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

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The NOAA research ship Ronald H. Brown taking calibration samples at the NANOOS Cha'ba monitoring mooring. Photo credit: R. Feely, Pacific Marine Environmental Laboratory/NOAA.

Chapter 7 of the original 2012 Panel report outlined the importance of understanding the causes and effects of 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 as we continue to move from knowledge to action. Critical information needs that are addressed by the Panel's research and monitoring recommendations include:

- Understanding the status of and trends in ocean acidification in Washington's marine waters
- Quantifying the relative contribution of different acidifying factors to ocean acidification in Washington's marine waters
- Understanding the biological responses of local species to ocean acidification and associated stressors
- Developing capabilities to identify real-time corrosive seawater conditions, as well as short-term forecasts and long-term projections of global and local acidification effects

This chapter describes accomplishments related to monitoring and investigations since 2012, revised and new actions, and key next steps to continue progress in this area. Refer to Chapter 7 in the original 2012 Panel report for a full summary of why monitoring and scientific investigations are critical and for descriptions of each original action in this area.

7.1. Accomplishments since 2012

A first step in revisiting the Panel's recommendations for monitoring and investigations was to review accomplishments and implementation of actions since 2012. Below is a list of high-level accomplishments.

Gained a better understanding of the status and trends of ocean acidification through a distributed monitoring network: Since its creation, the Washington Ocean Acidification Center (WOAC) has expanded an ocean acidification monitoring network for chemical and biological variables through various partnerships, including the National Oceanic and Atmospheric Administration (NOAA), King County, and state agencies, among others. This network established new monitoring of plankton species, including pteropods. WOAC funds seasonal cruises in the Salish Sea and offshore coastal waters, occupying stations, many of which were historical University of Washington stations since the 1930s. Ocean acidification variables were added in 2008 through other programs, and WOAC incorporated plankton monitoring in 2013. Several other advances include:

1. Research on existing mooring and cruise datasets yielded predictive relationships to estimate pH and aragonite saturation from pCO_2 and other hydrographic measurements[1].
2. New technologies are being developed and applied to chemical and biological monitoring, including new sensors and automation.
3. Data are being shared in near real-time through the Northwest Association of Networked Ocean Observing Systems (NANOOS) portal (www.nanoos.org).

Based on new monitoring data, we now know that ocean acidification in Washington's waters varies greatly depending on depth, season, and location[2]. At the same time, we also know that atmospheric CO_2 in the Puget Sound area is increasing faster than

[1] Fassbender et al., 2016.

[2] Feely et al., 2012.

Leveraging state resources to address ocean acidification

Over the past five years, state agencies have dedicated resources to help understand the threats that ocean acidification may pose to our shared natural resources and marine economies. To continue to advance our capacity to prepare for and understand the science of ocean acidification, three state agencies – the Washington State Department of Ecology, the Washington Department of Fish and Wildlife, and the Washington State Department of Natural Resources – are committed to establishing one to two monitoring locations within Washington. These locations, along with the WOAC monitoring effort, will help focus, align, and build on statewide monitoring and research efforts. By aligning and coordinating work, these agencies will be able to more completely assess and describe how ocean acidification is impacting the nearshore environment and important ecological and economic resources.

Collecting marine water quality data by plane

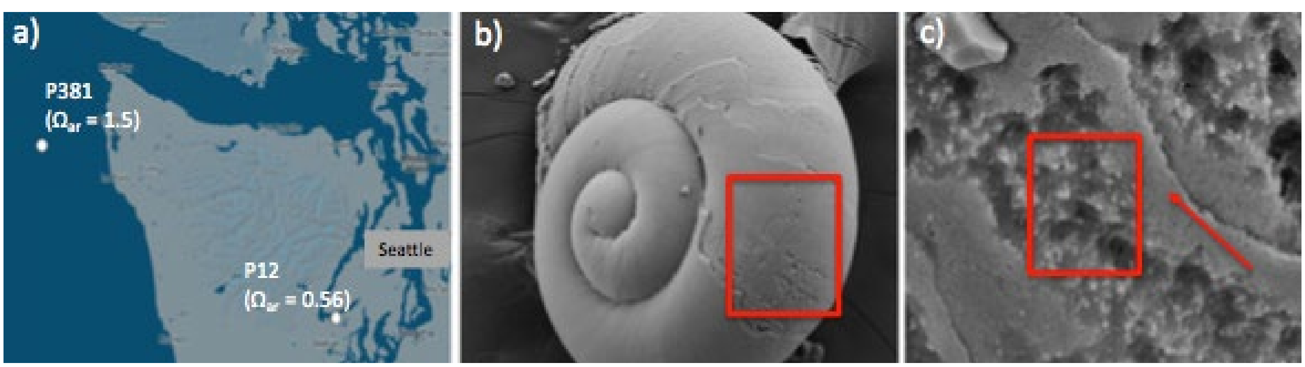
As part of state agency efforts, every month the Washington Department of Ecology collects marine water quality data from stations in Puget Sound, Grays Harbor, and Willapa Bay through their long-term marine water quality monitoring program. These monitoring activities are unique in that instead of collecting samples by boat, they are collected by floatplane, which allows a large geographic area to be sampled in a short amount of time. Water samples from approximately 40 stations are measured for many parameters, such as pH, temperature, salinity, dissolved oxygen, turbidity, and nitrates. Some of these stations have been surveyed by scientists since the 1950s, valuable for long-term trend analyses.

along the Washington coast and faster than the global average[3]. Additionally, Southern Hood Canal has the highest surface seawater values of pCO_2 in Washington coastal waters[4]. Direct, high-resolution observations of seawater pCO_2 and pH reveal that marine life is currently exposed to surface ocean pH and aragonite saturation values outside the envelope of preindustrial variability that they have evolved under, as measured at the La Push buoy, operated by University of Washington (UW), NOAA, and NANOOS[5].

While many advances have been made, sustained and enhanced monitoring is still necessary to identify patterns in time and space that can inform management actions and lead to effective adaptation.

Additionally, research has shown that human-generated atmospheric CO_2 is substantially increasing ocean acidification in surface waters[6]. This is also true even for subsurface waters off the Washington coast, which replace surface water pushed away during strong northwesterly winds, a process known as upwelling. Scientists have found that upwelled water now is more corrosive to calcifying (i.e., shell-making) organisms than it was in the past, with 30-50 percent of the enriched CO_2 concentration in surface waters attributable to human activities, and 20 percent at 100 meters depth[7]. Corrosive waters have been observed very close to the surface in many locations off the coast, and some organisms have already been impacted by acidified waters[8].

Research in Willapa Bay has shown how this unique embayment is being affected by ocean acidification. Due to input to Willapa



Dissolution of pteropods in Washington. Figure b is from station p381 and Figure c is from station P12. Image credit: Bednaršek et al., 2016

[3] Alin et al., 2016.

[4] Reum et al., 2015. Reum et al., 2016. Fassbender et al., 2016.

[5] Sutton et al., 2016.

[6] Feely et al., 2016.

[7] Feely et al., 2016.

[8] Feely et al., 2016. Bednaršek et al., 2014. Bednaršek et al., 2017a.

Bay from both upwelled CO_2-rich ocean waters (primarily during summer) and the Columbia River's low alkalinity plume waters (primarily during winter), this bay receives corrosive waters from two different sources. Research on carbonate chemistry within the bay revealed that aragonite saturation state levels often fall below thresholds that in laboratory experiments are associated with poor oyster production[9]. Notably, temperature and carbonate conditions favorable for early oyster larval development co-occurred for only a few weeks to a month each year during 2012 through 2014 and not at all in 2011. In contrast, without the effect of ocean acidification, calculations reveal that in the pre-industrial period, aragonite saturation states would have been higher and the duration of periods favorable for larval development (when both temperature and carbonate conditions are conducive to survival and development) were significantly longer, lasting several months. Another study[10] conducted in Willapa Bay found temperature to have a dominant influence on oyster larval settlement patterns. However, larval survival was found to be equal on both sides of the bay despite differences in water chemistry.

Determined that local anthropogenic nutrient sources contribute to ocean acidification in the Puget Sound region, and that there is spatial variation in the degree to which these contributions influence local water bodies:

One key research question raised by the Panel was how much local land-based pollution contributes to ocean acidification. It is clear that local sources do affect local waters. Even more clear is that the degree to which these local sources contribute to ocean acidification shows quite a bit of spatial variation (see figure below). The complexity of processes and inputs driving local ocean acidification requires a robust understanding of various influencing factors, an understanding we now have that was not available in 2012. Based on the Salish Sea Model developed by the Washington Department of Ecology and the Pacific Northwest National Laboratory, we now know that local human-derived nutrient sources originating from within the state of Washington contribute to ocean acidification conditions in the Puget Sound region and that these effects vary by location[11].

The aragonite saturation state in certain regions appears to be very sensitive to anthropogenic nutrient loadings. Specifically, portions of the main basin, South Sound, Port Susan, Skagit Bay, and

[9] Hales et al., 2017.

[10] Miller et al., 2016.

[11] Pelletier et al., 2017.

Increasing acidification impacts on U.S. West Coast

A synthesis of data from four NOAA cruises between 2007 and 2013 along the west coast of North America provides new evidence for increasing acidification of coastal waters and corresponding impacts on calcium carbonate ($CaCO_3$) shell dissolution of planktonic pteropods[1]. This represents the first time that pteropod shell dissolution has been quantitatively related to anthropogenic carbon concentrations on the continental shelf. Findings suggest that ocean acidification may be seriously impacting marine life on our continental shelf right now. The cruise results show high anthropogenic carbon concentrations in surface waters along the coast, with the lowest anthropogenic carbon values in strong upwelling regions off southern Oregon and northern California, and higher anthropogenic carbon values to the north and south of this region. Data show that:

- The most severe biological impacts occur in the nearshore waters, where corrosive waters are closest to the surface[2].
- Pteropods were ~22 percent more likely to be affected by severe shell dissolution in nearshore waters compared with offshore waters.
- Since pre-industrial times, models estimate that pteropod shell dissolution has likely increased approximately 20-25 percent in both nearshore and offshore waters[3].

These results clearly indicate that humankind may already be having a significant impact on a species that may play a vital role in this important marine ecosystem. Since pteropods are an important prey species for salmon, cod and herring, there is a need to obtain a better understanding of pteropod interactions with their predators in coastal waters.

[1] Feely et al., 2016.
[2] Feely et al., 2010. Feely et al., 2016. Bednaršek et al., 2014. Bednaršek et al., 2017a.
[3] Feely et al., 2016. Bednaršek et al., 2014. Bednaršek et al., 2017a.

The combined impacts of acidification and hypoxia in Washington coastal waters

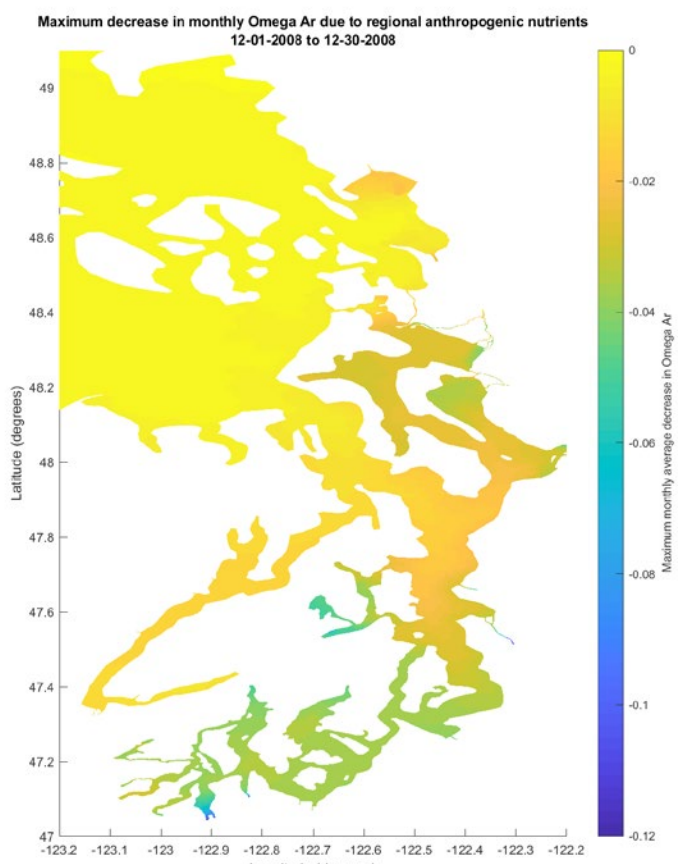
A newly published study by Feely et al. (2017) demonstrates that Washington coastal waters are particularly vulnerable to the synergistic effects of acidification and hypoxia.

The naturally high surface productivity in these waters results in high respiration at depth, which produces CO_2 and consumes oxygen, such that relatively low pH and aragonite saturation state and hypoxia are found at depth. These conditions are substantially enhanced by two other natural factors in our region: a lower buffering capacity of the seawater due to freshwater input from the Columbia, Fraser, Skagit, and other rivers, and the high amount of oxygen originally available for respiration because of relatively low surface water temperatures. A lower buffering capacity reduces the ability of the water to retain CO_2,

Whidbey Basin all show higher sensitivity of aragonite saturation levels in response to anthropogenic nutrient loadings. The impact of these sources is predicted to be greatest at the bottom of the water column, suggesting gradients in vertical habitats as well.

The changes in Ω_A due to regional anthropogenic nutrient sources in 2008 range from near zero in the Strait of Juan de Fuca, to around -0.01 in Hood Canal and the northern Main Basin, to about -0.02 to -0.05 in the Whidbey Basin, southern Main Basin, and most of South Puget Sound, and as much as -0.12 in inner Budd Inlet. For comparison, another study[12] reported basin-average changes in Ω_A in the bottom layer due to global anthropogenic sources of as much as -0.16. Consequently, the local nutrient-derived sources of acidification may be a significant fraction of the total in some locations.

Future model scenarios will examine local source attribution by location and perform more extensive analyses using this new tool to quantify the degree to which these nutrients impact ocean acidification over the recent past.



Predicted maximum monthly average decrease in Ω_A in the bottom layer in 2008 due to regional anthropogenic nutrient sources, originating within Washington. Credit: Pelletier et al., 2017.

[12] Feely et al, 2010.

Characterized biological responses of local species: Many life processes, including photosynthesis, growth, respiration, recruitment, reproduction, and behavior are sensitive to carbon dioxide and pH. The Panel recommended laboratory and field studies be implemented to understand the effects of ocean acidification, alone and in combination with other stressors, on local species.

New findings reveal responses of local species to ocean acidification:

- Early life stages of Dungeness crab show sensitivities to pH that could ultimately cause population declines[13].
- Krill larval development and survival are sensitive to low pH levels that are currently observed in Washington's marine waters[14].

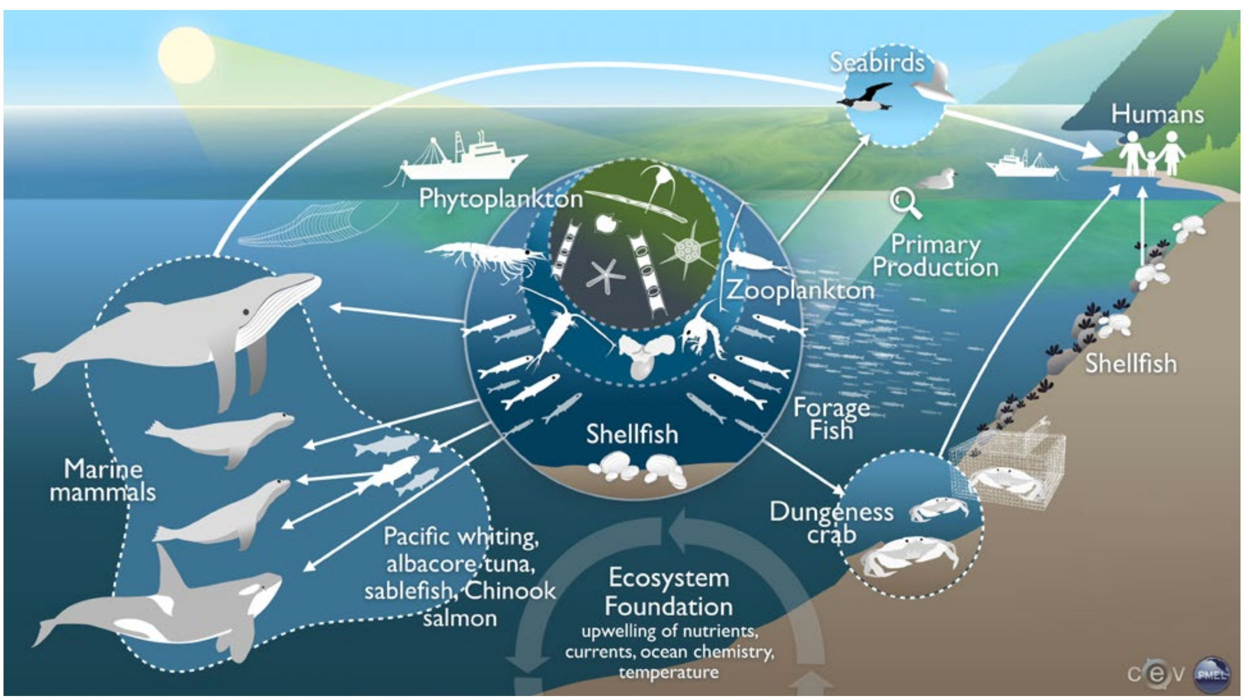
The food web and ocean acidification

The marine food web is highly interconnected. While some species, like shelled organisms, are directly affected by ocean acidification, other species are affected because they depend on those species for food or habitat. Thus, ocean acidification threatens the well-being of a variety of species, as affects can flow throughout the food web.

and cold water has the potential to hold more gas.

Additional inputs of CO_2 from human sources over time will further reduce the buffering capacity of seawater, leading to more rapid decreases in pH in the future and increases in hypercapnia (biological effects of high pCO_2) that can affect fish behavior. This means we should expect to see, and be able to measure, increases in the magnitude of the daily and seasonal variability of pH and pCO_2. This effect will be greater in Washington coastal waters compared to conditions that would be found in warmer coastal regions, such as the Gulf of Mexico, and will result in crossing key biological thresholds and tipping points more quickly in our region[1].

[1] Feely et al., 2017.



Credit: Simone Alin (NOAA) and Hunter Hadaway (Center for Environmental Visualization-UW)

[13] Miller et al., 2016.
[14] McLaskey et al., 2016.
[15] Martin & Nesbitt, 2015.

Informing tribal shellfish management decisions with stable isotopes

Examining stable isotope ratios in fish otoliths, a calcium carbonate structure in the inner ear used for hearing and directional orientation, can be used to track a fish's life history and environmental conditions. In an innovative twist on this method of biological monitoring, scientists with the Makah Tribe in Washington state are analyzing carbon isotope ratios in bivalve shells to detect the effects of ocean acidification. This research will help the tribe make informed decisions about shellfish resource protection and economic development. In addition to shellfish research, the tribe conducts regular water quality monitoring and obtains environmental parameters (e.g., temperature, salinity, pH, dissolved oxygen concentration and pressure), adding to regional data on ocean conditions.

Olympia oysters provide critical habitat for a variety of marine plants and invertebrates. Photo credit: Benjamin Drummond / benjandsara.com

- Species diversity among benthic foraminifera in Puget Sound appears to be declining and shell dissolution appears to be increasing[15]. Moreover, non-calcified species of foraminfera appear to be replacing calcified species. Forams are prey for many small marine invertebrates and fish; changes in their abundance and distribution could affect marine food webs.

- Shell dissolution in pteropods is evident off Washington's coast and is severe in the Salish Sea[16]. Their ability to build and repair their shells is greatly reduced in corrosive waters, consequently they may be useful indicators of ocean acidification conditions[17].

- Native and non-native seagrass species (*Zostera marina* and *Z. japonica,* respectively) both appear to have the capacity to effect short-term changes to seawater carbonate chemistry via photosynthesis. Notably, elevated total CO_2 appears to enhance photosynthesis in *Z. japonica* but not *Z. marina*[18].

- Numerical models suggest that bottom-dwelling invertebrates (crabs, shrimps, benthic grazers, benthic detritivores, bivalves) in Washington waters will show strong negative responses to ocean acidification. Some bottom-dwelling fish species, sharks, and invertebrates such as Dungeness crab could be subject to strong indirect effects of ocean acidification because they consume species known to be sensitive to changing pH[19].

- Modeling studies indicate that the indirect effects of ocean acidification, as mediated by trophic interactions, are likely to vary by taxon and functional group. Copepods may play a key role in affecting trophic interactions under ocean acidification conditions[20].

Studies are underway to examine:

- The sensitivity of Coho salmon to elevated CO_2. Early findings suggest that juvenile Coho salmon exhibit behavioral sensitivity to CO_2 that may impair their ability to detect predators.

- The sensitivity of adult Olympia oysters to low pH, particularly with respect to reductions in reproductive potential.

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[16] Bednaršek et al., 2016. Busch et al., 2014.

[17] Bednaršek et al., 2017b.

[18] Miller et al., 2017.

[19] Marshall et al., 2017.

[20] Busch et al., 2013.

Built 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. Additionally, long-term projections give the "long view" of what conditions may be like decades from now. Researchers are working on forecast models for daily, seasonal, and decadal timescales. On the daily scale, a LiveOcean model was developed by UW modelers showing pH and aragonite saturation state, as well as oxygen, nutrients, phytoplankton, salinity and temperature for today, tomorrow, and the next day. The output is live on the NANOOS data portal (nvs.nanoos.org) and can be compared to real-time data to assess model performance. On the seasonal scale, the J-SCOPE project (www.nanoos.org/products/j-scope) produces forecasts three to six months in the future for variables including pH and aragonite saturation state[21]. This product is being used by state and tribal fisheries managers as one tool to inform their management decisions. On the decadal scale, UW scientists are working to project environmental variables (temperature, pH, oxygen) 50 years into the future and to evaluate the sensitivities of local species under different climate scenarios to understand longer-term regional ecological responses to ocean acidification in Washington.

Established partnerships to advance monitoring and investigation efforts: Since its creation in 2013, WOAC has served to enhance and coordinate efforts across several partners working within the ocean acidification landscape, including government agencies and research programs, tribal groups, shellfish industry representatives and universities. WOAC's coordination has included:

- Bringing a regional focus to research priorities and serving as a regional hub for research endeavors
- Hosting a biennial science symposium to foster sharing of emerging ocean acidification research and hosting an ocean acidification session at the Salish Sea Ecosystem in alternate years
- Training the next generation of scientists, managers, and decision-makers to face the challenges posed by ocean acidification
- Using a distributed network model of organization to join the expertise of UW scientists with that of other regional academic institutions, agencies and organizations
- Engaging with industry representatives, state, local, federal and tribal policy makers, and public opinion makers through specific activities

Seattle Aquarium partnering for ocean acidification innovation

In 2015, the Seattle Aquarium hosted coastal environment pilot testing for the Wendy Schmidt Ocean XPrize competition, where 15 teams from across the globe tested their pH sensors designed to affordably and accurately measure ocean acidification. The aquarium continues to work with scientists at the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory (NOAA PMEL) to measure ocean acidification in Puget Sound.

[21] Siedlecki et al., 2016.

7.2 Updated Actions

Specific revisions to the Panel's 2012 action language are underlined for easy reference.

Action	Original Language	Updated Language	Rationale
7.2.1	Quantify key natural and human-influenced processes that contribute to acidification based on estimates of emission sources, sinks, and transfer rates of carbon and nitrogen	Quantify key natural and human-influenced processes that contribute to acidification based on estimates of [removed emission] sources, sinks, and transfer rates of carbon and nitrogen	• Removed "emission" to broaden the types of sources considered

7.3 New Actions

Action	Language	Rationale
7.5.1	Support coordination at the state level to capitalize on existing data and efforts for monitoring ocean acidification	• Recognizes the importance for continued coordination and collaboration on research efforts • Working together has led to leveraging resources to accomplish more than a single entity would have been able to accomplish alone
7.5.2	Support co-location of observational resources and coordinate lab and field efforts for mutual benefit	• Recognizes the diverse capacity and expertise of various partners, and supports efforts to leverage these resources during research
7.6.1	Identify and share a summary of key findings from monitoring and investigations actions with ocean acidification communicators to support outreach and communications efforts designed to raise public awareness of ocean acidification *(Related to New Action 8.1.6)*	• As part of developing a strong ocean acidification outreach and communications strategy, each topic area is charged with sharing key findings, success stories, and relevant information to ensure communicators can successfully develop accurate key messages