Washington State Blue Ribbon Panel on Ocean Acidification

Ocean Acidification: From Knowledge to Action

Washington State's Strategic Response

November 2012

WASHINGTON STATE BLUE RIBBON PANEL ON OCEAN ACIDIFICATION

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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). C*ommercial 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

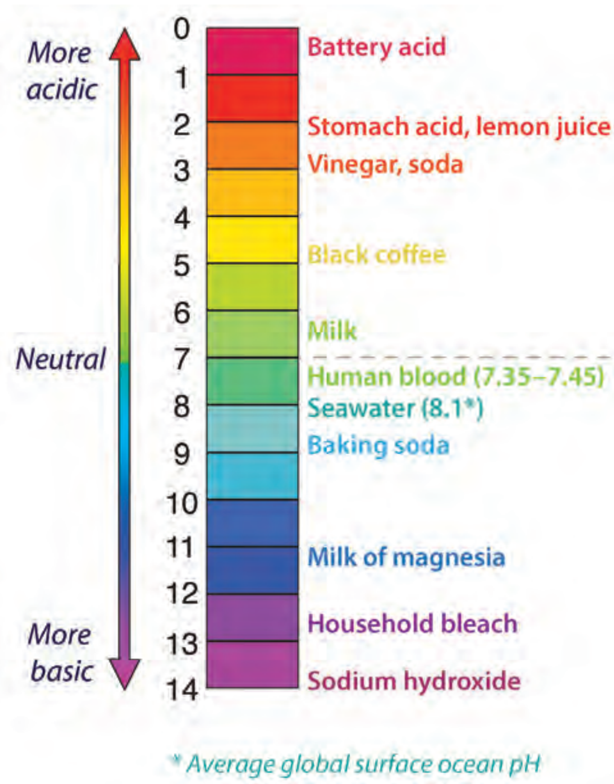


Figure 1. The pH Scale. pH is defined as the negative log of the hydrogen ion concentration in a solution. Neutral pH is 7.0. Solutions with pH values less than 7.0 are "acidic," and those with pH values greater than 7.0 are "basic." Because pH is expressed on a logarithmic scale, a small change in pH 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).

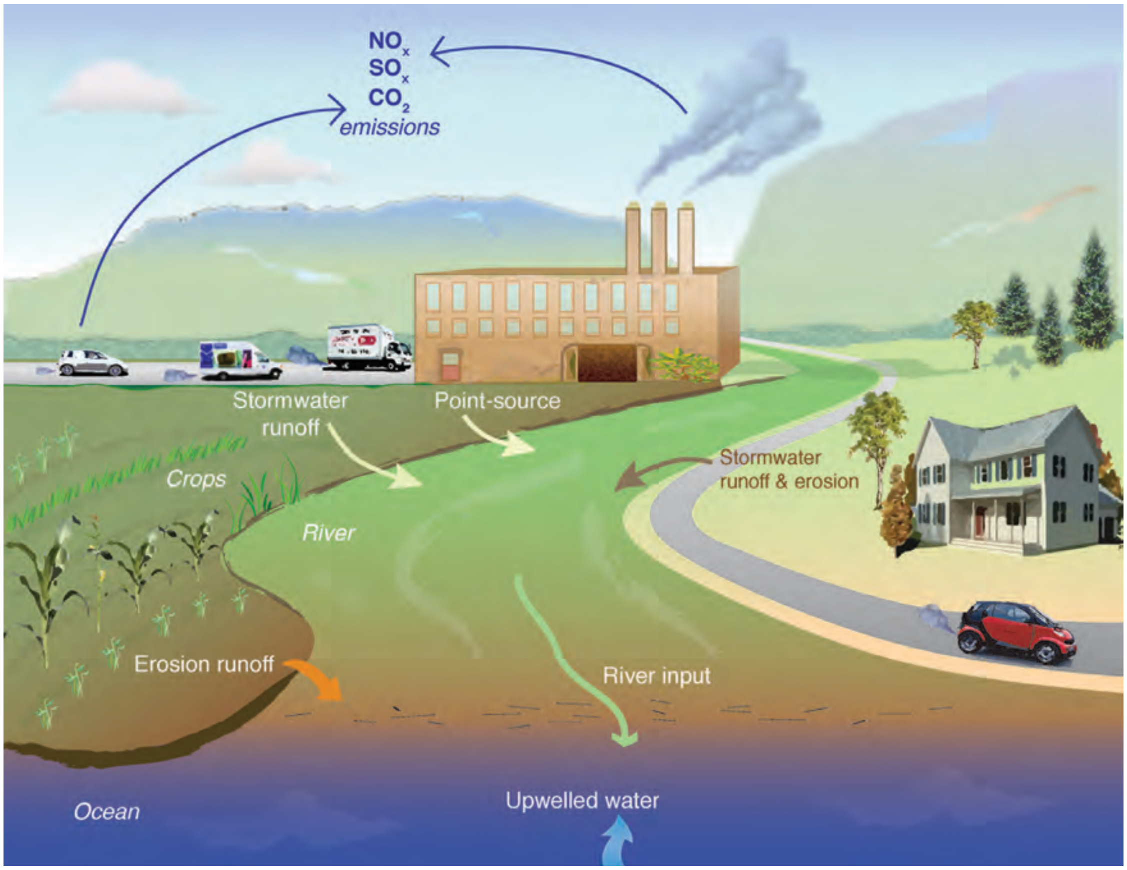


Figure 2. A range of sources, including upwelled seawater rich in carbon dioxide (CO_2) and excess nutrients and organic carbon from point and nonpoint sources, can contribute to acidification of marine waters. Absorption of carbon dioxide, nitrogen oxides (NO_X), and sulfur oxides (SO_X) from the atmosphere 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

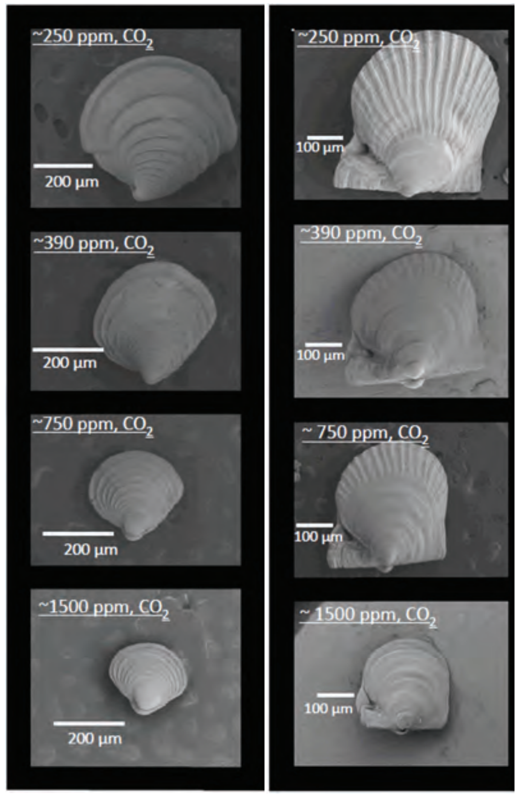


Figure 3. Scanning electron microscope images of 36-day-old hard clam larvae (*Mercenaria mercenaria*, left) and 52-day-old bay scallop larvae (*Argopecten irradians*, right) grown under different carbon dioxide levels: near-preindustrial atmosphere (about 250 ppm), ambient present-day atmosphere (about 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.

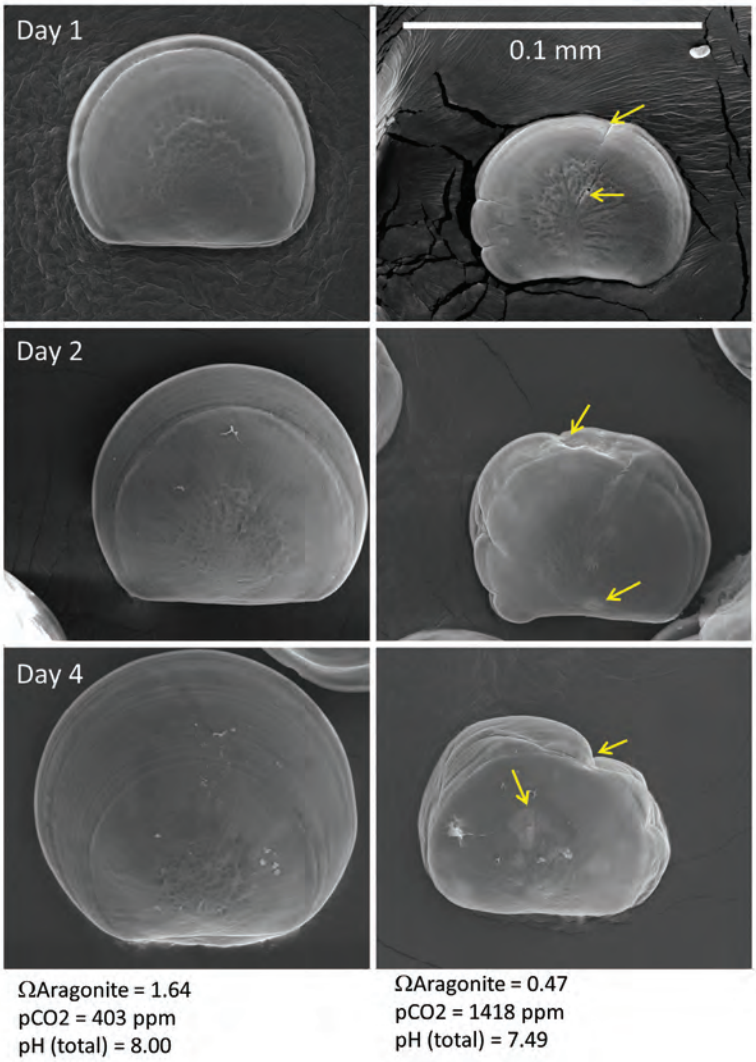


Figure 4. Pacific oyster larvae from the same spawn, raised by the Taylors Shellfish Hatchery in natural waters of Dabob Bay, Washington under favorable (left column, pH (total) = 8.00) and unfavorable (right column, pH (total) = 7.49) carbonate chemistry. The carbonate chemistry conditions shown below 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.

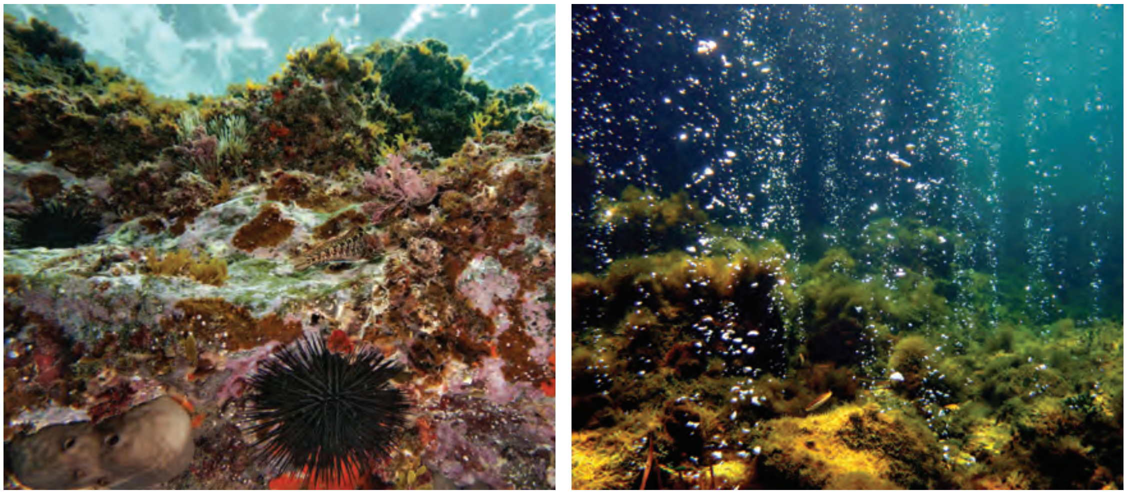


Figure 6. Low and high carbon dioxide communities. The figure on the left shows a diverse marine environment in normal (low) carbon dioxide conditions (mean pH 8.2). The photo on the right shows the impact of high carbon dioxide conditions found near naturally occurring carbon dioxide vents near Ischia 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

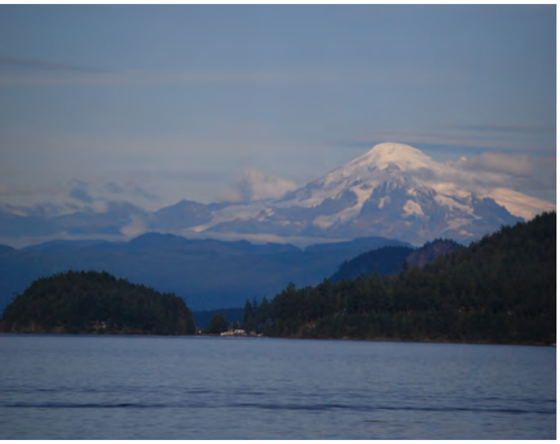
Global ocean acidification is well-documented from observations and its impacts are being felt in the Northwest. The transfer of carbon dioxide from the atmosphere to the oceans is rapidly and measurably lowering seawater pH. Local land-based sources of nutrients and organic carbon can add additional 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.

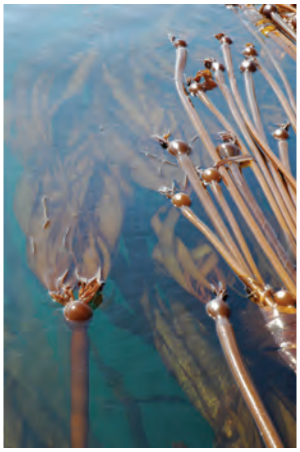
Wastewater facilities are permanent infrastructure, which is costly to construct, maintain, and operate. Reducing nutrients from wastewater point-source discharges often requires technologies that must be tailored to local conditions and facilities. As a result, these technologies can be costly.

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.

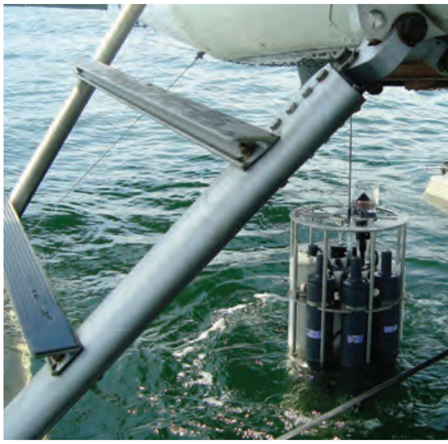
Northwest native and cultivated shellfish may be able to adapt to some changes in ocean chemistry. This potential comes from three mechanisms, which may vary across species and populations: (a) some species may already be able to tolerate acidified conditions by, for example, producing a wide range of 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.

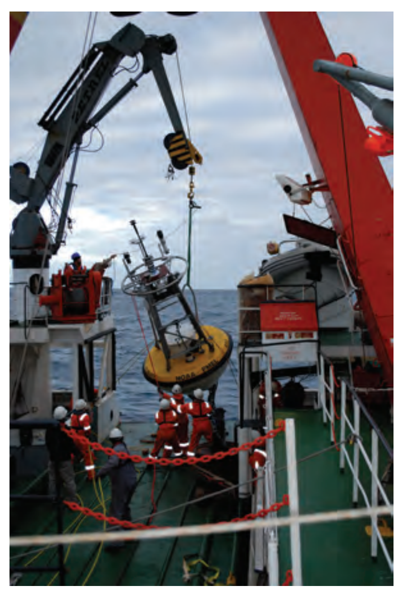
Washington's coast encompasses a great variety of environments, including high-energy sandy shores; rocky bluffs and sea stacks; deep, dark fjords; and sunlit, shallow bays. Some sites are relatively remote from human influence, while others support intensive use by humans. Strategic surveys of these 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.

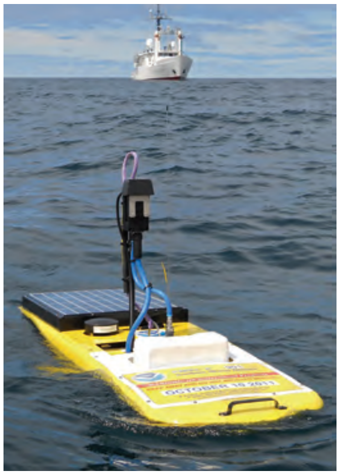
Shellfish growers, under the aegis of the Pacific Coast Shellfish Growers Association, have established several sites for collecting such data. The scientific information obtained at these sites is essential not only for shellfish growing operations, but also to increase our scientific understanding 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.

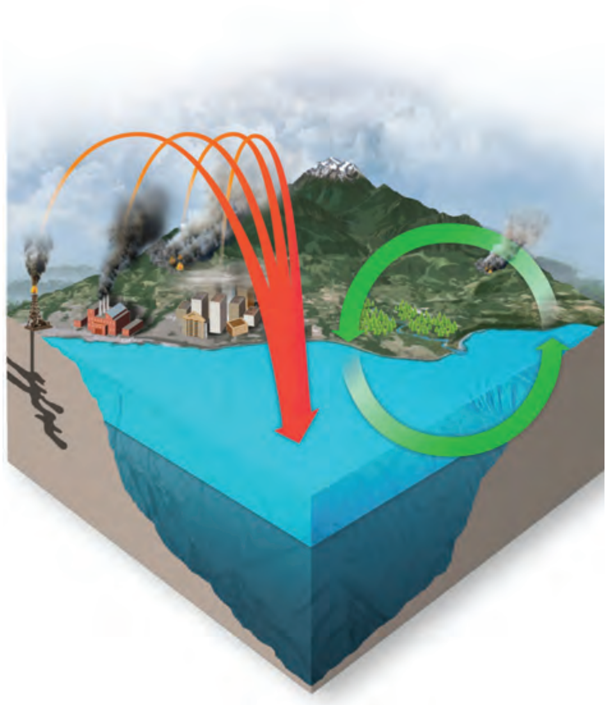
Monitoring plankton in conjunction with chemical parameters can reveal correlations between changing ocean chemistry and changes in plankton communities, a primary impact of ocean acidification. The current monitoring method—collecting plankton with nets for manual identification—is costly, inefficient, 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]

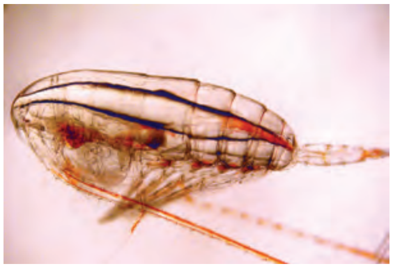
Laboratory studies to assess the direct effects of pH and carbon system parameters on survival, growth, and reproduction of species living in Washington waters will improve our understanding of species-specific responses to ocean acidification and the capacity of species to adapt. This information, in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

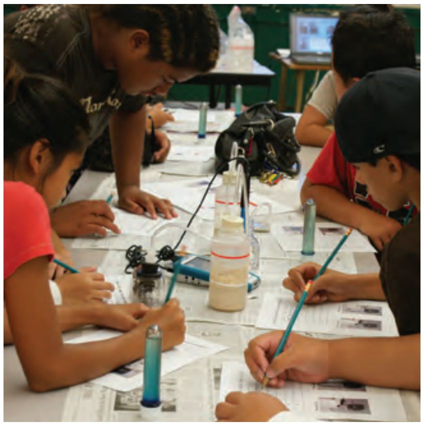
Action 7.4.3: Enhance the ability to model the response of organisms and populations to ocean acidification to improve our understanding of biological responses.

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, Non-governmental 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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Oyster harvesters Samish Bay, WA—Liz O. Baylen, Los Angeles Times

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

Figure S-1: David Liittschwager/National Geographic Stock

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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

Indian Island clam seeding—Northwest Indian Fisheries Commission

Chapter 2

Cover page (left to right): calcifying algae and sea urchins—Vlad Karpinkskiy; Willapa Bay—Jim Culp; Olympia oyster seed (6 months old)—Benjamin Drummond / bdsjs.com

Aerial image Bainbridge Island—Hugh Shipman

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

Figure 5: David Liittschwager/National Geographic Stock

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

Wave glider—NOAA Pacific Marine Environmental Laboratory

Carbon schematic—NOAA Pacific Marine Environmental Laboratory

Pacific herring—Washington Sea Grant

Oyster larvae—Benjamin Drummond / bdsjs.com

Copepod—Michael J. Bok

Chapter 8

Cover page (left to right): beach outreach—Jefferson Co. Marine Resources Committee; ocean acidification in the classroom—Center for Microbial Oceanography: Research and Education; Nisbet Oyster Company harvest—Benjamin Drummond / bdsjs.com ; 'Ask Me About Pteropods' button—Matt Chadsey

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:

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Madrona Venture Group
1000 2nd AV, Suite 3700
Seattle, WA 98014

Jay Manning
Cascadia Law Group
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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

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