOARAM) Act, passed in 2009, provides another estimate of funding needs. The bill authorizes $8 million for NOAA in FY09, ramping up to $20 million in FY12. It authorizes $6 million for NSF in FY09, ramping up to $15 million in 2012, for a FY12 total of $35 million for two agencies. The bill clearly indicates that other federal agencies should be involved as well, even though specific funding authorizations are not provided.[15]

Through discussions with several federal agency officials, we learned that some efforts have been made to estimate needed investments, over the next ten years, for crosscutting activities such as a national program office, as well as for funding within agencies. Funding information collected through these discussions, also displayed in the graph below, should be viewed as a broad estimate of the need for ocean acidification (OA) funding.

Since significant cuts in the federal budget are likely for FY12 and beyond, flat funding may be the best-case result, with reductions in agency research budgets a more likely outcome.

FIGURE 1. ACTUAL FUNDING AND FUTURE PROJECTED INVESTMENT NEEDS FOR FEDERAL OA RESEARCH AND MONITORING (in millions of dollars)



* We selected FY09 as the start date for the OCB estimates because the white paper was published in 2009, and because federal funding in FY09–FY11 was already approximately in the $30 million range estimated as needed for the start-up period.

14. OCB White Paper, pp. 12–13.
15. Federal Ocean Acidification Research and Monitoring (FOARAM) Act, Public Law 111-11, Section 12409.

The draft "Strategic Plan for Research and Monitoring on Ocean Acidification," prepared by the federal Interagency Working Group on Ocean Acidification (IWG-OA), does not estimate budget needs but does outline a number of activities, to be carried out by various federal agencies, that would require additional investment. The draft Strategic Plan also proposes a National Program Office and funding for cross-cutting national activities on data management, technology development and standardization of measurements, and education and outreach. These interagency activities are important to the success of the Strategic Plan. At this time, only NOAA has a program office dedicated to ocean acidification, and cross-cutting activities are coordinated by the IWG-OA with a minimal amount of staff and funding resources.

Federal funding will be needed in the near and long term for mitigation—alleviating the causes of ocean acidification. Funding will also be needed for adaptation—reducing the vulnerability of marine ecosystems to ocean acidification. Several relevant actions are moving forward under the Clean Water Act and Endangered Species Act. Currently, federal agencies are focusing their activities primarily on research, rather than mitigation or adaptation, because so many questions remain to be answered about the effects of ocean acidification on marine species and food webs.

The federal government must begin to grapple with the profound impacts ocean acidification will have on our coastal and ocean resources, and the impacts we will see on our economy, society and environment. There are untold costs associated with these impacts, both in terms of federal funds needed to manage resources such as fisheries, endangered species, and public waters, and in terms of the broader toll on the environment and humanity.

III. Direction from Congress and the Administration

Although scientists identified the phenomenon of oceans absorbing greater carbon dioxide in the early 1970s,[16] the topic remained below the radar for years after that. A 2005 report on ocean acidification by the Royal Society in the UK, in 2005, focused the attention of the scientific community on the issue.[17] In the U.S., scientists have called for a national program on ocean acidification.[18] In response, over the past several years, Congress and the Administration have taken steps to direct federal agencies' resources toward the problem of ocean acidification.

Magnuson-Stevens 2006 Reauthorization

The first request from Congress for action specifically on ocean acidification appeared in legislation reauthorizing the primary law governing marine fisheries management in federal waters of the United States.[19] In the "Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006," Congress directed the Secretary of Commerce to ask the National Research Council (NRC) of the National Academies to conduct a study of the acidification of the oceans and how this process affects the United States. The final bill passed Congress in December 2006 and was signed into law on January 12, 2007.[20]

The request for an NRC study was reinforced in the Consolidated Appropriations Act of 2008, which was signed into law on December 26, 2007. The committee report accompanying the bill directed the National Oceanic and Atmospheric Administration (NOAA)

16. "An Introduction to Ocean Acidification," Coral Reef Watch website, NOAA Satellite and Information Service, http://coralreefwatch.noaa.gov/satellite/oa/description/oaps_intro_oa.html, accessed fall 2011. The article cites Broecker et al., 1971; Bacastow and Keeling, 1972.

17. Dr. Phillip Taylor, personal communication, September 26, 2011. The Royal Society, *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide* (London: Royal Society, June 2005), http://royalsociety.org/policy/publications/2005/ocean-acidification/.

18. OCB White Paper.

19. Rep. Jay Inslee (D-WA) led a bipartisan effort to add the provision to the House version of the bill. Beth Osborne, Office of Rep. Jay Inslee, personal communication, October 14, 2011.

20. Magnuson-Stevens Fishery Conservation and Management Act, Public Law 94-265, as amended by the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act, H.R. 5946, P.L. 109-479 (2007). H.R. 5946, Section 701 states, "The Secretary of Commerce shall request the National Research Council to conduct a study of the acidification of the oceans and how this process affects the United States."

to enter into an agreement with the National Academy of Sciences to initiate a study on acidification of the oceans, as authorized in the Magnuson-Stevens bill in 2006.[21]

Funded by four federal agencies and conducted by the Ocean Studies Board of the NRC, the report was released in April 2010.[22] Titled *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean,* the study provided a detailed review of the current knowledge of the issue and recommended six key elements for a successful national research program on ocean acidification.[23] (See the section on the research agenda on page 12 for a summary of the report's findings.)

Federal Ocean Acidification Research and Monitoring Act of 2009

As the Magnuson-Stevens Act was moving forward in 2007, the first—and, thus far, only—federal legislation dedicated to the issue of ocean acidification was taking shape. The Federal Ocean Acidification Research and Monitoring (FOARAM) Act was introduced by Senator Frank R. Lautenberg of New Jersey, in June 2007.[24] Representative Tom Allen of Maine introduced the House companion in November 2007.[25]

The FOARAM Act's main goals are to establish an interagency research and monitoring program on ocean acidification and to set up an ocean acidification program within NOAA. At the time, research on ocean acidification was in its infancy. The Senate Commerce Committee conducted a public hearing on the bill in May 2007 (and again in April 2010).[26] Professional societies and other interested parties worked to build support for the bill.[27]

The bill was reintroduced in the next Congress, again by Senator Lautenberg,[28] with the House companion bill introduced by Representative Brian Baird of Washington.[29] The final version was included in the Omnibus Public Lands Act of 2009, which was signed into law March 30, 2009,[30] around the same time that the NRC was moving forward with the congressionally mandated study.

The FOARAM Act directs the Joint Subcommittee on Ocean Science and Technology of the National Science and Technology Council to establish an interagency working group on ocean acidification, develop a strategic research and monitoring plan, and oversee the

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21. Consolidated Appropriations Act of 2008, H.R. 2764, P.L. 110-161, Division B-Commerce, Justice, Science and Related Agencies Appropriations Act, House Appropriations Committee Print, p. 235. "NOAA is directed to enter into an agreement with the National Academy of Sciences to initiate a study on acidification of the oceans. This study, authorized by the Magnuson-Stevens Fishery Conservation and Management Act of 2006, shall examine the impacts of ocean acidification on the United States."

22. The study is funded by NOAA, NASA, the U.S. Geological Survey, and the NSF. News from the National Academies, "CO_2 Emissions Causing Ocean Acidification to Progress at Unprecedented Rate," news release, April 22, 2010, http://www8.nationalacademies.org/onpinews/newsitem.aspx?RecordID=12904.

23. National Research Council, *National Strategy.* See n. 2.

24. S. 1581, introduced by Sen. Lautenberg (D-NJ) on June 7, 2007 with 8 original cosponsors (6 Democrats, 2 Republicans), http://thomas.loc.gov/home/thomas.php.

25. H.R. 4174, introduced by Rep. Tom Allen (D-ME) on November 14, 2007, with 11 original cosponsors (9 Democrats, 2 Republicans).

26. U.S. Senate Commerce Committee hearing, "Effects of Climate Change and Ocean Acidification on Living Marine Resources," May 10, 2007, http://commerce.senate.gov/public/.

27. Martha McConnell, NRC/former staff for Senator Lautenberg, personal communication, September 18, 2011.

28. S. 173, introduced by Sen. Lautenberg (D-NJ) on January 8, 2009, with 7 original cosponsors (6 Democrats, 1 Republican).

29. H.R. 14, introduced by Rep. Brian Baird (D-WA) on January 6, 2009, with 2 cosponsors (1 Democrat, 1 Republican). Rep. Tom Allen had left the House of Representatives for an unsuccessful bid for the U.S. Senate.

30. The FOARAM Act is Title XII, Subtitle D (33 USC § 3701-3708) of Public Law 111-11, the Omnibus Public Land Management Act of 2009.

development of assessments of potential impacts of ocean acidification, the development of adaptation and mitigation strategies, and outreach to stakeholders. It calls for participation of the following agencies in the working group: NOAA, the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the U.S. Geological Survey (USGS), the U.S. Fish and Wildlife Service (USFWS), and other federal agencies as appropriate.

The Act contains sections giving specific direction to NOAA, NASA, and NSF, while authorizing appropriations specifically for NOAA and NSF for FY09–FY12. It requires an initial report to Congress with a summary of federally funded ocean acidification research and monitoring activities, including budgets for these activities, and an update on development of the strategic research plan.

The Interagency Working Group on Ocean Acidification (IWG-OA) required by the Act was chartered by the Subcommittee on Ocean Science and Technology in October 2009 and includes representatives of nine agencies that have mandates for research on, or management of, resources likely to be affected by ocean acidification. The agencies represented are NOAA, NSF, Bureau of Ocean Energy Management (BOEM), Department of State (DOS), Environmental Protection Agency (EPA), NASA, USFWS, USGS, and U.S. Navy. Chaired by NOAA, with a vice-chair from NSF, the group meets regularly to coordinate the federal government's activities on ocean acidification.[31]

The President's Executive Order on Oceans (EO 13547)

The Administration has highlighted the importance of improved ocean governance, identifying climate change and ocean acidification as one of the causes for concern, thus providing another basis for engagement on ocean acidification.

In June 2009, President Barack Obama established an Interagency Ocean Policy Task Force to develop recommendations for improving stewardship of the ocean, coasts, and Great Lakes. The Task Force recommended nine priority objectives, including: "[s]trengthen[ing] resiliency of coastal communities and marine and Great Lakes environments and their abilities to adapt to climate change impacts and ocean acidification."[32]

In July 2010, the President signed an executive order adopting the recommendations of the task force, establishing a national policy for the "Stewardship of the Ocean, Our Coasts, and the Great Lakes," and creating a new National Oceans Council to strengthen ocean governance and coordination. The National Oceans Council includes representatives of 27 federal agencies and offices that have roles overseeing the oceans, coasts, and Great Lakes. The executive order also provides for the establishment of a Governance Coordinating Committee to engage with state, tribal, and local authorities, as well as regional advisory councils.[33]

The executive order highlights ocean acidification in the description of the purposes of the order:

> …this order establishes a national policy to ensure the protection, maintenance, and restoration of the health of ocean, coastal, and Great Lakes ecosystems and resources,

31. The working group usually meets by conference call rather than in person.

32. White House Council on Environmental Quality, "Interim Report of the Interagency Ocean Policy Task Force," September 10, 2009, p. 7.

33. Presidential Executive Order, "Stewardship of the Ocean, Our Coasts, and the Great Lakes," E.O. 13547, July 19, 2010, 75 Fed. Reg. 43023 (July 22, 2010).

> enhance the sustainability of ocean and coastal economies, preserve our maritime heritage, support sustainable uses and access, provide for adaptive management to enhance our understanding of and capacity to respond to climate change and *ocean acidification,* and coordinate with our national security and foreign policy interests.[34] (Emphasis added.)

In June 2011, the National Ocean Council released nine draft strategic action plans that provide an initial outline of the steps federal agencies might take to achieve the nine objectives identified in the Task Force recommendations as the most pressing challenges facing the ocean, coasts, and Great Lakes.[35] The ocean acidification elements of the draft plan on "Resiliency and Adaptation to Climate Change and Ocean Acidification" were drawn from the draft "Strategic Plan for Federal Research and Monitoring on Ocean Acidification" (not yet available to the public) prepared by the IWG-OA.[36] In January 2012, the National Ocean Council released the "Draft National Ocean Policy Implementation Plan," which identifies "Resiliency and Adaptation to Climate Change and Ocean Acidification" as one of nine "National Priority Objectives."[37]

Existing Agency Authorizations

Although the initiatives by Congress and the Administration discussed above provide a significant impetus for action, the federal agencies currently taking the lead on activities related to ocean acidification can draw upon a number of other, already-existing authorities, as discussed agency by agency in Section V, to conduct research, monitoring, adaptation, and mitigation.

34. E.O. 13547, Federal Register, p. 43023.

35. "Strategic Action Plans," National Ocean Council, The White House website, http://www.whitehouse.gov/administration/eop/oceans/sap, accessed fall 2011.

36. Dr. Ned Cyr, NOAA, email message to author, October 25, 2011.

37. National Ocean Council, "Draft National Ocean Policy Implementation Plan," January 12, 2012, p. 8, http://www.whitehouse.gov/sites/default/files/microsites/ceq/national_ocean_policy_draft_implementation_plan_01-12-12.pdf.

IV. Development of the Research Agenda

The federal government's research agenda on ocean acidification has been shaped by a series of symposia and reports involving scientists from governmental, academic, and non-profit institutions. Building upon prior workshops and symposia, such as those convened by the Ocean Carbon and Biochemistry Program, the National Research Council of the National Academies (NRC) issued an extensive report and recommendations in 2010. Also drawing on the exchange of ideas and information at scientific symposia, the National Oceanic and Atmospheric Administration (NOAA) produced an agency research plan in 2010. The Interagency Working Group on Ocean Acidification (IWG-OA)has built further upon these efforts in drafting a strategic research plan for all the federal agencies engaged in research on ocean acidification.

Research Recommendations from the Scientific Community

In recent years, riding the surge of interest sparked by the 2005 Royal Society report mentioned on page 7, scientists have held a number of workshops and symposia to develop the research agenda on ocean acidification. The research recommendations from five of these symposia are summarized in the NRC report.[38]

Two of these sessions were organized by the Ocean Carbon and Biochemistry Program (OCB), an independent project that promotes and coordinates collaborative, multidisciplinary research on the ocean's role as a component of the global earth system. Ocean acidification is a priority of OCB, which is supported by the National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and NOAA.[39] Most recently, in March 2011, OCB held a meeting in Woods Hole to bring together scientists working on ocean acidification in a wide range of disciplines to "identify research commonalities, untapped resources, and collaborative opportunities."[40] The OCB program continues to serve an important convening function on the topic of ocean acidification.

38. National Research Council, *National Strategy,* Appendix D, pp. 183–188.

39. OCB website, http://www.us-ocb.org/, accessed fall 2011.

40. Sarah Cooley, "Ocean Carbon and Biochemistry Program: Ocean Acidification Principle Investigators' Meeting, March 22–24, 2011, Woods, Hole, MA, Meeting Report," (Woods Hole: OCB, July 2011), https://www.whoi.edu/fileserver.do?id=90204&pt=2&p=107329.

National Research Council Report on Ocean Acidification

As described on page 7, Congress called for a study of ocean acidification by the NRC. The report was funded by four federal agencies—NOAA, NASA, USGS, and NSF.[41] The Ocean Studies Board of the NRC convened a committee of experts and a team of staff members to produce the study. The four agencies directed the study committee to:

- Review current knowledge of ocean acidification;
- Identify critical uncertainties and key science questions; and
- Recommend a strategy of research, monitoring, and assessment for federal agencies, the scientific community, and other partners.[42]

In its final report, *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean,* released in April 2010, the committee put forward the following overarching conclusion:

> The chemistry of the ocean is changing at an unprecedented rate and magnitude due to anthropogenic carbon dioxide emissions; the rate of change exceeds any known to have occurred for at least the past hundreds of thousands of years. Unless anthropogenic CO_2 emissions are substantially curbed, or atmospheric CO_2 is controlled by some other means, the average pH of the ocean will continue to fall. Ocean acidification has demonstrated impacts on many marine organisms. While the ultimate consequences are still unknown, there is a risk of ecosystem changes that threaten coral reefs, fisheries, protected species, and other natural resources of value to society.[43]

The committee concluded that the federal government had taken initial steps to respond to the nation's long-term needs on ocean acidification and to coordinate activities among government agencies, and numerous previous reports on research needs and priorities had provided a path forward.

The committee's recommendations for a national ocean acidification program were framed around six key elements:

1) a robust observing network;

2) research to fulfill critical information needs;

3) assessments and support to provide relevant information to decision-makers;

4) data management;

5) facilities and training of ocean acidification researchers; and

6) effective program planning and management.[44]

The timing of the NRC study was fortuitous, since shortly after it commenced, Congress passed the FOARAM Act, calling for the development of an interagency research and monitoring program and requiring a strategic plan laying out this program. The NRC report provided valuable guidance to the IWG-OA in formulating the strategic plan.[45]

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41. News from the National Academies, April 22, 2010, see n. 22.
42. National Research Council, *National Strategy,* pp. 2–3
43. Ibid., p. 5.
44. Ibid., pp. 5–6.
45. Dr. Richard Feely, NOAA, personal communication, October 11, 2011.

Although the FOARAM Act directs the Interagency Working Group to develop a ten-year strategic plan for research and monitoring on ocean acidification, the NRC committee anticipates that the program may take 15 to 20 years, which is comparable to the length of other major research programs.[46]

NOAA Research Plan

In April 2010, NOAA issued a comprehensive strategy to guide the agency's research and monitoring activities on ocean acidification, to be executed at the regional level with coordination at the national level.[47] As required by the FOARAM Act, NOAA established a formal Ocean Acidification Program and set up a program office in 2011 to coordinate the program's activities.[48]

In summary, the agency is:

- developing and deploying enhanced ocean and coastal observing systems,
- conducting research and developing outreach plans to ensure protection of NOAA managed resources including fishery species and place-based protected areas,
- developing models to forecast future ocean chemistry and impacts on fishery species, and
- educating the general public.[49]

Draft Strategic Plan for Federal Research and Monitoring on Ocean Acidification

The FOARAM Act requires the development of "a strategic plan for Federal research and monitoring on ocean acidification that will provide for an assessment of the impacts of ocean acidification on marine organisms and marine ecosystems and the development of adaptation and mitigation strategies to conserve marine organisms and marine ecosystems."[50] The IWG-OA has drafted this plan, which was still under internal review at this time this report went to press.[51] As noted above, the IWG-OA drew upon the NRC report in preparing the strategic plan.

The draft Strategic Plan is organized around seven priority themes, largely corresponding to the instructions in the FOARAM Act: 1) monitoring, 2) research, 3) modeling, 4) technology development, 5) socioeconomic impacts, 6) education, outreach, and engagement strategies, and 7) data management and integration.[52]

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46. National Research Council, *National Strategy,* pp. 126–127.

47. NOAA Ocean Acidification Steering Committee, "NOAA Ocean and Great Lakes Acidification Research Plan," April 2010, http://www.oar.noaa.gov/oceans/ocean-acidification/feel3500_without_budget_rfs.pdf.

48. NOAA, "Dr. Elizabeth Jewett selected to lead NOAA's Ocean Acidification Program," news release, May 16, 2011, http://www.noaanews.noaa.gov/stories2011/20110513_oceanacidification.html.

49. "US Agency Programs Involved in Ocean Acidification Research," Interagency Working Group on Ocean Acidification website, http://www.st.nmfs.noaa.gov/iwgoa/pages/activities.html, accessed fall 2011.

50. FOARAM Act, Public Law 111-11, Section 12405, 33 USC § 3704.

51. The report is under review by the Committee on Environment and Natural Resources of the National Science and Technology Council, in the White House Office of Science and Technology Policy.

52. Public Law 111-11, Section 12405, 33 USC 3704.

Under these themes, the draft Strategic Plan lays out recommendations and goals that emphasize:

- Building upon existing systems and developing new technology and systems that strategically monitor chemical and biological impacts of ocean acidification worldwide, document trends, and develop early warning systems.
- Undertaking laboratory, mesocosm,[53] and *in situ* research[54] to examine species-specific physiological responses to ocean acidification and its interactions with other stressors, impacts to marine food webs and ecosystems, and mechanisms necessary to develop indices to track marine ecosystem responses.
- Developing comprehensive models to predict changes in the ocean carbon cycle and impacts on marine ecosystems and organisms.
- Ensuring the ability to measure all required parameters and adequate data quality through technology development and standardization of measurements.
- Fostering a coordinated Federal approach to technology development and standardization efforts.
- Assessing the socioeconomic impacts of ocean acidification.
- Identifying and engaging stakeholders in developing adaptation and mitigation strategies for responsible stewardship of marine organisms and ecosystems.
- Designing and coordinating activities that foster ocean acidification literacy through educational resources and public outreach.
- Developing and implementing domestic and international engagement strategies and facilitating partnerships.
- Ensuring that results and assessments of monitoring and research efforts are accessible to and understandable by managers, policy makers, and the general public.
- Ensuring that ocean acidification data are properly managed and integrated across disciplinary, organizational, and data management technology boundaries.[55]

The Strategic Plan provides a vision of the breadth and depth of information that we as a society require to evaluate the phenomenon of ocean acidification in a manner commensurate with the threat to ocean ecosystems and the services they provide to humanity.

53. "Aquatic mesocosms, or experimental water enclosures, are designed to provide a limited body of water with close to natural conditions, in which environmental factors can be realistically manipulated." From "What is a mesocosm?" MESOCOSM, http://mesocosm.eu/node/16, accessed February 18, 2012.

54. Examining a phenomenon in the place where it occurs. From "In situ," *Wikipedia,* last modified February 12, 2012, http://en.wikipedia.org/wiki/In_situ.

55. Interagency Working Group on Ocean Acidification, "Executive Summary," in "Strategic Plan for Federal Research and Monitoring on Ocean Acidification," May 2011—draft for review.

v. Federal Agency Research and Monitoring Activities and Funding (FY08–FY11)

This section contains a discussion of each federal agency that is engaged in activities relating to ocean acidification, including a review of how each agency's mission and mandates have led to its involvement, a concise description of the agency's activities relating to ocean acidification, and a table with budget figures from FY08 through FY11.

Examples of "primary" and "contributing" projects from the Initial Report:

PRIMARY: Adaptation of food web models of Puget Sound and the California Current to predict how these ecosystems will respond to future ocean acidification (NOAA)

CONTRIBUTING: Stony coral assessments conducted in U.S. Virgin Islands to document regional distribution and to test reef indicators for sensitivity to human disturbance (EPA)

FY08–FY09 Budget Figures

Budget figures for FY08 and FY09 are drawn from the interagency working group's "Initial Report on Federally Funded Ocean Acidification Research and Monitoring Activities and Progress in Developing a Strategic Plan," issued in March 2011.[56] Required by the FOARAM Act,[57] the Initial Report summarized federally funded ocean acidification and monitoring activities and the budget for these activities, and described progress in developing the Strategic Plan. In the Initial Report, each federal agency's projects and funding are organized into six categories: 1) monitoring of ocean chemistry and biological impacts, 2) research on responses of species and ecosystems, 3) modeling to predict changes and impacts, 4) technology development, 5) assessment of socioeconomic impacts, and 6) education and outreach.

The budget information from the Initial Report has been incorporated in the agency-specific tables in this report, reorganized to show which agency programs are housing the activities, rather than using the six categories of activities in the original report.

The Initial Report also divided all activities into two categories: "Activities are classified as having either a primary focus on ocean acidification or being 'contributing' activities, in that they were designed for other purposes but clearly provide information useful for understanding ocean acidification."[58] In this report, these categories of "primary" and "contributing" have been maintained for FY08 and FY09.

56. Interagency Working Group on Ocean Acidification, "Initial Report on Federally Funded Ocean Acidification Research and Monitoring Activities and Progress in Developing a Strategic Plan," submitted to Congress March 2011, http://www.st.nmfs.noaa.gov/iwgoa/documents/Ocean_Acidification_Initial_Report_final.pdf.

57. Section 12404(c) of the FOARAM Act, Public Law 111-11.

58. IWG-OA, "Initial Report," p. 1.

FY10–FY11 Budget Figures

The budget figures for FY10 and FY11 have been obtained primarily through personal communications with agency staff, since most of the information is not available from public sources. In most cases, we were not able to obtain information that was as detailed as that in the Initial Report, particularly regarding contributing activities. Therefore, the budget figures for FY10–FY11 should be regarded as providing a general sense of the direction of each agency's program, rather than as a precise representation of funding in those two years. In fact, the FY08–FY09 figures should be viewed in the same way, since agencies applied their own internal methods to determining which projects were contributing versus primary, and which should be included at all.

National Aeronautics and Space Administration

The National Aeronautics and Space Administration (NASA), established in 1958 "to provide for research into problems of flight within and outside the earth's atmosphere,"[59] carries out the largest federal program studying the earth and its environment[60] under its Earth Science Directorate. The purpose of the Earth Science Program is to develop a scientific understanding of Earth's systems—its air, water, land, and life, and interactions among them—and their responses to natural or human-induced changes, and to improve predictions concerning climate, weather, and natural hazards.

The Carbon Cycle and Ecosystems Focus Area of the Earth Science Program "addresses the distribution and cycling of carbon among the land, ocean, and atmospheric reservoirs and ecosystems as they are affected by humans, as they change due to their own biogeochemistry, and as they interact with climate variations."[61] Projects on ocean acidification in the carbon cycle focus area have supported observation, research, modeling, the development of satellite instruments, and education and public outreach.[62]

A coordinated series of satellites that conduct long-term global observations, launched and for the most part operated by NASA, are central to the Earth Science Program. Using these observations, NASA sponsors research by scientists at many institutions, conducts research, develops new technologies, provides science education, and delivers scientific information to policy makers.[63] NASA's fleet of Earth Observing Satellites represents an investment of billions of dollars, and the data obtained is used by some 330,000 people for purposes ranging from research to commercial. Although NASA does not break down the cost of the satellite fleet according to how the information is used, it is useful to bear in mind that this investment makes a significant contribution to research on ocean acidification.[64]

About a third of the Earth Science research budget is awarded competitively each year though the Research Opportunities in Space and Earth Science (ROSES) program. Selected projects are usually funded for three years. Thus, projects selected in 2011 in response to

59. National Aeronautics and Space Act of 1958, Public Law 85-568, 72 Stat. 426.

60. Congressional Research Service, abstract for NASA's Earth Science Enterprise, RS20673.

61. "Carbon Cycle and Ecosystems," NASA website, http://science.nasa.gov/earth-science/focus-areas/carbon-cycle-and-ecosystems/, accessed fall 2011.

62. "US Agency Programs Involved in Ocean Acidification Research," IWG-OA website, http://www.st.nmfs.noaa.gov/iwgoa/pages/activities.html#NASA, accessed fall 2011.

63. "Earth," NASA website, http://nasascience.nasa.gov/earth-science/, accessed fall 2011.

64. Dr. Paula Bontempi, NASA, personal communication, November 1, 2011.

the ROSES-11 announcement typically will be funded in FY12 through FY13.[65] Funding for ocean acidification projects varies, depending on whether the issue is related to the research topic for which Earth Sciences is soliciting applications, and whether the projects are of sufficient quality to be selected through the peer review process. Projects are also constrained by the requirement to use data from NASA satellites.[66]

NASA Funding for FY08–FY11[67]

NASA programs related to ocean acidification are carried out in the Science Mission Directorate, in Earth Science Research and Analysis. NASA is funded in the Commerce, Justice, Science, and Related Agencies Appropriations Act, and the appropriations category is "Science—Earth Science."

NOTE: The significantly lower figures for FY10 and FY11 are due to the unavailability of information on "contributing" activities, not to a significant change in NASA's commitment to the issue.

TABLE 2. NATIONAL AERONAUTICS AND SPACE ADMINISTRATION FUNDING
(in thousands of dollars)

APPROPRIATION: SCIENCE—EARTH SCIENCE	FY08	FY09	FY10	FY11	Activity classification
Earth Science Research & Analysis	4,882	4,654	n/a	n/a	Contributing
Earth Science Research & Analysis	207	192	500	500	Primary
TOTAL	5,089	4,846	500	500	Total

National Oceanic and Atmospheric Administration

The mission of the National Oceanic and Atmospheric Administration (NOAA) is to understand and predict changes in climate, weather, oceans, and coasts; to share that knowledge and information with others; and to conserve and manage coastal and marine ecosystems and resources. Established by executive order in 1970, NOAA can trace its genesis back to the Survey of the Coast, the nation's first scientific agency, launched in 1807.[68] NOAA is a bureau of the U.S. Department of Commerce.

Both NOAA's mission and numerous legislative mandates, including most recently the FOARAM Act, direct the agency to seek understanding of the process of ocean acidification and its consequences, and to adapt the management of fisheries and ecosystems in response. Other statutory authorities for these activities include the Magnuson-Stevens Fishery Conservation and Management Act, Marine Mammal Protection Act, National

65. "Budget Information: FY 2012 Budget Estimate by Section," see "Earth Science, Earth Science Research," NASA website, http://www.nasa.gov/pdf/516645main_NASAFY12_Budget_Estimates-Science_Earth-508.pdf, accessed fall 2011.

66. Dr. Paula Bontempi, NASA, personal communication, September 19, 2011.

67. Dr. Paula Bontempi, NASA, Personal communication/email, November 1, 2011.

68. John Cloud, "The 200th Anniversary of the Survey of the Coast," *Prologue Magazine: Quarterly Journal of the National Archives and Records Administration* 39, no. 1, (Spring 2007), 24–33, http://www.archives.gov/publications/prologue/2007/spring/coast-survey.html.

Marine Sanctuaries Act, Endangered Species Act, Coral Reef Conservation Act, and Clean Water Act.[69]

As described above, the NOAA Ocean Acidification Steering Committee issued the "Ocean and Great Lakes Acidification Research Plan" in April 2010 to guide the agency's research activities.[70] The plan is organized by region to respond to the specific research needs regarding fisheries and ecosystems of each region.

As directed by Congress in the FOARAM Act,[71] NOAA has established an ocean acidification program, which will plan, oversee, and coordinate NOAA's ocean acidification activities.[72] Funding will appear as a line item for the program office and from there will be distributed to the various program offices described below. Also, in FY12, the program will offer competitive grants for projects on the ecological effects of ocean acidification.[73]

Within the **OFFICE OF ATMOSPHERIC RESEARCH**, NOAA's main research arm, the Pacific Marine Environmental Laboratory (PMEL) and the Atlantic Oceanographic and Meteorological Laboratory (AOML) are taking the lead, particularly on ocean chemistry and large-scale observations. Oceanographers at PMEL have been studying the effects of carbon dioxide emissions on the oceans for more than three decades; they collect carbon measurements, as well as other measurements of importance to the research effort, in oceans around the world, using monitoring equipment on research vessels, moorings, and commercial vessels. PMEL researchers and their partners at academic institutions are using this data to gain a better understanding of how ocean acidification affects the chemistry of the oceans and marine ecosystems.[74] Researchers at AOML, in close coordination with their West Coast colleagues, also collect carbon measurements and study the exchange of carbon dioxide between the atmosphere and the oceans.[75]

The **NATIONAL MARINE FISHERIES SERVICE** (NMFS) is responsible for the stewardship of living marine resources in the U.S. exclusive economic zone, from three to 200 nautical miles offshore.[76] Each of NMFS' six regions includes a science center to provide the scientific basis for the region's resource management activities,[77] and most of these are conducting ocean acidification research. In sum, researchers are focusing on commercially or ecologically important species in order to identify which species show a response to reduced pH, at what levels of acidification this occurs, and how ecosystems will be affected by changes in the composition of species. The Pacific Island Fisheries Science Center and the Southeast Fisheries Science Center, working with NOAA's Coral Reef Conservation Program and other partners, are engaged in research on coral reefs.[78] With acidification increasing more rapidly in the Arctic and northern Pacific, the Alaska Fisheries Science

69. "NOAA Ocean and Great Lakes Acidification Research Plan," p. ix, see n. 47.

70. Ibid.

71. Public Law 111-11, Section 12406.

72. NOAA, "Dr. Elizabeth Jewett selected to lead NOAA's Ocean Acidification Program," news release, May 16, 2011, see n. 48.

73. Dr. Elizabeth Jewett, NOAA, personal communication, September 21, 2011.

74. "Ocean Acidification: The Other Carbon Dioxide Problem," PMEL Carbon Program website, http://www.pmel.noaa.gov/co2/story/Ocean+Acidification, accessed fall 2011.

75. "CO_2 Research in AOML: About Our Research," NOAA's Atlantic Oceanographic and Meteorological Laboratory website, http://www.aoml.noaa.gov/ocd/gcc/co2research/, accessed fall 2011.

76. "About National Marine Fisheries Service," NOAA Fisheries Service website, http://www.nmfs.noaa.gov/aboutus.htm, accessed fall 2011.

77. The six regions are Alaska, Northwest, Pacific Islands, Southwest, Southeast, and Northeast. NOAA Fisheries Service website, http://www.nmfs.noaa.gov/aboutus.htm, accessed fall 2011.

78. "Coral Reef Ecosystem Division," NOAA Pacific Islands Fisheries Science Center website, http://www.pifsc.noaa.gov/cred/, accessed winter 2012; "Coral Early Life History and Climate Change Impacts," NOAA Southeast Fisheries Science Center website, http://www.sefsc.noaa.gov/species/corals/spawn.htm, accessed winter 2012.

Center and the Northwest Fisheries Science Center significantly increased their capacity, through investment in new equipment and facilities, to investigate the effects of reduced pH on specific species in laboratory and field settings.[79]

The **NATIONAL OCEAN SERVICE** includes a number of programs that are becoming more engaged in research and education on ocean acidification. *National Marine Sanctuaries*, marine protected areas that include 13 sanctuaries and one marine national monument,[82] will play a key role in research and education; see page 20 for an expanded discussion. The 28 *National Estuarine Research Reserves*, which protect more than 1.3 million acres in estuaries and coastal areas in 22 states and Puerto Rico, were established in large part for the purposes of long-term research, environmental monitoring, and education.[83] These reserves are well suited to expand knowledge of ocean acidification, and plans are being developed to add ocean acidification related parameters to their water-quality monitoring programs.[84] The Office of Ocean and Coastal Resource Management implements the Coastal Zone Management Act, assisting states in managing coastal resources.[85]

The *Integrated Ocean Observing System* (IOOS), established by law in 2009, is a system to obtain and disseminate ocean, coastal, and Great Lakes data—including physical, chemical, geological, and biological data[86]—rapidly and systematically, in order to meet critical societal needs.[87] In partnership with academic institutions and the private sector, IOOS links data from thousands of tools, ranging from underwater sensors to satellites,[88] including data on ocean acidification.[89]

A considerable portion of ocean acidification research has focused on coral reefs, because of their ecological and economic importance, and their vulnerability to reduced pH. The *Coral Reef Conservation Program* (CRCP), coordinated by the National Ocean Service, is a partnership among NOAA line offices that work on coral reef issues, bringing a multidisciplinary approach to understanding and managing coral reef

In recent years, oyster hatcheries in the Pacific Northwest have experienced massive losses of oyster larvae, and wild oysters in some parts of the region have not reproduced.[80] Researchers at the Pacific Marine Environmental Laboratory, the Northwest Fisheries Science Center, Sea Grant, and other institutions are working with shellfish growers to investigate whether the oyster losses are related to ocean acidification. NOAA researchers have observed levels of acidified seawater off the Pacific Coast that had not been predicted to occur for another 100 years. The normal, seasonal upwelling of more acidic waters from the deeper ocean may be contributing to more rapid acidification in the region. Some oyster hatcheries now continuously monitor seawater and pump water into their hatcheries only when it is less corrosive.[81]

79. Dr. John Stein, Dr. Elizabeth Jewett, and others at NOAA, personal communications, October 2011.

80. National Research Council pamphlet, "Ocean Acidification: Starting with the Science," (Washington, DC: The National Academies Press, 2011), p. 15.

81. "Is Ocean Acidification Affecting Shellfish? A NOAA Sea Grant West Coast Workshop Seeks Answers, July 7–8, 2010, Costa Mesa, CA," brochure, http://c-can.msi.ucsb.edu/materials/FINAL-OAWSoutsidelr.pdf/view.

82. "About Your Sanctuaries: Frequently Asked Questions," NOAA's National Marine Sanctuaries website, http://sanctuaries.noaa.gov/about/faqs/welcome.html, accessed fall 2011.

83. "Background," NOAA's National Estuarine Research Reserve System website, http://www.nerrs.noaa.gov/Background.aspx, accessed fall 2011.

84. Agency Activities, IWG-OA website, http://www.st.nmfs.noaa.gov/iwgoa/pages/activities.html#NOAA, accessed fall 2011.

85. "Office of Ocean and Coastal Resource Management," NOAA's National Ocean Service website, http://oceanservice.noaa.gov/programs/ocrm/, accessed fall 2011; "What is OCRM Doing to Respond to Climate Change? Ocean and Coastal Resource Management, NOAA's National Ocean Service website, http://coastalmanagement.noaa.gov/issues/climate_activities.html, accessed fall 2011.

86. Integrated Ocean Observing System, "Integrated Ocean Observing System Report to Congress," (2008), p. 1, http://www.ioos.gov/library/ioos_report_congress.pdf.

87. "About U.S. Integrated Observing System, IOOS®," Integrated Ocean Observing System website, http://www.ioos.gov/about/welcome.html, accessed fall 2011.

88. "Integrated Ocean Observing System," NOAA's National Ocean Service website, http://oceanservice.noaa.gov/programs/ioos.html, accessed fall 2011.

89. Agency Activities, IWG-OA website, http://www.st.nmfs.noaa.gov/iwgoa/pages/activities.html#NOAA, accessed fall 2011.

ecosystems. CRCP projects on ocean acidification involve scientists in other federal agencies and academia as well.[90]

The National Environmental Satellite, Data, and Information Service (NESDIS) operates a system of environmental satellites and related data centers that provide information on the global environment, including ocean acidification.[91] NESDIS includes the Coral Reef Watch, which uses satellites to monitor conditions of coral reef ecosystems.[92]

National Marine Sanctuary System

The National Marine Sanctuary System serves as a good case study of a federal natural resource management program that is seeking to contribute to knowledge and understanding of ocean acidification within the constraints of its limited funding.

National marine sanctuaries are designated areas in the ocean and Great Lakes with special national significance due to their conservation, recreational, ecological, historical, scientific, cultural, archeological, educational, or aesthetic qualities. Created by Congress in 1972, the National Marine Sanctuary System is managed by NOAA. The System includes 13 sanctuaries and the Papahānaumokuākea Marine National Monument, designated by Presidential Executive Order in 2006 to protect the Northwestern Hawaiian Islands and co-managed with the Department of the Interior.[93]

Concern about ocean acidification first arose within the sanctuary system on the West Coast, where the periodic upwelling of deep ocean waters is contributing to unexpectedly rapid acidification. In September 2008, the Channel Islands National Marine Sanctuary Advisory Council adopted a report from its Conservation Working Group titled "Ocean Acidification and the Channel Island National Marine Sanctuary: Cause, effect, and response."

Recognizing ocean acidification as a serious threat to the sanctuaries, as well as an emerging national issue, all 13 Sanctuary Advisory Councils in rapid succession produced resolutions, motions, or letters encouraging the sanctuaries and NOAA to take action on ocean acidification. These are the key recommendations from a total of 63 included in the Sanctuary Advisory Councils' resolutions:

- **Make sanctuaries sentinel monitoring sites,**
- **Coordinate regionally,**
- **Support research,**
- **Develop specific education and outreach programming,**
- **Explore adaptive management actions, and**
- **Pursue other climate change actions.**

In response, the five West Coast sanctuaries joined together to write the "National Marine Sanctuaries of the West Coast Ocean Acidification Action Plan," completed in August 2011.[94] The plan proposes the following seven strategies for the West Coast sanctuaries, as well as

90. NOAA's Coral Reef Conservation Program is a partnership among the NOAA Line Offices working on coral reef issues: the National Marine Fisheries Service, the National Ocean Service, the Office of Oceanic and Atmospheric Research, and the National Environmental Satellite, Data and Information Service. "Who We Are," NOAA Coral Reef Conservation Program website, http://coralreef.noaa.gov/aboutcrcp/whoweare/, accessed fall 2011.

91. "What is the NESDIS Satellite and Information Service?" NOAA Satellite and Information Service website, http://www.nesdis.noaa.gov/AboutNESDIS.html; "NESDIS and Climate," http://www.nesdis.noaa.gov/ClimateResources.html.

92. "Coral Reef Watch Satellite Monitoring," NOAA Satellite and Information Service website, http://coralreefwatch.noaa.gov/satellite/index.html, accessed fall 2011.

93. "Our National Marine Sanctuaries," National Marine Sanctuary Foundation website, http://www.nmsfocean.org/our-national-marine-sanctuaries, accessed fall 2011.

94. Dave Lott, Ed Bowlby, Dan Howard, Kelley Higgason, Karen Grimmer, Laura Francis, Linda Krop, Richard Feely, and Libby Jewett, "National Marine Sanctuaries of the West Coast: Ocean Acidification Action Plan," (National Marine Sanctuary Program, August 15, 2011).

identifying numerous activities to carry out each strategy, and funding levels needed to carry out the plan over five years:

1) Monitoring for ocean acidification,
2) Research on ocean acidification,
3) Education and outreach,
4) Mitigating damages to sanctuary resources,
5) Influencing regional and national policy,
6) Demonstrate leadership by reducing carbon emissions, and
7) Internal coordination on ocean acidification issues.

Even as they were writing the plan, the West Coast sanctuaries began moving forward to implement the plan using existing funds, but many of the activities in the plan will be contingent on additional funding, whether through NOAA or grants from private sources.

West Coast sanctuaries are participating in cutting-edge research with NOAA's Pacific Marine Environmental Laboratory (PMEL) and other research institutions. For example, sanctuaries are supplying water samples to PMEL to assist in the development of an algorithm that can derive the parameters for ocean acidification from measurements of temperature, salinity, and oxygen.[95]

The sanctuaries' ongoing conservation activities can also contribute to knowledge of ocean acidification. For example, long-term monitoring of coral reefs in the Flower Garden Banks National Marine Sanctuary, conducted in partnership with the Department of the Interior's Bureau of Ocean Energy, includes a baseline of data on pH as well as coral growth rates.[96] Cordell Banks National Marine Sanctuary is working with NOAA Fisheries Science Centers to study deepwater corals. In 2010, the sanctuary used its own funding to add water chemistry measurements to the project, and in 2011, the deepwater coral budget covered water chemistry.[97] A number of studies are underway in the Florida Keys National Marine Sanctuary on coral growth rates and other processes in relation to changes in ocean chemistry.[98]

The Office of National Marine Sanctuaries is developing the concept of sanctuaries as "sentinel sites," which would provide information on an ongoing basis to improve forecasts, assess vulnerability of marine species and ecosystems, and develop adaptation strategies. The National Ocean Council's draft strategic plan incorporates the sentinel site concept. National marine sanctuaries, along with other marine areas that are protected, are likely candidates for this approach.[99]

In addition to their outstanding natural assets, sanctuaries have assets in the form of infrastructure and personnel that can be put to use. Sanctuaries' infrastructure includes boats, buoys, and instruments that can be used for monitoring coastal and ocean chemistry. Their programs include education and outreach activities that incorporate education on ocean acidification and on mitigation activities—such as reducing pollution that flows into coastal waters from on-shore activities—which can be carried out at the local and regional levels.

Each national marine sanctuary has the capacity to tie the challenge of ocean acidification to a special place known and loved by residents and visitors, whether they are schoolchildren, business people, fishermen, birdwatchers, beachcombers, sailors, or surfers. Through these special connections, sanctuaries can bring the public into the search for answers and solutions to ocean acidification.

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95. Dan Howard, NOAA, personal communication, September 21, 2011; Dr. Richard Feely, personal communication, October 11, 2011.

96. Greg Boland, BOEM, personal communication, October 4, 2011.

97. Dan Howard, NOAA, personal communication, September 21, 2011.

98. Dr. Steve Gittings, NOAA, personal notes, September 2010.

99. National Ocean Council, "Draft National Ocean Policy Implementation Plan," January 12, 2012, p. 55, http://www.whitehouse.gov/sites/default/files/microsites/ceq/national_ocean_policy_draft_implementation_plan_01-12-12.pdf.

NOAA Funding for FY08–FY11

As described above, many of NOAA's programs are involved in work on ocean acidification.[100] NOAA is funded in the Commerce, Justice, Science, and Related Agencies Appropriations Act, and the appropriations category is "Operation, Research, and Facilities."

(See funding table on next page.)

100. Sources for FY10 and FY11 budget figures: Dr. Elizabeth Jewett, NOAA, personal communication, October 24, 2011, and email to author, February 9, 2012; "CRCP Ocean Acidification Funding, Fiscal Years 2008–2011," Coral Reef Conservation Program (internal document).

TABLE 3. NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION FUNDING
(in thousands of dollars)

	APPROPRIATION: OPERATION , RESEARCH AND FACILITIES	FY08	FY09	FY10	FY11	Activity classification
Contributing & primary funding in FY08–FY09	Oceanic and Atmospheric Research (OAR)					
	➤ Pacific Marine Environmental Laboratory and Atlantic Oceanographic & Meteorological Laboratory	4,228	3,982			Contributing
	National Marine Fisheries Service (NMFS)					
	➤ NMFS Regional Science Centers	75	120			Primary
	➤ NMFS's contribution to National Research Council Study	200	197			Primary
	National Ocean Service (NOS)					
	➤ Coral Reef Conservation Program/Coral Reef Ecosystem Division of Pacific Islands Fisheries Science Center	20	52			Primary
	➤ Coral Reef Conservation Program/AOML	83	169			Primary
	➤ National Marine Sanctuaries, National Estuarine Research Reserves, etc.	n/a	n/a			
	National Environmental Satellite, Data, and Information Service (NESDIS)	22	14			Primary
Funding in FY10–FY11	Oceanic and Atmospheric Research (OAR)					
	➤ Pacific Marine Environmental Laboratory and Atlantic Oceanographic & Meteorological Laboratory & cooperative partners and Ocean Acidification Program*			4000	4420	
	National Marine Fisheries Service/NMFS Regional Science Centers			1500	1757	
	National Ocean Service (NOS)					
	➤ Coral Reef Conservation Program/Coral Reef Ecosystem Division of Pacific Islands Fisheries Science Center			150	150	
	➤ Coral Reef Conservation Program/AOML			410	435	
	➤ Coral Reef Conservation Program/Southeast Fisheries Science Center				125	
	➤ National Marine Sanctuaries, National Estuarine Research Reserves, etc.			n/a	n/a	
	➤ Integrated ocean observing systems				175	
Totals	Total Contributing	4,228	3,982			Contributing
	Total Primary	400	552			Primary
	TOTAL	4,628	4,534	6,060	7,062	Total

* NOAA's Ocean Acidification Program was officially established in May 2011. Funding for OA research in NOAA is largely managed by the program going forward. Funding in blue was handled by the Ocean Acidification Program.

National Science Foundation

The National Science Foundation (NSF) plays a major role in research on ocean acidification, primarily in the investigation of the basic chemical and biological mechanisms of ocean acidification and the nature of ocean acidification's impact on Earth system history. This role is a natural fit for NSF, given its mission and purpose, as established when this independent federal agency was created in 1950: "To promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense . . . ."[101] NSF funds research and education in most fields of science and engineering, through grants and cooperative agreements to colleges, universities, elementary and secondary schools, businesses, and other science and research organizations.[102]

Although the FOARAM Act of 2009 reinforced the role of NSF in ocean acidification, as well as authorizing funding specifically for NSF, the agency was already involved in ocean acidification research. Prior to 2010, however, research proposals on ocean acidification were largely unsolicited. Most were funded in the Division of Ocean Sciences, which is part of the Directorate for Geosciences.[103]

In 2010, NSF began tracking ocean acidification as a formal initiative. In January 2010, NSF put out a formal call for research proposals on ocean acidification[104] under the ocean acidification theme of its Climate Research Investment, an NSF-wide effort to provide insight into the fundamental processes underlying climate change and related impacts.[105] The goal of the solicitation is to:

a) understand the chemistry and physical chemistry of ocean acidification;
b) understand how ocean acidification interacts with processes at the organismal level; and
c) understand how the earth system history informs our understanding of the effects of ocean acidification on the present day and future ocean.

In October 2010, NSF announced 21 awards totaling $24,099,080[106] to "foster research on the nature, extent and effects of ocean acidification on marine environments and organisms in the past, present and future—from tropical systems to icy seas." The grants are managed by NSF's Office of Polar Programs, Directorate for Geosciences, and Directorate for Biological Sciences. The duration of the grants can be as long as four years for full research projects, with shorter periods for Early Concept Grants for Exploratory Research (EAGER) (two years) and community and capacity-building projects.[107]

In October 2011, NSF issued its second acidification solicitation[108] as part of the Science, Engineering and Education for Sustainability (SEES) portfolio. NSF anticipates making 10 to 15 awards totaling $10 million, depending on availability of funds. As with the first

101. National Science Foundation Act of 1950, Public Law 81-507.

102. "About NSF: How We Work," National Science Foundation website, http://www.nsf.gov/about/how.jsp.

103. Dr. Phillip Taylor, personal communication, September 26, 2011.

104. National Science Foundation, "Ocean Acidification: Program Solicitation, NSF 10-530," January 25, 2010, http://www.nsf.gov/publications/pub_summ.jsp?ods_key=nsf10530 and http://www.nsf.gov/pubs/2010/nsf10530/nsf10530.htm.

105. "NSF Climate Research Investment," NSF website, http://www.nsf.gov/geo/cri/, accessed fall 2011.

106. National Science Foundation, " NSF Awards Grants to Study Effects of Ocean Acidification: Projects Address Concern for Acidifying Marine Ecosystems," Press Release 10-186, October 13, 2010, http://nsf.gov/news/news_summ.jsp?cntn_id=117823; National Science Foundation, "Ocean Acidification: Program Solicitation, NSF 12-500," see Important Information and Revision Notes, p. 1.

107. Ocean Acidification, Program Solicitation, NSF 10-530, p. 2, see n. 104.

108. Ocean Acidification, Program Solicitation, NSF 12-500, see n. 106.

round, the grants will be managed by NSF's Office of Polar Programs, Directorate for Geosciences, and Directorate for Biological Sciences. The duration of the grants can be as long as four years for regular research projects, five years for Research Coordination Networks, or two years for EAGER.[109] Researchers' proposals were due in January 2012.

While most NSF funding for ocean acidification research is distributed through grant programs, several other programs are making contributions on this issue as well, such as the Long Term Ecological Research (LTER) network. NSF funds LTER through universities and research institutions that are conducting research on ecological processes at 26 sites around the U.S. over an extended period of time; seven of the sites are coastal.[110] Other NSF programs that have invested in research on ocean acidification include the Biological Oceanography Program, the Chemical Oceanography Program, the Marine Geology and Geophysics program, the Antarctic Organisms and Ecosystems Program, the Geobiology and Low-Temperature Geochemistry Program, and the Program on Dynamics of Coupled Natural and Human Systems.[111] With assistance from NOAA and the Office of Naval Research, NSF funds the Centers for Ocean Science Education Excellence (COSEE) program to educate students and the public about oceans and the Great Lakes through a network of regional centers.[112]

The Ocean Observatories Initiative (OOI), set up under a cooperative agreement with the Consortium for Ocean Leadership, will provide significant contributions to our understanding of ocean acidification. The OOI is in the process of constructing a network of sensors to measure the physical, chemical, geological, and biological variables in the ocean and seafloor.[113] These interactive sensors, both stationary and mobile, will collect data at high sampling rates, which will be available to researchers for measuring short-lived events (such as storms) and longer-term phenomena, such as acidification. The need for improved instrumentation to study ocean acidification provided an important rationale for OOI. Core sensors, which will be installed as part of the initial investment, include measurements related to ocean acidification.[114] The first data streams will come from coastal gliders in 2012, and all core infrastructure and instruments are expected to be operating by late 2014.[115]

NSF Funding for FY08–FY11[116]

NSF is funded in the Commerce, Justice, Science, and Related Agencies Appropriations Act, and the appropriations category under NSF is "Research and Related Activities."

109. Ibid., p. 7.

110. Agency Activities, IWG-OA website, http://www.st.nmfs.noaa.gov/iwgoa/pages/activities.html#NSF; "The US Long Term Ecological Research Network," LTER website, http://www.lternet.edu/, accessed fall 2011; Dr. David Garrison, NSF, email to author, February 17, 2012.

111. Agency Activities, IWG-OA website, http://www.st.nmfs.noaa.gov/iwgoa/pages/activities.html#NSF; accessed fall 2012, Dr. Phillip Taylor, NSF, email to author, February 6, 2012.

112. "COSEE: Centers for Ocean Science Education Excellence," COSEE website, http://www.cosee.net/accessed fall 2011.

113. "OOI Embarks on New Era of Ocean Observing," Ocean Observatories Initiative website, http://www.oceanobservatories.org/about/, accessed fall 2011.

114. OOI Science Prospectus, "Ocean Observatories Initiative (OOI) Scientific Objectives and Network Design: A Closer Look," (October 10, 2007), p. 8, and Appendix B: Legend for Sensors Listed in Science Traceability Matrices, http://www.oceanleadership.org/files/Science_Prospectus_2007-10-10_lowres_0.pdf.

115. "About: OOI Frequently Asked Questions," OOI website, http://www.oceanobservatories.org/about/frequently-asked-questions/#5, accessed fall 2011.

116. FY10 and FY11 budget information: Dr. David Garrison, NSF, mail and personal communications with author, February 17 and 21, 2012.

TABLE 4. NATIONAL SCIENCE FOUNDATION FUNDING (in thousands of dollars)

	APPROPRIATION: RESEARCH AND RELATED ACTIVITIES	FY08	FY09	FY10	FY11	Activity classification
Contributing & primary funding in FY08–FY09	Directorate of Geosciences, Division of Ocean Sciences (GEO/OCE) Directorate of Biological Sciences (BIO) Office of Polar Programs (OPP)	3,923	8,618			Contributing
	Directorate of Geosciences, Division of Ocean Sciences (GEO/OCE) Directorate of Biological Sciences (BIO) Office of Polar Programs (OPP)	912	2,861			Primary
Funding in FY10–FY11	Directorate for Geosciences, Division of Ocean Sciences (GEO/OCE) Directorate of Biological Sciences (BIO) Office of Polar Programs (OPP)			20,848	10,264	Classification unavailable
TOTALS	Total Contributing	3,923	8,618			Contributing
	Total Primary	912	2,861			Primary
	TOTAL	4,835	11,479	20,848	10,264	TOTAL

U.S. Department of the Interior—United States Geological Survey

The United States Geological Survey (USGS), established in 1879 and later folded into the U.S. Department of the Interior, conducts research on ocean acidification on the basis of numerous statutes authorizing scientific inquiry. Its mission is to "serve the Nation by providing reliable scientific information to describe and understand the Earth; minimize loss of life and property from natural disasters; manage water, biological, energy, and mineral resources; and enhance and protect our quality of life."[117]

USGS is researching ocean acidification in regions that are polar (the Arctic), temperate and subtropical (Florida/Gulf of Mexico), and tropical (Caribbean and other areas). Researchers are developing new approaches to observing and modeling seawater chemistry and are assessing the effects of acidification on the physiology of organisms and on marine ecosystem structure. Researchers are building comprehensive records of the growth of coral reefs in modern times, taking core samples to measure growth of corals in pre-industrial times in relation to changes in ocean pH, and using underwater chambers to test responses of coral colonies to the more acidic conditions likely in future years. This information will enable scientists to develop predictions of the future impacts of ocean acidification and sea-level rise on coral reefs.[118]

117. "About USGS," USGS website, http://www.usgs.gov/aboutusgs/, accessed fall 2011.

118. "Ocean Acidification, Tropical Regions: Coral Reefs," USGS's St. Petersburg Coastal and Marine Science Center website, http://coastal.er.usgs.gov/ocean-acidification/tropical.html, accessed fall 2011; K.K. Yates and R.P. Moyer, "Effects of Ocean Acidification and Sea-Level Rise on Coral Reefs: U.S. Geological Survey Fact Sheet 2010-3091," (USGS, 2010) http://pubs.usgs.gov/fs/2010/3091/.

USGS and its partners are collecting high-resolution chemical oceanographic and microbial data in the Arctic Ocean and on temperate and tropical shelves in the U.S. in order to map and investigate the role of ocean acidification on processes associated with sinks and sources of carbon. These data are being used to refine predictive models of future water quality and ecosystem change. The results will be used by managers and policy makers to govern natural resources more effectively.[119]

USGS Funding for FY08–FY11[120]

USGS is funded in the Department of the Interior, Environment, and Related Agencies Appropriations Act, and USGS activities on ocean acidification are funded under the "Surveys, Investigations, and Research" appropriation category. Prior to FY12, funding fell primarily under these programs:[121]

- Geologic Hazards, Resources, and Processes—Coastal and Marine Geology
- Biological Research—Terrestrial, Freshwater and Marine Environment

The President's FY12 budget request reflected the reorganization of USGS, and ocean acidification will be primarily funded under these programs:[122]

- Ecosystems—Terrestrial, Freshwater and Marine Environment
- Natural Hazards—Coastal and Marine Geology

NOTE: The significantly lower figures for FY10 and FY11 are due to the unavailability of information on many "contributing" activities, not to a significant change in USGS's commitment to the issue.

TABLE 5. UNITED STATES GEOLOGICAL SURVEY FUNDING (in thousands of dollars)

APPROPRIATION: SURVEYS, INVESTIGATIONS, AND RESEARCH	FY08	FY09	FY10	FY11	Activity classification
Research in several program categories	7,635	7,666	614	614*	Contributing
Research in several program categories	1,253	1,546	1431	1431*	Primary
TOTAL	8,888	9,212	2,045	2,045	TOTAL

* Budget figures were unavailable for FY11 but expected to be similar to FY10.

119. Dr. Lisa Robbins, USGS, email message to author, February 20, 2012.

120. FY10 and FY11 budget information: Dr. Lisa Robbins, USGS, email to author, October 31, 2011.

121. USGS 2011 budget highlights, see Highlights of Budget Changes on p. BH-52, http://www.doi.gov/budget/2011/11Hilites/BH047.pdf; Posted on "FY 2011 Budget and Related Information," USGS Office of Budget, Planning and Integration website, http://www.usgs.gov/budget/2011/2011index.asp, accessed fall 2011.

122. USGS 2012 budget highlights, see Highlights of Budget Changes on p. BH-55, http://www.doi.gov/budget/2012/12Hilites/BH051.pdf. Posted on "FY 2012 Budget and Related Information," USGS Office of Budget, Planning and Integration website, http://www.usgs.gov/budget/2012/2012index2.asp, accessed fall 2011.

U.S. Department of the Interior—Bureau of Ocean Energy Management

The Bureau of Ocean Energy Management (BOEM), an agency of the U.S. Department of the Interior, is responsible for overseeing the development of energy and mineral resources on the Outer Continental Shelf, the submerged federal lands off the U.S. coasts. Created as a separate agency on October 1, 2011, BOEM was previously part of the Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE), which was formerly named the Minerals Management Service and renamed BOEMRE in June 2010.[123]

BOEM is contributing to our understanding of ocean acidification through research in the Arctic Ocean and the Gulf of Mexico under its Environmental Studies Program, which conducts ocean research to provide science in support of decisions regarding oil and gas leasing of the Outer Continental Shelf. BOEM scientists and partners are currently engaged in research in the Chukchi Sea on the current status of the ecosystem and its vulnerability to acidification or other aspects of climate change.[124] The agency is also engaged in long-term monitoring, including pH measurements at coral reefs on the Flower Garden Banks in the Gulf of Mexico. In addition, monitoring of deepwater corals in the Gulf, conducted in collaboration with NOAA, is not focused primarily on ocean acidification but can provide useful information.[125]

BOEM/BOEMRE/MMS Funding for FY08–FY11[126]

As described above, the agency was renamed and subdivided in this time period. In each fiscal year, these research activities were funded through the agency's Environmental Studies Program, which is now part of the BOEM.[127] The Environmental Studies Program falls under the Office of Environmental Programs.

BOEM is funded in the Department of the Interior, Environment, and Related Agencies Appropriations Act. Through FY11, the Environmental Studies Program was under the "Royalty and Offshore Minerals Management" appropriations category. In FY12, it was in the "Environmental Assessment" category.[128]

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123. U.S. Department of the Interior, "Salazar Swears-In Michael R. Bromwich to Lead Bureau of Ocean Energy Management, Regulation and Enforcement: Secretarial Order Begins Reorganization of Former MMS," news release, June 21, 2010, http://www.doi.gov/news/pressreleases/Salazar-Swears-In-Michael-R-Bromwich-to-Lead-Bureau-of-Ocean-Energy-Management-Regulation-and-Enforcement-Secretarial-Order-Begins-Reorganization-of-Former-MMS.cfm.

124. Dr. Richard Prentki,BOEM, email messages to author, September 23, 2011, and February 1, 2012. This project requires equal matching funds ($757,000 in dollars or other support) from the University of Alaska Fairbanks, BOEM's partner in the study through a cooperative agreement. This is the "primary" research project in the BOEM funding table.

125. Greg Boland, USGS, personal communication and email message to author, October 4, 2011.

126. FY10 and FY11 information for USGS is from communications with Dr. Richard Prentki (email messages to author, September 23, October 5 and 24, 2011, and February 1, 2012); Greg Boland (personal communication and email message, October 4, 2011); and Dr. Mary Boatman (email message to author, October 27, 2011).

127. *Organizational structure for FY08 through FY10:* Minerals Management Service → Royalty and Offshore Minerals Management (ROMM) → Offshore Minerals Management (OMM) → Leasing and Environmental Subactivity → Environmental Studies Program.

Organizational structure for FY11: Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) → Royalty and Offshore Minerals Management (ROMM) → Offshore Minerals Management (OMM) → Leasing and Environmental Subactivity → Environmental Studies Program.

128. Joint Statement of the Managers, Division E-Department of Interior, Environment, and Related Agencies, p. 58I, http://rules.house.gov/Media/file/PDF_112_1/legislativetext/HR2055crSOM/psConference%20Div%20E%20-%20SOM%20OCR.pdf.

TABLE 6. BUREAU OF OCEAN ENERGY MANAGEMENT AND PREDECESSOR AGENCIES FUNDING
(in thousands of dollars)

APPROPRIATION THROUGH FY11: ROYALTY AND OFFSHORE MINERALS MANAGEMENT FY12: ENVIRONMENTAL ASSESSMENT	FY08	FY09	FY10	FY11	Activity classification
Environmental Studies Program	3,012	125	1,050	845	Contributing
Environmental Studies Program	490	0	67	200	Primary
TOTAL	3,502	125	1,117	1,045	Total

U.S. Department of the Interior—Fish and Wildlife Service

The mission of the U.S. Fish and Wildlife Service (FWS), a bureau of the U.S. Department of the Interior, is to "work with others to conserve, protect and enhance fish, wildlife and plants and their habitats for the continuing benefit of the American people."[129] The FOARAM Act identified the FWS as one of the agencies to participate in the Interagency Working Group on Ocean Acidification (IWG-OA).[130] The FWS has responsibility for conservation of many species that may be affected directly or indirectly by changes in marine food webs, including migratory seabirds, threatened and endangered species, and some species protected under the Marine Mammal Protection Act. The FWS also manages the 556-unit National Wildlife Refuge System, which includes 180 units that protect ocean, coastal, or Great Lakes habitats and resources,[131] and shares responsibility for managing four large marine national monuments in the Pacific Ocean.[132] These refuges protect some of the most remote and pristine coral reefs in the world, which serve as natural laboratories for studying the effects of climate change and ocean acidification in the absence of other major human disturbances.[133]

The FWS is developing a National Biological Inventory and Monitoring (I&M) Partnership for the National Wildlife Refuge System, as part of the strategic plan to respond to climate change. The goal of the program is to implement a nationally coordinated effort to support inventories and monitoring—on a refuge, landscape, regional, and national scale—to inform management and evaluate the effectiveness of strategies to support adaptation to climate change and other major environmental stressors. The I&M program is compiling a suite of monitoring parameters to assess impacts of increasing seawater pH on coral organisms and other reef-building species that may be affected by ocean acidification. With the development of a comprehensive I&M program, the National Wildlife Refuge System will serve as a valuable research tool and natural laboratory for monitoring the effects of global climate change and ocean acidification.[134]

129. "About the U.S. Fish and Wildlife Service," USFWS website, http://www.fws.gov/help/about_us.html, accessed fall 2011.

130. FOARAM Act, Public Law 111-11, Section 12404(a)(2).

131. "Welcome to the National Wildlife Refuge System," U.S. Fish and Wildlife Service National Wildlife Refuge System website, http://www.fws.gov/refuges/, accessed fall 2011.

132. NOAA shares management of all four, and the State of Hawaii also shares management for one. IWG-OA website, http://www.st.nmfs.noaa.gov/iwgoa/pages/activities.html#DOI, accessed fall 2011.

133. Bret Wolfe, FWS, email message to author, February 16, 2012.

134. Bret Wolfe, FWS, email message to author, February 16, 2012; also, U.S. Fish and Wildlife Service, "Strategic Plan for Inventories and Monitoring on National Wildlife Refuges: Adapting to Environmental Change," (National Wildlife Refuge System, Natural Resources Program Center, 2009).

U.S. Department of State & U.S. Agency for International Development

Ocean acidification is an emerging issue in various international forums and has implications for a broad array of ocean issues for the United States. The complexity of the issue and its interconnections with many other ocean and marine resource issues—such as sustainable fisheries, ocean ecosystem health, and food security—indicate that it will grow in importance in many international forums, including regional and bilateral bodies.

The State Department, as the federal agency with primary responsibility for foreign relations, will play an increasingly important role as the issue of ocean acidification gains greater prominence in international relations. The Bureau of Oceans and International Environmental and Scientific Affairs (OES) is taking the lead for the Department in developing policy.[135] Within OES, the Office of Ocean and Polar Affairs and the Office of Marine Conservation are the most involved in crafting a policy framework.[136] The OES Office of Global Change is also following this issue. At some point, the State Department will lead an interagency process to develop a U.S. government position to guide representatives of the U.S as they participate in international meetings and negotiations.[137]

While the OES bureau is the most active within the department on issues related to ocean acidification, the Special Envoy for Climate Change, who reports directly to the Secretary of State, represents the United States in climate change negotiations, including the United Nations Framework Convention on Climate Change, which is the primary forum for international negotiations on reducing greenhouse gas emissions.[138] The envoy works closely with experts in OES.[139]

The U.S. Agency for International Development (USAID) is working to incorporate climate considerations into its programs, with the goal of helping developing countries invest in sustainable economic growth that will be resistant to climate change, as well as reducing greenhouse gas emissions.[140] In January 2012, USAID released its "Climate Change and Development Strategy 2012–2016," which identifies ocean acidification as one of the challenges climate change poses to developing countries.[141]

U.S. Environmental Protection Agency

A broad range of statutory authorities underpin the mission of the Environmental Protection Agency (EPA) to "protect human health and the environment,"[142] including ocean and coastal waters. As a regulatory agency, EPA is likely to play a larger role in implementing strategies to mitigate ocean acidification than in the research arena.

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135. IWG-OA website, Agency Activities, http://www.st.nmfs.noaa.gov/iwgoa/pages/activities.html#DOS, accessed fall 2011.

136. These two offices are in the Oceans and Fisheries Directorate within the Bureau of Oceans and International and Environmental and Scientific Affairs (OES), http://www.state.gov/g/oes/ocns/index.htm.

137. Adrianna Muir, State Department, personal communication, October 12, 2011.

138. "Office of the Special Envoy for Climate Change," U.S. Department of State website, http://www.state.gov/s/climate/index.htm, accessed fall 2012.

139. Personal communication, Adrianna Moore and Gillian Bowser, State Department, October 12, 2011.

140. Kit Batten, "A Leader in Green Development: Message from the Global Climate Change Coordinator," USAID Frontlines (June/July 2011), http://www.usaid.gov/press/frontlines/fl_jun11/FL_jun11_BATTEN.html.

141. USAID Climate Change Policy Task Team, "USAID Climate Change and Development Strategy, 2012–2016," January 2012, http://www.usaid.gov/our_work/environment/climate/policies_prog/development_strategy.html.

142. "About EPA: Our Mission," U.S. Environmental Protection Agency website, http://www.epa.gov/aboutepa/, accessed fall 2011.

EPA scientists in the Office of Research and Development (ORD) have conducted several studies on corals and ocean acidification. While no ocean acidification-specific studies are currently underway, EPA is conducting assessments of the size of stony corals in reefs in the Virgin Islands (completed) and Puerto Rico (underway), which will contribute information useful for understanding ocean acidification.[143] In addition, ORD has been manipulating carbonate chemistry in seawater flow-through experiments to develop assays and models for predicting stressor effects on estuarine species and food webs.[144]

EPA Funding for FY08–FY11[145]

EPA is funded in the Department of the Interior, Environment, and Related Agencies Appropriations Act. Funding for these research activities falls under the "Environmental Programs and Management" appropriation, in ORD, the agency's scientific research arm.

TABLE 7. ENVIRONMENTAL PROTECTION AGENCY FUNDING
(in thousands of dollars)

APPROPRIATION: ENVIRONMENTAL PROGRAMS AND MANAGEMENT	FY08	FY09	FY10	FY11	Activity Classification
Office of Research and Development, Gulf Ecology Division	2,000	2,000	2,279	2,279	Contributing
Office of Research and Development, Gulf Ecology Division	550	0	0	0	Primary
Total	2,550	2,000	2,279	2,279	Total

U.S. Navy

In 2009, the Navy set up Task Force Climate Change, directed by the Oceanographer of the Navy, to make recommendations to Navy leadership regarding the implications of climate change for its mission in the Arctic region and around the world.[146] As a participant in the IWG-OA, the Navy has as its main interest the implications of acidification for fisheries. Reductions or regional shifts in fisheries, such as from the middle latitudes to the Arctic, could increase instability around the world by threatening food supplies.[147] Concerns have been raised that changes in pH, by changing the acoustics in the ocean, could affect naval operations. However, recent research shows no observable change in acoustical absorption in the upper levels of the ocean, and a statistically insignificant change in the deep water environment.[148]

143. Dr. William Fisher, EPA, personal communication, September 22, 2011.

144. Dr. Jason Grear, EPA, email message to author, February 8, 2012.

145. FY10 and FY11 funding information: Dr. William Fisher, EPA, personal communication on September 22 and November 25, 2011, and email messages to author, November 23, 2011.

146. "Climate Change," U.S. Navy Energy Environment and Climate Change website, http://greenfleet.dodlive.mil/climate-change/.

147. "Agency Activities," IWG-OA website, http://www.st.nmfs.noaa.gov/iwgoa/pages/activities.html#Navy.

148. D.B. Reeder, C.-S. Chiu, "Ocean Acidification and its Impact on Ocean Noise: Phenomenology and Analysis," JASA Express Letters, published online, *Journal of the Acoustical Society of America* 128, no. 3 (August 19, 2010): EL137-EL143.

Total Agency Funding for Ocean Acidification

The figures from the individual agency tables above are summarized in this table. As explained on page 16, the budget figures for FY10–FY11 should be regarded as providing a general sense of the direction of each agency's program, rather than as a precise representation of funding in those two years. Comparisons between FY08–FY09 and FY10–FY11 should be general in nature, since the methodologies used by most of the agencies for preparing the FY08–FY09 figures, and for categorizing projects as "primary" or "contributing," were not available to us for this report. In addition, we were not able to obtain figures for "contributing" projects for FY10–FY11 for some agencies (NASA, USGS), or to distinguish between primary and contributing projects for some agencies (NOAA, NSF).

TABLE 8. TOTAL OCEAN ACIDIFICATION FUNDING (in thousands of dollars)

	FY08	FY09	FY10	FY11	Activity classification
NASA contributing	4,882	4,654	n/a	n/a	Contributing
NASA primary	207	192	500	500	Primary
NASA Total	5,089	4,846	500*	500*	Total
NOAA contributing	4,228	3,982	n/a	n/a	Contributing
NOAA primary	400	552	n/a	n/a	Primary
NOAA Total	4,628	4,534	6,060	7,060	Total
NSF contributing	3,923	8,618	n/a	n/a	Contributing
NSF primary	912	2,861	n/a	n/a	Primary
NSF Total	4,835	11,479	20,848**	10,263	Total
USGS contributing	7,635	7,666	614	614	Contributing
USGS primary	1,253	1,546	1431	1431	Primary
USGS Total	8,888	9,212	2,045*	2,045*	Total
BOEM contributing	3,012	125	1,050	845	Contributing
BOEM primary	490	0	67	200	Primary
BOEM Total	3,502	125	1,117	1,045	Total
EPA contributing	2,000	2,000	2,279	2,279	Contributing
EPA primary	550	n/a	n/a	n/a	Primary
EPA Total	2,550	2,000	2,279	2,279	Total
GRAND TOTAL	29,492	32,196	32,849	23,192	GRAND TOTAL

* The significantly lower figures for NASA and USGS in FY10 and FY11 are due to the unavailability of information on many "contributing" activities, not to a significant change in commitment to the issue.

** FY10 increase is due to the FY10 solicitation for proposals on ocean acidification.

VI. Projections for Future Federal Agency Research and Monitoring Funding

The previous section reviewed and estimated actual federal agency expenditures for ocean acidification research and monitoring for FY08 through FY11. This section surveys estimates of investments needed by these agencies to carry out a comprehensive program of research and monitoring on ocean acidification. Sources include estimates from the research community, the Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009, and agency staff.

Estimate from the Research Community

Although scientists have repeatedly come together to develop the research agenda on ocean acidification, estimates of the funding needed to support the agenda have not been part of these discussions. An estimate is available from the Ocean Carbon and Biochemistry (OCB) program, however, which supports study of the evolving role of the ocean in the global carbon cycle. In March 2009, the OCB program's Ocean Acidification Subcommittee issued a white paper that laid out a strategy for a U.S. national research program and included estimates of the costs of a comprehensive program.[149]

Based on the budgets for carrying out previous multi-agency research programs, the OCB white paper estimated that a U.S. national research program on ocean acidification would need in the order of $50–$100 million per year to provide timely information for managers and decision-makers. According to the white paper, "$30 million may be appropriate for the first 2–3 years, while large-scale efforts are still being planned, but once the program is fully engaged, $50–$100 million per year is considered the *minimum* if scientists are to provide useful information regarding how the oceans are responding to acidification, and how we should change our mitigation and adaptation strategies."[150] (Emphasis in original.)

Federal Ocean Acidification Research and Monitoring Act of 2009

The FOARAM Act, passed in 2009, provides another estimate of investment needs. The bill authorizes $8 million for the National Oceanic and Atmospheric Administration (NOAA) in FY09, ramping up to $20 million in FY12. It authorizes $6 million for NSF in FY09, ramping

149. OCB Ocean Acidification Subcommittee White Paper, "Ocean Acidification: Recommended Strategy for a U.S. National Research Program," May 25, 2009, p. 8, http://www.us-ocb.org/publications/OCB_OA_Whitepaper.pdf.

150. Ibid

up to $15 million in 2012, for a FY12 total of $35 million for two agencies. The bill clearly indicates that other federal agencies should be involved, as well, even though specific funding authorizations are not provided.[151]

Strategic Plan for Federal Research and Monitoring on Ocean Acidification

As described on page 13, the Interagency Working Group on Ocean Acidification has prepared a draft of the ten-year Strategic Plan required by the FOARAM Act. Rather than categorizing activities by federal agency, the Strategic Plan is organized around seven priority themes. Above, we list the seven themes and the detailed recommendations and goals emphasized under the themes. The draft plan also proposes a national program and national program office to coordinate and integrate the activities in the plan; a national data management office; and national program activities in the area of technology development and standardization of measurements, as well as the area of education, outreach, and engagement.[152]

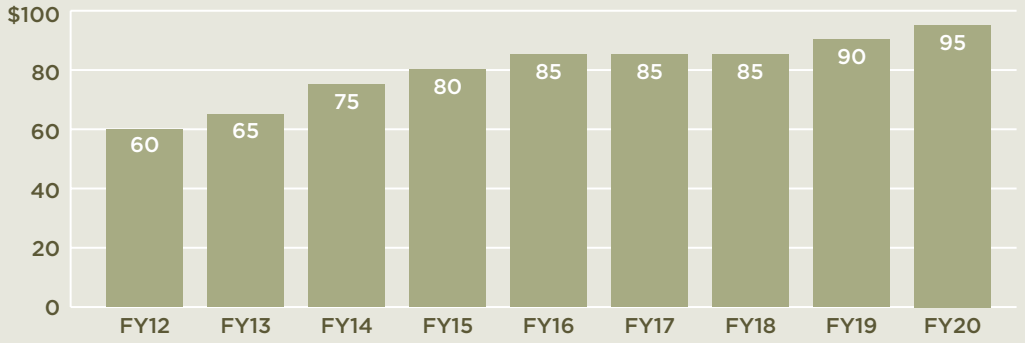
Some of the activities and approaches described in the plan are underway in the federal agencies involved in ocean acidification research, while others—such as the socioeconomic impacts of ocean acidification—are in early stages of development.

The draft Strategic Plan does not contain estimates of the funding that would be needed to execute it. Comparing the activities in the Strategic Plan to current activities, however, makes it clear that federal agencies' ocean acidification projects and programs will need to ramp up significantly in order to carry out the plan.

Other Estimates of Agency Resources Needed

Through discussions with individuals at a number of different federal agencies, we learned that some efforts have been made to estimate investment needs over the next ten years, both for cross-cutting activities such as a national program office and for funding within agencies. This information should be viewed as a broad estimate of the need for ocean acidification funding.

FIGURE 2. INTERNAL ESTIMATES OF FUNDING NEEDED (millions of dollars)



151. FOARAM Act, Public Law 111-11, Section 12409.

152. Interagency Working Group on Ocean Acidification, "Strategic Plan for Federal Research and Monitoring on Ocean Acidification," May 2011—draft for review.

VII. Existing Legal Authorities on Ocean Acidification

Federal funding is also needed in the near and long term for mitigation—alleviating the causes of ocean acidification—and for adaptation—reducing the vulnerability of marine ecosystems to ocean acidification. Federal agencies are focusing their activities on research, rather than mitigation or adaptation, because so many questions remain to be answered about the effects of ocean acidification on marine species and food webs.

To a significant degree, mitigation and adaptation in the U.S. are likely to be accomplished through existing environmental laws, as well as new laws and regulatory approaches. However, little attention has been paid to regulatory activities specifically relating to ocean acidification. Estimates of staff and budget resources needed by federal agencies to carry out regulatory activities on this issue appear to be largely non-existent, other than some estimates obtained for this report on potential regulation of corals under the Endangered Species Act.

Nonetheless, as described below, regulatory actions that have the potential to mitigate local and regional effects of acidification are moving forward under the Clean Water Act and Endangered Species Act. In each case, federal government activities are driven by litigation.

Legal Authorities under the EPA

EPA's role in research and monitoring of ocean acidification is minor, but EPA will play a significant role in the use of existing laws and regulations, and new laws in the future, to mitigate ocean acidification.

Clean Water Act

Recently, the Clean Water Act (CWA) has come into play as a tool for reducing the impacts of ocean acidification on coastal ecosystems. The CWA[153] is the primary law protecting the quality of surface water in the United States. Its objective is "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters."[154] The CWA requires

153. 33 U.S.C. §1251 et seq. (1972), officially titled the Federal Water Pollution Control Amendments of 1972.
154. 33 U.S.C. § 1251(a).

each state and territory to designate uses for each of its water bodies (such as drinking water or recreation), and then to set criteria that protect those uses.[155]

Although the CWA is often seen as a law governing freshwater rivers and lakes, in fact, it is highly relevant to ocean acidification. In addition to covering inland waters, the law covers coastal waters within state jurisdiction (within three miles of land) and federal ocean waters (beyond three miles).[156] In addition, streams and rivers flowing into the ocean have considerable impact on the pH of coastal waters. Benefits of employing the CWA could include increased monitoring and assessment of ocean water quality, developing baseline information against which to gauge impacts, elevating ocean acidification as a priority for water quality management, and identifying areas that are especially vulnerable to acidification.[157]

Under Section 303(d) of the CWA, states[158] are required to develop lists of impaired surface waters, such as specific lakes, segments of streams or rivers, and coastal waters. For the impaired waters on their lists, states must prepare a prioritized schedule for cleanup by developing Total Maximum Daily Loads (TMDLs)—the maximum amount of pollution from various sources that a water body can receive and still meet water quality standards—and an allocation of that load among the various sources of the pollutants. States submit their 303(d) lists to EPA every other year; EPA reviews the lists and sometimes adds additional waters to a state's list.[159]

EPA's current water quality criteria include a criterion for marine pH. In April 2009, in response to a petition from the Center for Biological Diversity to impose stricter standards for ocean pH quality, EPA announced a review of the current criteria for marine pH to determine whether a revision would be warranted, as well as soliciting additional information.[160] In April 2010, EPA announced its decision that the available data is currently not sufficient to revise the national criteria for marine pH, given the natural variability in pH among coastal regions.[161]

In the meantime, the Center for Biological Diversity brought suit against EPA under the CWA for failing to require the state of Washington to list its coastal waters as impaired due to ocean acidification, since pH had declined further than allowed by the state's water quality standard.[162] In 2010, EPA settled the lawsuit, agreeing to consider how states can address ocean acidification in the context of the CWA.[163] EPA announced this review and solicited public comment, receiving more than 30,000 responses.[164]

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155. "Water Quality Standards for Surface Waters," USEPA Water: Water Quality Standards website, http://water.epa.gov/scitech/swguidance/standards/.

156. Public Law 107-303, Sections 101 and 502; 33 U.S.C. § 1362.

157. Miyoko Shakashira, Center for Biological Diversity, email message to author, February 7, 2012.

158. "States" includes territories and authorized tribes. Public Law 107-303, Section 502.

159. USEPA Office of Water, "TMDL Program Results Fact Sheet," July 17, 2009, http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/upload/2009_08_07_tmdl_results_aug_7_integrated_reproting.pdf.

160. "Aquatic Life: Ocean Acidification and Marine pH," USEPA Water: Aquatic Life website, http://water.epa.gov/scitech/swguidance/standards/criteria/aqlife/marine-ph.cfm.

161. "EPA Decision on Whether to Re-evaluate and Revise its Recommended Marine pH Water Quality Criterion," USEPA Water: Total Maximum Daily Loads (303d) website, http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/marine_pH_WQ_criterion_decision_apr2010.cfm.

162. Center for Biological Diversity, "Lawsuit Filed Against Environmental Protection Agency for Failure to Combat Ocean Acidification," news release, May 14, 2009.

163. Center for Biological Diversity, "Legal Settlement Will Require EPA to Evaluate How to Regulate Ocean Acidification Under Clean Water Act," news release, March 11, 2010.

164. Clean Water Act Section 303(d): Notice of Call for Public Comment on 303(d) Program and Ocean Acidification. 75 Fed. Reg. 13537-13540 (March 22, 2010), http://edocket.access.gpo.gov/2010/2010-6239.htm; Miyoko Shakashira, Center for Biological Diversity, email message to author regarding number of public comments, February 8, 2012; see also docket: EPA-HQ-OW-2010-0175 at http://www.regulations.gov.

In November 2010, EPA issued a memorandum affirming that states should include waters that do not meet the water quality standards because of ocean acidification (OA) in their lists of impaired waters. EPA committed to providing additional formal guidance to the states "when future OA research efforts provide the basis for improved monitoring and assessment methods, including approaches being developed under other Federal efforts. EPA also encourages States to focus their efforts on OA-vulnerable waters (e.g., waters with coral reefs, marine fisheries, shellfish resources) that already are listed for other pollutants (e.g., nutrients) in order to promote ecological restoration."[165]

As part of the settlement with the Center for Biological Diversity, EPA agreed to publish technical guidance for establishing coral reef biological criteria. As with physical and chemical standards, biological standards and criteria are enforceable when they support designated aquatic life uses, i.e., assuring water quality that provides for the protection and propagation of fish, shellfish, and wildlife, and recreation in and on the water. States that establish biological criteria for coral reefs (or other sensitive species) would have legal recourse to protect the resources from all anthropogenic threats, including ocean acidification. Biological criteria would most effectively reduce exacerbating pollutants delivered by watershed runoff, because impaired waters could be restored through stricter zoning and permitting requirements in the watershed and coastal zones. But biological criteria are also an important and highly visible reporting mechanism—water bodies impaired by ocean acidification are reported to Congress every two years, which, as was the case with acid rain, could ultimately serve to strengthen Clean Water Act regulations and enforcement.[166]

A number of additional approaches have been proposed for using the CWA to reduce the impacts of ocean acidification on marine life, particularly in coastal areas, by reducing local stressors and increasing the *resilience* of vulnerable species and ecosystems.[167] Resilience can be defined in various ways, among them "the amount of change or disturbance that a system can absorb before it undergoes a fundamental shift to a different set of processes and structures."[168] By reducing other stressors—polluted run-off from the land, overdevelopment of coastal areas, invasive species, and overharvesting of fish and shellfish—marine species and ecosystems may be made more *resilient* to ocean acidification, as well as to warming of the oceans caused by climate change. Given the rapid rate of acidification, however, increasing resilience at best will provide some additional time in which to address the larger problem.

Clean Air Act

Although a detailed discussion of Clean Air Act authorities on greenhouse gases is beyond the scope of this report, it is important to acknowledge that laws and regulations reducing the amount of carbon dioxide entering the atmosphere will be essential to slowing the absorption of excess carbon dioxide by the oceans. On December 7, 2009, EPA Administrator Lisa Jackson took a historic step, signing an "endangerment finding" under the Clean

165. "EPA issues November 15, 2010 Memorandum: Integrated Reporting and Listing Decisions Related to Ocean Acidification," USEPA Water: Total Maximum Daily Loads (303d), http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/oa_memo_nov2010.cfm.

166. William Fisher, EPA, email to author, February 7, 2012. Also, P.A. Bradley, L. S. Fore, W. S. Fisher, and W. S. Davis, "Coral Reef Biological Criteria: Using the Clean Water Act to Protect a National Treasure," EPA/600/R-10/054 (July 2010).

167. L.S. Fore, J.R. Karr, W.S. Fisher, and W.S. Davis, "Editorial: Heeding a Call to Action for US Coral Reefs: The Untapped Potential of the Clean Water Act," *Marine Pollution Bulletin* 58 (2009) 1421–1423.

168. West et al., 2009, cited in National Research Council, "National Strategy," p. 81, see n.2.

Air Act stating that "six greenhouse gases taken in combination endanger both the public health and the public welfare of current and future generations." The endangerment finding includes a specific mention of ocean acidification among the reasons greenhouses gases are endangering public welfare.[169]

Following up on the endangerment finding, EPA moved to set greenhouse gas standards for mobile sources. In 2010, EPA and the National Highway Traffic Safety Administration (NHTSA) issued a joint rule for passenger cars and light-duty vehicles (model years 2012–2016) that improved fuel economy and for the first time set standards for greenhouse gas emissions from vehicles. In August 2011, the two agencies announced final greenhouse gas emissions standards and fuel efficiency standards for medium- and heavy-duty engines and vehicles. In November 2011, EPA and NHTSA proposed standards to reduce greenhouse gas emissions and improve fuel economy standards for passenger cars and light-duty trucks for model years 2017–2025.[170]

EPA is preparing to set greenhouse gas emissions standards for major stationary sources. In March 2012, EPA issued proposed New Source Performance Standards to reduce greenhouse gas emissions from new fossil fuel power plants and petroleum refineries. Proposed standards for existing sources will also be issued in the future.[171]

EPA economists are in the initial stages of incorporating the costs of ocean acidification to society into economic models of the "social cost of carbon," i.e., the cost to society of rising levels of carbon dioxide, expressed in monetized terms. This work is likely to be incorporated in "integrated assessment models" that provide estimates of the social-welfare benefits of reducing carbon emissions and are used to analyze the costs and benefits of specific regulatory proposals.[172]

Other Authorities for Protecting Coastal Resources

Pollutants and soil erosion can contribute directly to acidification of coastal waters, as local studies in the Gulf of Maine, Chesapeake Bay, and Australian waters have shown. Reducing these local and regional stressors on the marine environment will require the use and further development of local, state, regional, and national laws and regulations.

In addition to the CWA, other federal laws (Clean Air Act, Coastal Zone Management Act), state laws, and local ordinances "provide multiple layers of protection for coastal waters by controlling emissions, runoff, and land-use patterns through zoning and permitting. Implementing measures that reduce residential and agricultural runoff, for example, can minimize beach and river contamination and algal blooms, while reducing pollutants that acidify the local coastal ocean."[173]

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169. Endangerment and Cause or Contribute Findings for Greenhouse Gases under Section 202(a) of the Clean Air Act, Final Rule, 74 Fed. Reg. 66496-66546 (December 15, 2009); see also EPA Climate Change—Regulatory Initiatives website, http://epa.gov/climatechange/endangerment.html.

170. "Regulations and Standards," EPA Transportation and Climate/Air and Radiation website, http://epa.gov/otaq/climate/regulations.htm. "Clean Air Task Force's Schneider Discusses Latest Delay on NSPS," E&E Publishing, February 2, 2012.

171. "Addressing Greenhouse Gas Emissions," EPA Air Quality Planning and Standards website, http://www.epa.gov/airquality/ghgsettlement.html.

172. Dr. Chris Moore, EPA, personal communication, September 27, 2011. "About the Office of Policy, National Center for Environmental Economics (NCEE)," EPA website, http://www.epa.gov/aboutepa/opei.html#OSEM.

173. R.P. Kelly et al., "Mitigating Local Causes of Ocean Acidification with Existing Laws," *Science* 332 (May 27, 2011): 1036–1037.

Legal Authorities under NOAA

NOAA is on the verge of a significant expansion of regulatory activity, due in part to the threat posed to coral species by ocean acidification. The Office of Protected Resources within NOAA's National Marine Fisheries Service (NMFS) is responsible for protecting endangered marine life under the Endangered Species Act (ESA).[174] Currently, two coral species, elkhorn and staghorn coral, are listed as threatened.[175]

In October 2009, the Center for Biological Diversity petitioned the agency to protect 83 coral species under the Endangered Species Act (ESA), arguing that these species are facing extinction due to increasing ocean temperatures caused by climate change and the related threat of ocean acidification.[176] In February 2010, NOAA responded to the petition, finding that the threatened or endangered designation may be warranted for 82 of the 83 species, all of which can be found in the U.S., its territories, or its freely associated states.[177] The agency is conducting a status review of the 82 species of corals, which by law was due in October 2010 but is still underway due to the complexity of the review.[178]

Should some or most of the coral species under review be listed as threatened or endangered, as is likely, a number of additional activities will be triggered:[179]

- Decisions regarding whether critical habitat should be designated, and analysis to identify critical habitat, which is either where the species is found, or habitat that will be essential for its conservation;
- Development of recovery plans for the newly listed corals to bring them back to healthy population levels;
- For species listed as "threatened," rather than "endangered," the promulgation of protective regulations, known as 4(d) regulations, which determine to what extent "take"[180] of the threatened species is prohibited; and
- Consultations under ESA Section 7 for all actions by federal agencies that could affect the listed coral species.[181]

Listing the 82 species, or most of them, under the ESA would approximately double the number of species under the jurisdiction of the Office of Protected Resources, greatly exceeding the current resources of the agency to conduct the activities described above. The

174. "Welcome to the Office of Protected Resources," NOAA Fisheries: Office of Protected Resources, http://www.nmfs.noaa.gov/pr/.

175. "Staghorn Coral (Acropora cervicornis)," NOAA Fisheries Office of Protected Resources, http://www.nmfs.noaa.gov/pr/species/invertebrates/staghorncoral.htm.

176. Center for Biological Diversity (CBD), "Protections Sought for 83 Coral Species as Coral Heads for Worldwide Extinction," news release, October 20, 2009. CBD then notified EPA of its intent to sue to compel the agency to respond to the petition: Center for Biological Diversity, "Suit Will Be Filed to Protect 83 Corals Threatened by Global Warming, Ocean Acidification," news release, January 20, 2010.

177. Federal Register Notice, February 10, 2010, 75 Fed. Reg. 6616.

178. NOAA staff, personal communication with author, September 16, 2011.

179. M. Lynne Corn, Eugene H. Buck, and Kristina Alexander, "CRS Report for Congress RL31654/The Endangered Species Act: A Primer," August 2, 2007.

180. The term "take" under the ESA means "to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct." 16 U.S.C. § 1532.

181. CRS RL31654, p. CRS-9: "Federal agencies must ensure that their actions are 'not likely to jeopardize the continued existence' of any endangered or threatened species, nor to adversely modify critical habitat. If federal actions or actions of non-federal parties that require a federal approval, permit, or funding might affect a listed species, the federal action agencies must complete a biological assessment. To be sure of the effects of their actions, the action agency must consult with the appropriate Secretary."

Coral Reef Conservation Program would play an important role in providing scientific support for these ESA activities, since the Office of Protected Resources will need additional expertise on coral species.[182]

To carry out the actions required by the ESA, a significant boost in funding will be needed by the Office of Protected Resources, the Pacific and Southeast regional offices and science centers of the NMFS, and the Coral Reef Conservation Program. According to internal estimates, an additional $5 million per year is likely to be needed starting in FY13.[183] Failure to carry out actions required by the ESA is almost certain to generate additional litigation and the payment of attorneys' fees should the plaintiff prevail.

182. NOAA staff, personal communication with author, September 2011.

183. Ibid.

VIII. Closing Comments

A major, coordinated federal research and monitoring effort is essential to determining the effects of ocean acidification on species and ecosystems; predicting the implications for the future, as carbon dioxide levels in the ocean continue to rise; and making management decisions regarding specific species and habitats. Although this effort has begun through the legislative and administrative mandates and authorities discussed in this report, a much greater effort needs to be undertaken.

Furthermore, this effort needs to be undertaken with much greater urgency. More funding is needed, and research must be expedited.

Lastly, the federal government must begin to grapple with the profound impacts ocean acidification will have on our ocean and coastal resources, and the impacts we will see on our economy, society, and environment. There are untold costs associated with these impacts, both in terms of federal funds needed to manage resources such as fisheries, endangered species, and public waters, and in terms of the broader toll on the environment and humanity.

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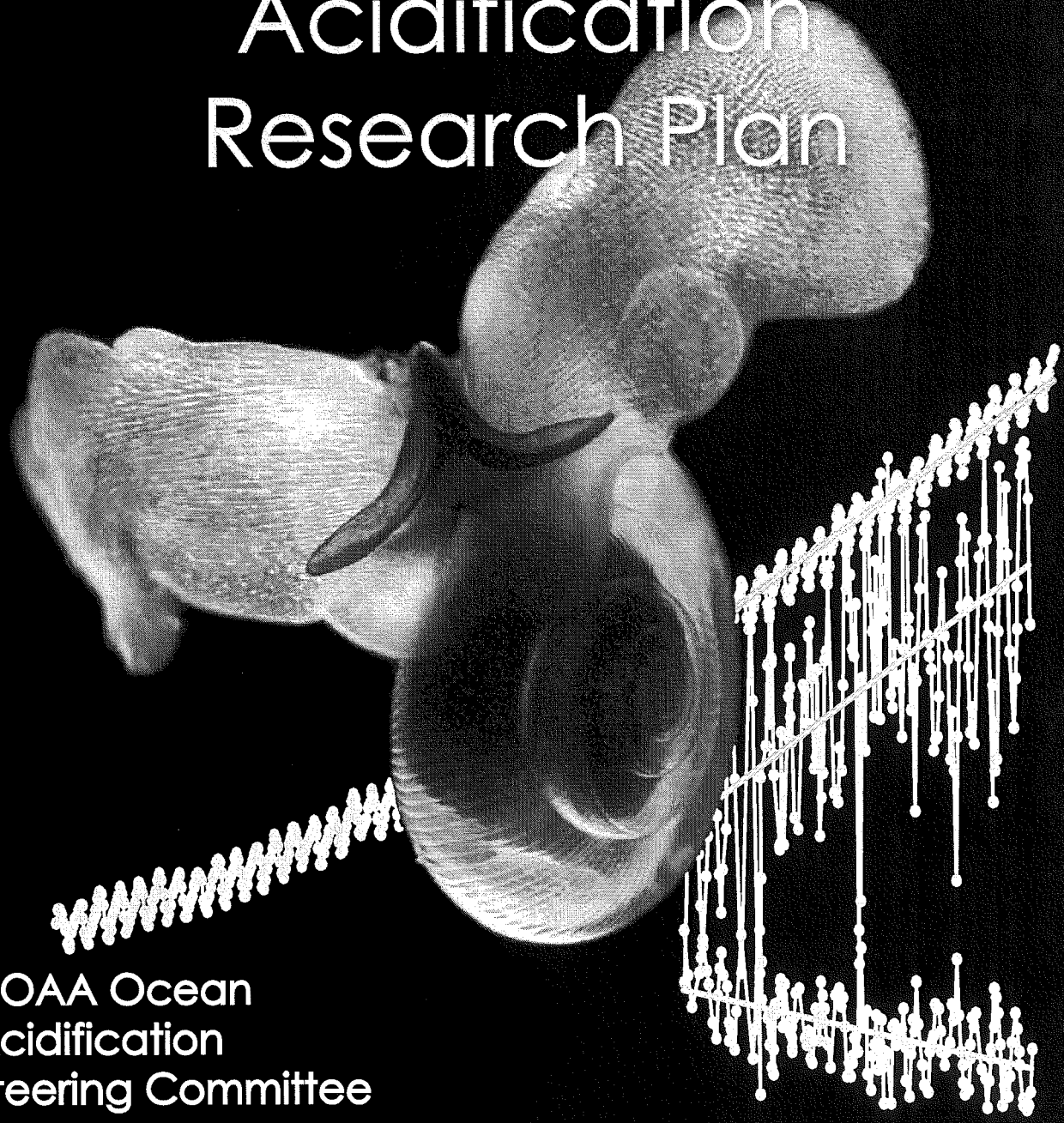
NOAA Ocean and Great Lakes Acidification Research Plan



NOAA Ocean
Acidification
Steering Committee

April 2010

NOAA Ocean and Great Lakes Acidification Research Plan

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Front cover photo: pteropod, *Limacina helicina*
Credit: Russ Hopcroft (University of Alaska Fairbanks)
Front cover graphic: see Figure 1.1 on page 2

Acknowledgments

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April 2010

UNITED STATES
DEPARTMENT OF COMMERCE

Gary Locke
Secretary

6. Northeast Region Ocean Acidification Research Plan

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6.0 Ocean Acidification in the Northeast Region

Decreases in pH and the saturation state (Ω) of the surface oceans and subsurface waters are larger at higher latitudes, due in large part to the strong temperature dependence of the solubility of CO_2 in seawater. It is expected that the saturation state of surface waters off the coast of New England will decline sooner than other areas of the Northeast, especially during the winter months. In addition, hypoxia is a growing threat in all estuaries in the Northeast, particularly Narragansett Bay, Long Island Sound, and Chesapeake Bay. A relationship exists between hypoxia (low oxygen) and ocean acidification because respiration which causes hypoxia is also producing high levels of CO_2, lowering the carbonate ion levels. In all, OA has the potential to significantly affect living marine resources in the Northeast, as well as alter the ecosystem's structure, function, and productivity. Given the social and economic importance of living marine resources on the Northeast U.S. continental shelf, the potential large-scale and long-term impacts of OA must be evaluated.

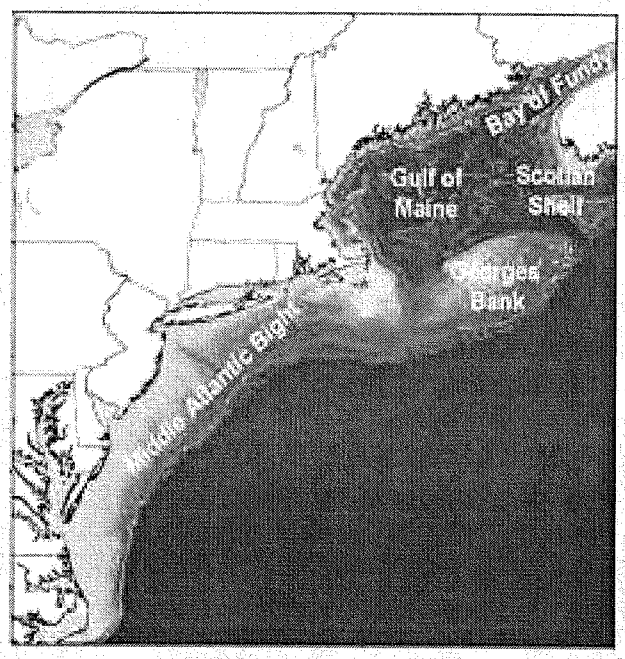
We describe here a coordinated research plan with the goal of providing the first assessment of the effects of OA on living marine resources in the Northeast U.S. continental shelf ecosystem. During the Marine Resources Monitoring Assessment and Prediction Program (MARMAP, 1977–1987), some pH and alkalinity measurements were made as part of primary productivity studies. Preliminary analyses of those data show seasonal and spatial variability. These observations also demonstrate differences between surface and near-bottom conditions, which are likely related to the strong stratification that occurs seasonally in different parts of the system. We intend to conduct a monitoring program that will define and track the status of OA in the shelf ecosystem. Since the effects of acidification are not well studied, a large part of this plan includes experimental research. These laboratory and field efforts will be directed at collecting specific information for the parameterization of single-species and ecosystem models, which will then be used to assess the effect of acidification on living marine resources and overall ecosystem productivity.

6.1 Developing a Northeast Ocean Acidification Monitoring Network (Theme 1)

Task 6.1: Develop and conduct a monitoring program to assess the current state of ocean acidification and track its development in the northeast U.S. shelf ecosystem.

A baseline for OA on the Northeast U.S. shelf must be determined along with potential changes in the carbonate chemistry as part of the larger ecosystem monitoring programs. A collection of long-term monitoring data can then be coupled with forecast models to provide assessments of the effect of OA on marine resources. The monitoring data will also be used to direct field work resource species. Preliminary analysis of MARMAP data (1977–1987, Figure 6.1) shows spatial variability in pH and total alkalinity, which indicates that measurements are needed over the entire ecosystem to assess the potential effects of OA on resource species. Further, these observations need to be made both at the surface and through the water column, since few marine species inhabit the surface

Northeast Region Description



The Northeast U.S. region (for the purposes of this report) extends from the Virginia/North Carolina border to the western Scotian Shelf (see above) and spans a large latitudinal gradient from south to north. Structurally, this ecosystem is complex, with temperature and climactic changes, winds, river runoff, estuarine exchanges, tides, and multiple circulation regimes. The Northeast ecosystem has been divided into four regions: Mid-Atlantic Bight, Georges Bank, Gulf of Maine, and the Scotian Shelf/Bay of Fundy, each with different properties and dynamics. The circulation of the region is dominated by five large-scale processes: the Labrador Coastal Current inflow, estuarine and riverine input, the Gulf Stream, wind and tidal forcing. This area is characterized by a temperate climate, and local water temperatures have a large seasonal range from approximately 5–10°C in the northern Gulf of Maine to near 20°C along the Mid-Atlantic coast. The range in climatic conditions and the variety in geomorphology among regions contribute to a wide array of pelagic and benthic habitats, which contribute to the large productivity of the ecosystem. Approximately 30 marine mammal, 6 sea turtle, and 1,000 fish species occur in this ecosystem. Many of these fish species support a large fishing industry, which in 2006 produced fish and shellfish landings worth over $1.2 billion. Other Northeast economic activities include agriculture, natural resource extraction, a service industry dependent on large metropolitan areas, recreation and tourism, and manufacturing and transportation of industrial goods.

and there is extensive stratification in different parts of the water column and to provide a framework for the studies of the effects of OA on primary productivity and systems at different times of year.

We propose using the dedicated Ecosystem Monitoring (EcoMon) surveys as the primary basis for water column monitoring of OA. A Seabird Electronics 911+ CTD system with bottle carousel and auxiliary oxygen sensor will be deployed at stations along transect lines extending from the coast to the shelf break (Figure 6.2). Surface, mid-depth, and bottom samples will be collected and prepared at sea for onshore determination of pH, dissolved inorganic carbon (DIC), and total alkalinity (TA). We will also measure a suite of other parameters at these stations to elucidate relationships between OA, nutrient availability, carbonate formation, and dissolved oxygen. Further, we propose to install surface pCO_2 instrumentation on the two NOAA research vessels used by the Northeast Fisheries Science Center (NEFSC) in fishery and ecosystem surveys to acquire year-round measurements. This sampling design will be re-evaluated periodically after three years, based on temporal and spatial variability and through a comparison with the MARMAP era data.

In addition to shipboard sampling, we propose a number of fixed mooring sites that will be outfitted with OA sensors providing high-frequency measurements that will complement the survey-based measurements. Refer to Table 1.2 and 1.3 in Chapter 1

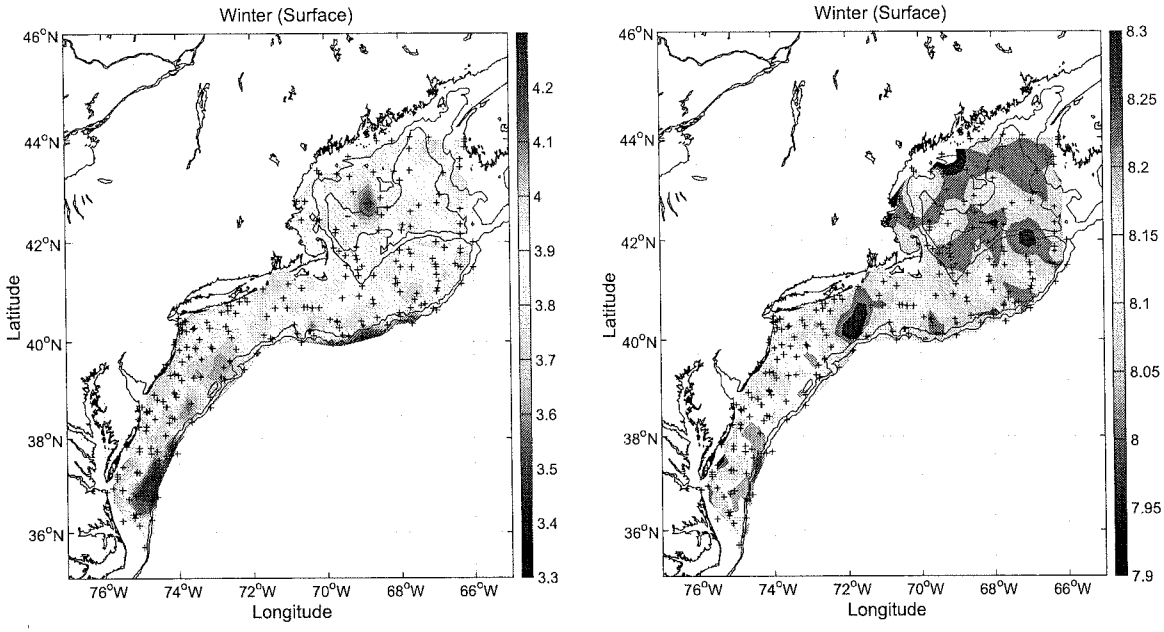


Figure 6.1: Winter climatology of surface layer pH (left) and total alkalinity (right) derived from MARMAP samples (1976–1984).

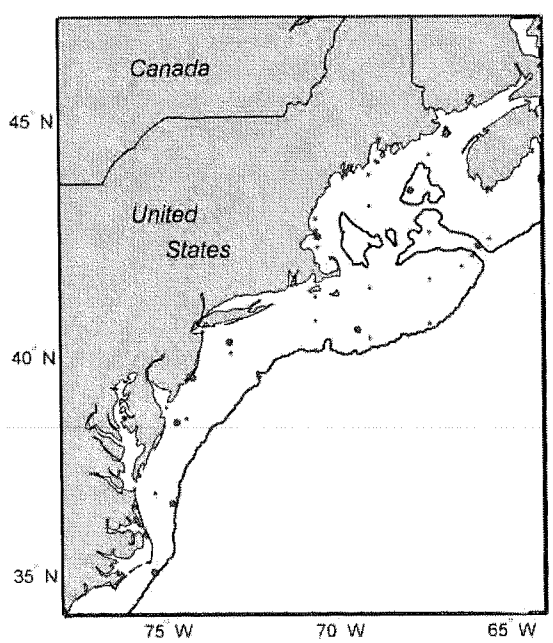


Figure 6.2: Proposed sampling design for an ocean acidification monitoring program. Program includes fixed station sampling during Ecosystem Monitoring cruises (blue) and moorings with OA sensors (red).

for a list of locations. The sensors will be phased in over a period of five years. As sensor technology advances, we would like to take advantage of the numerous moorings in the national Data Buoy Center to expand the spatial coverage of the system. Sensor technology is currently being developed, but will require regional involvement and participation to accelerate sensor development.

Marine protected areas in the northeast region, including nine National Estuarine Research Reserves (NERRs [Wells, Maine; Great Bay, New Hampshire; Waquoit Bay, Massachusetts; Narragansett Bay, Rhode Island; Hudson River, New York; Old Woman Creek, Ohio; Chesapeake Bay, Maryland and Virginia; Delaware Bay, Delaware and New Jersey, and Jacques Cousteau, New Jersey]) and two National Marine Sanctuaries (the Stellwagen Bank NMS in the western Gulf of Maine and the Monitor NMS off Cape Hatteras, North Carolina) are potential sentinel sites for existing and new monitoring programs to detect impacts from ocean acidification. Protected areas are ideal for long-term research, water-quality monitoring, education, and coastal stewardship. Reserves and sanctuaries provide sentinel sites that attract and support research collaborations and seek to understand processes that affect ecosystems. Further, they work with local communities and regional groups to address natural resource issues and improve our ability to intelligently manage, mitigate, and/or adapt to changes in the environment due to OA. Sentinel sites will provide opportunities for researchers to collabo-

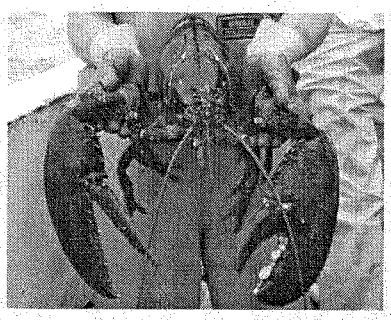
rate and will support research devoted to understanding OA patterns and processes that affect the Northeast ecosystem and living marine resources.

The monitoring network will also coordinate with other researchers measuring dissolved CO_2 in the ecosystem. The goal of this coordination is to develop a merged dataset based on the various OA activities in the ecosystem. Current cooperation will continue with AOML researchers who are measuring pCO_2 from vessels in the NEFSC Ship of Opportunity Program. The NEFSC, in collaboration with investigators from the National Aeronautics and Space Administration (NASA) and Old Dominion University (ODU), have started to make preliminary dissolved inorganic carbon and total alkalinity measurements as part of a shelf-wide monitoring effort. There have been several recent efforts to make surface pCO_2 measurements in the Gulf of Maine. The University of New Hampshire (UNH) Coastal Ocean Observing Center's Coastal Carbon Group has been working in the New Hampshire coastal regions since 2004. Two Regional IOOS (Integrated Ocean Observing System) Regional Associations (NERACOOS and MaCOORA) are active in the northeast ecosystem and have a broad range of observing platforms. Activities include satellite observations, buoys, glider transects, HF radar, and modeling. MaCOORA through Rutgers University has been collaborating with the NEFSC within the New York Bight on ECOS (Ecology of Coastal Ocean Seascapes), which has been measuring spatial changes in environmental parameters related to changing distribution patterns of living marine resources. Therefore, the regional associations are complementary to the NEFSC shipbased OA activities.

6.2 Organism Response to Ocean Acidification (Theme 2)

A comprehensive overview of the biological components of the northeast U.S. shelf ecosystem provided by NEFSC Energy Modeling and Analysis eXercise (EMAX) identified functional groups and established trophic relationships between them (Link *et al.*, 2006). The Northeast U.S. shelf ecosystem is highly interconnected through its trophic relationships, raising the expectation that OA effects could be propagated throughout it. To predict how ecosystems will respond to OA, it is important to first determine how individual species will respond under controlled experimental conditions. Results from these experiments will provide information about direct effects and predictions about priority species, data to refine models

Organisms of Near-Term Focus



Primary producers
Scallops
Lobster (American above)
Atlantic surf clams
Hard and soft shell clams
Mussels
Oysters
Summer and Winter Flounder
Black Sea Bass
Shortnose Sturgeon
Deep-sea Coral
North Atlantic Right Whale

of the ocean carbon cycle and data for models such as EMAX that could predict indirect effects of OA.

Given the diversity of fish and shellfish species, the numerous protected and endangered taxa (e.g., the North Atlantic Right whale and shortnose sturgeon) and the importance of bottom-up forcing (e.g., lower trophic levels), we will conduct research on a range of taxa utilizing regional expertise and then focus future research based on those results. In addition, NOAA's extramural research funds will be directed to fill the gaps in NOAA expertise and facilitate partnerships with academic institutions.

It will be important for NOAA researchers to work closely with academic partners given the wealth of expertise in the region. A research group at Woods Hole Oceanographic Institution (WHOI) is actively involved in working to understand the effects of OA on marine ecosystems and resources. Doney *et al.* (2008) document the state of knowledge regarding impacts of acidification on marine species, and Cooley and Doney (2009) provide a preliminary economic assessment of the effect of OA on commercial fisheries. A second group at WHOI (Ries *et al.*, 2009) is investigating the effect of acidification on calcification of invertebrates and algae. They have found OA can greatly affect initial shell formation in shellfish such

as bay scallops, which has potential major effects on the shellfish industry in the northeast region. Similar research at the State University of New York at Stony Brook (SUNY) confirms these results (Talmage and Gobler, 2009). At the University of Massachusetts at Amherst (UMass Amherst), preliminary research investigations have started to examine the relationship between OA and lobster shell disease.

Current priorities for NOAA research in the Northeast region on organism response to ocean acidification are: primary and secondary productivity, shellfish, finfish, deep-sea corals, and protected species.

6.2.1 Primary producers

Task 6.2.1: Conduct laboratory and targeted field studies to quantify the impact of ocean acidification on primary producers.

A critical concern is the effect of OA on primary and secondary productivity in the ecosystem. The Northeast U.S. shelf is strongly driven by bottom-up processes. Impacts on phytoplankton and zooplankton ecology could have important ramifications for overall system productivity. Understanding the relationship between acidification and nutrient chemistry is also a clear need, as primary productivity is ultimately limited by nutrient supply.

Ocean acidification can affect primary productivity both directly and indirectly. Many marine phytoplankton are sensitive to changes in pH and temperature. A series of experiments will be conducted that quantify the interactive effects of pH and temperature on phytoplankton growth, physiology, and competition. These experiments will be complemented by a retrospective analysis of field-collected data and targeted comparative field sampling, with a specific goal of examining some of the effects and relationships observed in the laboratory.

We will start with 15 individual strains of marine phytoplankton from the Milford Microalgal Culture Collection and add several calcifying strains (*Coccolithus huxleyi*; *Ochrosphaera neopolitana*) that will be acquired from the Provasoli-Guillard Center for the Culture of Marine Phytoplankton. Cells from each strain will be cultured at different pH levels and flowcytometry will be used to quantify phytoplankton abundance and cell-division rate and characterize selected physiological characteristics such as nutrient status and internal pH. The second stage of experiments will examine the competitive interactions between pairs of microalgal species under varying pH levels selected to examine important ecological and physiological contrasts. These experiments will provide broad generalizations about likely shifts in phytoplankton community structure as a consequence of competition modified by OA. The third stage of experiments will be based on phytoplankton communities (multi-species) with several cultured species. These experiments will be hypothesis-driven, in terms of ecological principles, e.g., does the presence of a calcifying species modify the interaction between diatom species and will present a more ecologically relevant simulation of OA effects upon phytoplankton communities.

In the field, we will examine the effect of pH on natural phytoplankton communities in the Northeast U.S. continental shelf ecosystem. Natural communities will be collected and experiments conducted at conveniently located facilities (i.e., Howard Laboratory, Stellwagen Bank National Marine Sanctuary). The laboratory experimental systems will be modified for field studies and will build upon the experience and knowledge gained in previous experiments.

A retrospective analysis of monitoring data will be examined to determine whether changes in phytoplankton species composition have occurred and evaluate the potential link to OA. The Ship of Opportunity Program has been collecting data on phytoplankton species composition since 1961 and there is spatial variability in pH throughout the system. A detailed analysis of the species composition with available dissolved CO_2 measurements will be examined. Based on lab results, predictions will be made as to components of the phytoplankton community that should be observed in areas of differing dissolved CO_2. These natural contrasts will inform both future experiments and help in understanding the laboratory results in the context of the natural system.

An additional approach will be to develop genomic assaying techniques to quantify genetic diversity and to look at variation in phytoplankton community structure over time. This technique can be used at different taxonomic resolutions (i.e., species, genera, families, etc.) and is being developed for several types of marine organisms by researchers working under umbrellas such as the Census of Marine Life and the Marine Barcode of Life. Stellwagen Bank National Marine Sanctuary will serve as the regional test-bed for the development of genetic diversity indices and assaying techniques through collaboration with other research partners. Indices will then be monitored over time to characterize the status of and changes in primary producer diversity in relation to available dis-

solved CO_2 and other environmental measures collected via EcoMon sampling in sanctuary waters.

6.2.2 *Shellfish and finfish*

Task 6.2.2: Create a state-of-the-art capability in the Northeast for conducting acidification experiments on individual species and species assemblages of shellfish and finfish and estimate the impact of ocean acidification on Northeast ecosystem resource species.

To evaluate how finfish and shellfish species in the ecosystems associated with the Northeast U.S.A. will respond to acidification, we will design and construct the capability for experimentally evaluating species' responses. The NEFSC facility will be located at the Howard Marine Sciences Laboratory and the first phase is scheduled to be completed in 2010 as part of the NMFS FY2010 OA Plan. The NEFSC has already developed a pilot-scale OA treatment system that is currently being tested. Knowledge gained in the development of the pilot system will be applied to the design of the larger one. The NEFSC system will be capable of conducting large-scale and replicated multi-factorial experiments. Analytical chemistry needs for the NEFSC facility will be met by a combination of on-site capabilities, collaboration with the Milford Laboratory, and quality control analysis with the Pacific Marine Environmental Laboratory (PMEL) carbon group.

We will use several test species of shellfish and finfish in order to draw the broadest levels of inferences about the potential effects of OA. Our selected species will be determined by economic value, habitat usage, season of spawning, and feasibility of captive rearing, among other criteria. We will estimate the effects of OA on shellfish and finfish resource species and measure responses that represent critical organismal functions.

6.2.2.1 Shellfish

Given preliminary results on the effect of OA on shell formation and calcification rates, research on the region's shellfish species is a clear priority. The sea scallop and lobster fisheries are two of the most valuable fisheries in the U.S., with landings exceeding $340 million in 2007. Other important shellfish fisheries in the region are Atlantic surf clams, ocean quahogs (hard clams), bay scallops, softshell clams, mussels, and oysters. Sea urchins and sea cucumbers are also minor fisheries in the Gulf of Maine. Several of these species are being used in aquaculture, raising the concern that OA will have an impact on commercial and stock enhancement culture operations.

Culture techniques for the Atlantic surf clam were developed in the NEFSC Milford Laboratory 20 years ago and this capability remains current at this facility. In the initial experiments, we will rear newly hatched larvae, juveniles, and adults. The formation of the shell will be measured in larvae and the growth of the shell will be measured in all life stages. Due to the variable salinity and pH of the seawater at the Milford Laboratory, we will be partnering with the Martha's Vineyard Shellfish Group (MVSG) to conduct the experiments. We will also evaluate the potential increase in predation risk as a consequence of increased pCO_2 by exposing Atlantic surf clams reared at different pH levels to natural starfish predators in the lab. Changes in shell growth may make Atlantic surf clams more susceptible to size-selective predation and changes in shell rigidity may facilitate predation at all sizes.

After the experiments have been fine tuned for Atlantic surf clams, a focused effort will be directed on the effects of OA on sea scallops. Sea scallop culture is notoriously difficult but its status as the most valuable fishery species in the U.S. warrants attention and effort. MVSG has some experience in culturing sea scallop and will be a valuable partner in these experiments.

6.2.2.2 Finfish

A clear need exists to understand the impacts of OA on finfish species. For fish, the limited number of prior reports has noted effects of OA on a suite of life stage, behavioral, and morphometric features important to the survival of young fish. Some research has shown that OA can affect the olfactory system and otolith growth in larval fish indicating potential ecological consequences environment (Checkley, Jr. *et al.*, 2009). The otolith is an important sensory organ and changes in calcification may affect behavior, including feeding and predator avoidance. In addition to direct metabolic, sensory, and calcification effects, there could be physiological consequences, reducing the energy available for activity, growth, and reproduction. These physiological costs could be magnified when OA conditions are combined with other climate change parameters such as reduced levels of dissolved oxygen, alterations in ocean temperatures, and changes in ocean circulations patterns. Moreover,

increased ocean acidity has the potential to elicit substantial sublethal effects on fish by means of affecting their normal developmental and behavioral capabilities during their sensitive early life-stages. For example, Munday *et al.* (2009) reported that settling reef fish reared at high levels of pCO_2 failed to successfully discriminate among reef microhabitat flora that are key to subsequent survival.

We have identified finfish species that would not only provide us with a high likelihood of experimental success but provide the broadest possible basis for inferences about OA effects in the Northeast U.S.A. Atlantic ecosystem. These fish species represent shelf and inshore waters and they differ in their economic and ecosystem values, ecology, habitat, and other key features relevant to projected OA and temperature regimes (Table 6.1).

All of these species have been maintained and reared under controlled laboratory conditions. These experiments will mostly focus on the reproductive and early life history features of the fish life cycle. The use of a diverse set of species allows us to quantify OA effects and address broader questions of interest including: (1) Are species that spawn and have early life-stages offshore more sensitive to changes in pH than species that spawn and have early life-stages inshore? (2) Are species that spawn in winter and whose early life-stages experience low temperatures more sensitive to change in pH than species that spawn and whose early life-stages experience warm summer temperatures? (3) Are populations of species near the extreme of their geographic distributions more likely to be sensitive to the individual and/or combined effects of projected OA and temperature regime shifts associated with climate change? (4) Do the data suggest that responses differ among taxonomic groupings?

In addition to the laboratory work, we also propose targeted field sampling to use the documented spatial variability in pH (Theme 1) to evaluate whether shell and otolith growth in selected shellfish and finfish species can be related to ambient pH and carbonate chemistry. Locations will be chosen based on dissolved CO_2 distribution resulting from the monitoring program. This work will include the collection of species of interest as well as the collection of DIC and TA samples to verify chemical conditions at the time of collection. The purpose of this component is to evaluate whether there are already signals of the effect of pH among species in the ecosystem.

6.2.2.3 Deep-sea coral

Habitats used by marine organisms may be impacted. Deep-sea corals are found along much of the shelf edge, especially near the Hudson canyon and at locations in the Gulf of Maine along with pockets of shallow water corals and areas of calcareous algae. These habitats, which may represent nursery grounds for finfish, may be especially vulnerable to OA.

Relatively little is known about the ecology of the deep-sea corals found in the northeast. Recent efforts have been made to characterize their distribution and abundance. In other oceanic regions, many commercial and non-commercial fish species are associated with deep corals. While most associations are believed to be facultative, fish and crabs use coral habitat as refuge and as focal sites of high prey abundance. During 2010, photo reconnaissance with a camera-equipped AUV will identify coral patches in the area around the Hudson Canyon. Collections of the solitary deep-sea hard coral *Dasmosmilia lymani* will be made to determine coral age and growth rates in collaboration with other collaborative partners (e.g., NOAA Coral Reef Conservation Program) in order to develop a baseline against which to monitor OA effects at the shelf edge.

6.2.2.4 North Atlantic Right Whale

Protected species will also be impacted and initial efforts will focus on forecasting the effect of OA on the North Atlantic right whale, owing to their extremely low population sizes. Endangered right whales feed on copepod zooplankton which are vulnerable to OA and some researchers have hypothesized that OA will affect low-frequency sound propagation with negative consequences for marine animal communication. This work will primarily involve data synthesis and modeling built from existing information with some focus on new data collection.

The North Atlantic right whale has become rare (300–400 individuals) and endangered and even marginal impacts can have grave consequences for the species. We will examine the potential effect of changes in sound propagation on right whale communication in Stellwagen Bank National Marine Sanctuary (SBNMS). Increasing acidification may affect frequency sound propagation conditions, which in turn could have negative consequences for vocalizing marine animal communication ranges. The Stellwagen Bank National Marine Sanctuary, the NEFSC, and Cornell University have established a high-resolution acoustic monitoring program to map

Table 6.1: Proposed finfish species for OA experiments and their economic and ecosystem values, ecology, habitat, and other key features.

Species	Spawning season	Spawning habitat	Egg/larval habitat	Primary value
(1) summer flounder (*Paralichthys dentatus*)	autumn	shelf	water column	economic
(2) winter flounder (*Pseudopleuronectes americanus*)	winter	estuaries	benthic/water column	economic
(3) black sea bass (*Centropristis striata*)	summer	shelf	water column	economic
(4) shortnose sturgeon (*Acipenser brevirostrum*)	spring–summer	estuaries (upper fresh)	benthic	endangered

human-induced noise in greater sanctuary waters in relation to the behavior of vocally active marine species. The sanctuary-based study has included empirically driven propagation modeling for this system, including calculations of communication range for individual calling animals. This model will be used to predict the consequences of OA on communication ranges for different species, and to better understand the influence of spatial and temporal variance in propagation conditions on low-frequency communication.

6.3 Biogeochemical and Ecosystem Models (Theme 3)

Task 6.3: Develop and implement models to assess the effects of ocean acidification on single-species dynamics, multi-species interactions, and overall ecosystem productivity.

The region has a strong modeling community and numerous regional models; however, these have yet to be applied to the OA issue. The NEFSC has vast experience with single-species population models and is continuing to develop environmentally explicit, single-species models as well as multi-species models, habitat suitability models, trophic network models, and aggregate production models. Through the Global Ocean Ecosystem Dynamics (GLOBEC) program, a number of numerical circulation models were developed for the region; some of these have been coupled with regional nutrient-phytoplankton-zooplankton (NPZ) models and some have included early life stages of fishes. NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) and other climate modeling centers have developed Earth System Models capable of hindcasting and forecasting OA globally over multiple decades that can be used to inform regional ecosystem simulations. Finally, there is strong expertise in ocean carbon and biogeochemistry at regional NOAA/academic institutions and this experience could be brought to bear within the region.

Initially, the results of single shellfish and finfish species will be used to parameterize population models relative to different levels of dissolved CO_2 in the system. As results become available for multiple species, models will be parameterized with the effects of acidification on growth, reproductive output, and natural mortality. The experimental results from larvae and juveniles will be included in population models as recruitment effects. The coupled OA-population models will then be used to forecast population productivity under several acidification "scenarios" which will be developed based on IPCC carbon emission scenarios and resulting forecasts of dissolved CO_2 on the northeast U.S. shelf. Comparison of the MARMAP data with present-day data will assist with estimating dissolved CO_2 from atmospheric CO_2. These forecasts will have a range of uncertainties, which we will try to capture, but the goal is to provide an initial assessment of the effect of OA on marine resource species over the coming decades and through the coming century.

The results of the research on phytoplankton will be used to assess the effect of OA on system-wide productivity and phytoplankton community structure. Existing planktonic ecosystem models (i.e., NPZ) will be expanded to include multiple phytoplankton types that encompass the range of important ecological phytoplankton groups studied. The response of each group to acidification will be parameterized based on experimental data generated in Task 6.2.2. The expanded ecosystem models will be embedded in regional hydrodynamic simulations, validated against past observations and those carried out as part of this study, and used to predict the impact of a range of plausible acidification changes. This will be translated to an estimate of total sustainable fisheries extractions through methods established at the Groundfish Assessment Review Meeting (GARM). Additional

modeling efforts will be developed as more information is generated during the course of laboratory and targeted field studies.

To address the effects of increasing acidification on the endangered right whale, the Whale Habitat Informatics Project (WHIP, `http://gmri.org/whales/`) is currently developing a right whale likelihood product which merges model forecasts with field observations and merges satellite sea surface temperature (SST) and chlorophyll to model the right whale's main zooplankton prey. A second model developed by collaborators at the Provincetown Center for Coastal Studies predicts individual right whale feeding behavior in relation to spatial distribution and abundance in Cape Cod Bay. The integration of higher-resolution empirical data that reflects a better understanding of OA impacts on the availability and quality of food resources could increase the predictive strength of these models and enhance NOAA's ability to manage right whales within northeast waters.

Ultimately, the expanded NPZ and biogeochemical models will be linked with upper trophic level responses and incorporated into regional ocean model simulations. Multi-decadal hindcast simulations forced by atmospheric reanalysis products will be conducted to refine model dynamics and provide a holistic understanding of past observed variations in primary productivity, phytoplankton community structure, and resource species. Climate change projections will also be conducted through either (a) off-line coupling to hydrodynamic fields from high resolution physical climate model simulations which are under development; or (b) regional hydrodynamic simulations driven by global ESM boundary conditions and atmospheric forcing. The approach taken will be contingent upon progress toward high-resolution global climate model development and progress toward robust nesting approaches for regional models of the eastern United States within coarse global climate simulations. This holistic model will be constructed through collaborations across NOAA line offices and in academia.

6.4 Human Dimensions (Theme 4)

Task 6.4: Estimate anticipated changes to northeast ecosystem services as a consequence of OA and develop a decision framework for adaptation strategies.

The analysis of the human dimensions of OA will consist of two interrelated components. First is estimating how acidification is likely to affect the human community though impacts on "ecosystem services" or the value of benefits to human communities as a result of functioning ecosystem processes. Analysis of the value of the fishery declines anticipated in the Northeast region is needed, although Cooley and Doney (2009) have done an initial analysis of the potential economic cost from a national perspective. The human dimension analysis also includes the development of a framework for deciding what to do about acidification. Choices about adopting various CO_2 emission strategies and the implications of those adopted scenarios will need to be informed by the best available science. In the Northeast, these choices will need to be considered within the broader context of how to confront other stressors to the ecosystem such as eutrophication, how to prepare fishing-based economies for ecosystem changes, whether to implement spatial or temporal fisheries changes, etc. Making these decisions will require consideration of ecological predictions, the value of ecosystem services, and the economic and social costs of proposed actions. The decision process will need to transparently incorporate the considerable uncertainty that exists in all of the input parameters. There is substantial technical work required among NOAA and academic partners in the Northeast to develop socioeconomic models and decision frameworks to address the unique impacts of ocean acidification on Northeast communities and the economy.

6.5 Synthesis of Data and Information Products (Theme 5)

Task 6.5.1: Provide a first integrated assessment of the effects of OA on the northeast U.S. continental shelf ecosystem.

The work described above is directed toward the development of an assessment of the effect of OA on the northeast U.S. continental shelf ecosystem. The audience of the assessment will be scientists and policymakers alike. The form of the assessment will be similar to other Integrated Assessments produced within NOAA. The assessment will draw heavily on work done as part of this project, but will also incorporate the results of all research that is relevant. There are several groups that are working within the northeast

U.S. shelf region (e.g., UNH, AOML, and WHOI) and there will certainly be additional research conducted around the globe that will be relevant. Data management staff and improvements to computer-based infrastructure will be required to ensure an organized and coordinated result. The resulting document will provide the first regionally specific assessment of the effects of OA and serve as a tool for identifying critical gaps in our understanding and providing a basis for future research to fill these knowledge gaps. Importantly, this assessment will provide a quantitative framework describing the effects of OA on resource species in the northeast U.S. continental shelf ecosystem. The assessment will be iterative, similar to that described for the IEA process; the timescale of reassessment will be approximately five years.

6.6 Engagement Strategy (Theme 6)

Task 6.6: Identify target audiences and determine appropriate programs and products utilizing innovative approaches for community involvement.

Using resources already present in the region, NOAA can begin the process of disseminating important information on the causes and potential effects of ocean acidification on our coast and ocean ecosystems to ocean user groups and the general public. The first steps in developing an action plan for education and outreach for the northeast are to:

1. Identify target audiences;
2. Determine appropriate programs and products for each audience;
3. Develop a comprehensive needs assessment to education and outreach programming;
4. Match ocean acidification needs with existing education and outreach activities; and
5. Develop innovative approaches for community involvement.

NOAA regional offices (NMFS, NERRS, NMS, Sea Grant, Office of Ocean and Coastal Resource Management, National Weather Service) and their research partners can provide OA information in general outreach tools and programs. The SBNMS can also include OA stories in publications, such as Stellwagen Banknotes and Stellwagen Soundings, as can other NOAA publications released in the region. Possible products for development include a standard PowerPoint presentation for the general public that illustrates the issues; a general traveling exhibit for use at public venues; press releases and backgrounders for dissemination through the NOAA public affairs network; the use of new media, including podcasts, blogs, YouTube videos, tweets, etc; and distance learning programs that are broadcast over the internet to reach educators and other interested members of the general public, and to serve as educational resources to supplement content in college courses. Education and outreach programs can include science experiments for the classroom, student data collections, workshops and training programs with constituents, and internet access to research findings and data that inform stakeholders and provide mutual understanding of issues related to OA.

Periodic workshops could be held for coastal managers. The purpose would be to communicate the status of OA investigations, provide information as to the current and potential future state of OA in the northeast region, and maintain a dialogue between NOAA OA scientists and the region's management community. Attendance would be open and would include: the regional fishery management councils, NOAA managers (e.g., NERR's and NMS's), state fishery managers, and others who have interest. The state managers would also be included through the involvement of the Northeast Regional Ocean Council, which is composed of state and provincial representatives for the New England region. A similar group is under development in the Mid-Atlantic region and would be included in these workshops.

The NEFSC is involved in numerous joint activities with the Canadians, providing multiple pathways for cooperation. Several fisheries stocks are assessed under a Transboundary Resource Assessment Committee; information on single species effects can be coordinated in this framework. Additionally, joint ecosystem-based management activities are underway in the Gulf of Maine, providing an avenue for communication and cooperation on ecosystem effects. To contribute to these management activities, the NEFSC already shares data with the Canadians and these existing protocols will be used. Canadian scientists also are involved in one of the Regional IOOS Associations and the Northeast Regional Ocean Council includes representatives of provincial governments providing additional venues for cooperation and communication. International cooperation exists with Norway.

6.7 Collaborators

Northeast Region Collaborators

Northeast Fisheries Science Center
Office of National Marine Sanctuaries
Geophysical Fluid Dynamics Laboratory
Atlantic Oceanographic and Meteorological Laboratory
Office of Ocean and Coastal Resource Management
Northeast and Mid-Atlantic Sea Grant Colleges (e.g., RI, MA, NH, DE)
Woods Hole Oceanographic Institution
University of New Hampshire
Old Dominion University
Regional OOS (NERACOOS, MACOORA)
National Estuarine Research Reserve System
Martha's Vineyard Shellfish Group
Stellwagen Bank National Marine Sanctuary
Cornell University
Provincetown Center for Coastal Studies