4. Arctic Region Acidification Research

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Abstract

The Arctic Region includes the broad continental shelf areas surrounding northern Alaska, including the Northern Bering, Chukchi and Beaufort seas (for information on the Gulf of Alaska and Eastern Bering Sea, refer to *Chapter 3: Alaska Region*). Ocean acidification (OA) in this region is influenced by increasing concentrations of atmospheric carbon dissolving in cold surface waters as well as regional changes in seawater chemistry driven by advective input from neighboring regions, sea ice melt and riverine input as well as seasonal fluctuations in productivity that both draw down and release dissolved carbon in Arctic waters. The Arctic and its marine ecosystems provide food and cultural identity to subsistence communities that call the Alaskan Arctic home. While the U.S. Arctic is not currently home to a commercial fishery, northward migration of major fisheries stocks (e.g., Alaska pollock, *Theragra chalcogramma*, and Pacific cod, *Gadus macrocephalus*) from the Eastern Bering Sea may support a commercial fishery in the future. NOAA's Arctic Region research goals are to:

- Support targeted OA monitoring to increase understanding of progression and processes driving OA in the vast region of the Arctic and to inform regional OA models;
- Conduct laboratory studies on the sensitivity and resilience of economically and ecologically important species to better understand ecosystem-level responses to OA and prudent management approaches; and
- Use physical and biological understanding of Arctic OA to inform and develop regional adaptation strategies for communities and fisheries management decisions.

Acidification in the Arctic Region

OA is rapidly advancing in the Arctic, producing newly corrosive conditions (e.g., Tanhua et al., 2009; Mathis et al., 2015a; Cross et al., 2018; AMAP, 2018). Other factors of rapid environmental change occurring in the Arctic, including advective transport (Tanhua et al., 2009; Qi et al., 2017), changes in the seasonal sea ice cycle, increasing river discharge, and more frequent upwelling exacerbate the region's naturally high vulnerability to OA. As a result, persistently corrosive water masses have emerged (Cross et al., 2018) and expanded (Qi et al., 2017) over the last several decades, generating unknown consequences for marine ecosystems.

U.S. national interests in the Arctic center on the northern Bering, Chukchi, and Beaufort seas. These shelf areas are the gateway to the international waters of the Arctic Ocean. The ecosystems in these areas are critical for cultural preservation given that they support important subsistence fisheries. While no commercial fisheries currently operate in the Arctic, some species are already federally managed for sustainability and conservation (e.g., snow crab, *Chionoecetes opilio*; Arctic cod, *Boreogadus saida*; and saffron cod, *Eleginus gracilis*). Although the vulnerability or resilience of these species to OA remains unclear, evidence suggests that the vulnerability of early life stages of some crab species to OA could eventually lead to declines in the adult population (e.g., king and tanner crab; Long et al., 2013a, b; Swiney et al., 2016;), while fish species such as Arctic cod may be more resilient to OA stresses (Kunz et al., 2016). Other non-managed species in the Arctic food web have also shown some vulnerability to OA e.g., pteropods and Arctic bivalves, important food sources for other species (Darnis et al., 2008, Lischka et al., 2011; Walkusz et al., 2013; Goethel et al., 2017).

Across the Arctic, NOAA is actively engaged in science and stewardship associated with recent, rapid environmental changes (see NOAA, 2014). Ocean warming, changes in atmospheric and oceanic circulation patterns, and sea-ice losses are rapidly propagating through the food web because Arctic ecological linkages lack complexity (comparatively few species and short food chains, which do not adapt well to a rapidly changing environment) and have stronger species interactions. For example, increases in primary production and shifts in lower trophic taxa are already visible in the diet and body condition of upper trophic marine mammals and birds (e.g., lower body mass and lipid content), which could impact their subsistence value (e.g., Moore & Gulland, 2014). NOAA supports research and monitoring of ongoing changes in these areas by contributing to the Distributed Biological Observatory, a network of ecosystem hotspots designed as an Arctic ecosystem change detection array. Recently, NOAA has also partnered with the Department of Fisheries and Oceans – Canada to explore more of the Arctic region through a bi-lateral partnership, bridging the gap between U.S. Arctic territories in the Pacific Arctic and the North Atlantic.

Given the inherent vulnerability of the Arctic's simple food web, OA introduces a significant additional risk factor to ecosystems already experiencing multiple stressors. The research community is beginning to explore these vulnerabilities in detail. The first reviews of current environmental exposure to corrosive conditions were completed over the last decade (Arctic Ocean: Yamamoto-Kawai et al., 2009; Bates & Mathis, 2009, Tanhua et al., 2009; AMAP, 2013, 2018; Atlantic: Azetsu-Scott et al., 2010, Shadwick et al., 2011; Pacific: Semiletov et al., 2007; Bates et al., 2011; Evans et al., 2015; Mathis et al., 2009, 2012, 2015a; Miller et al., 2014; Cross et al., 2018). Estimates of anthropogenic carbon dioxide (CO_2) concentrations in the region range from 39 to 62 μmol kg^{-1} and projections indicate that the frequency of exposure to acidified waters is likely to become more common over time (e.g., Tanhua et al., 2009; Mathis et al., 2009, 2015a; Cross et al., 2018; McGuire et al., 2009; Steinacher et al., 2009; Steiner et al., 2014; Harada, 2016). Understanding these components of present and future exposure provides a baseline for laboratory studies to assess species- and population-specific vulnerabilities for U.S. Arctic species. Linking this exposure to the ecosystem is a critical next step, especially as the research community investigates whether commercial fish stocks could emerge in the U.S. Arctic (e.g., Bluhm et al., 2009; Orensanz et al., 2004), or whether important subsistence species will decline (Moore & Gulland, 2014).

Overall, Arctic OA research is in its infancy compared to other U.S. regions. As NOAA pursues an Arctic observing system that can contribute to OA research over the next decade, there is a wealth of experience from other regional NOAA acidification networks to draw from. Based on those successes, NOAA will pursue OA research in the Arctic over the next decade by maintaining and developing partnerships with regional academic institutions, other federal and state agencies, international partners, and local industries and communities to evaluate, understand, and respond to the risk that OA poses to the U.S. Arctic regions. This will require marked increases in efforts to understand OA in the context of ongoing ecosystem changes. Emerging OA impacts will be only part of a growing portfolio of other stressors for U.S. Arctic residents, and community adaptation plans will necessarily need to take into account a diverse array of environmental factors.

Environmental Change in the Arctic Region

Over the last 10 years, NOAA's OA research activities in the Arctic have been limited relative to other U.S. regions. As part of its emphasis on long-term ecosystem studies, NOAA has participated in sustained monitoring in the Arctic, including through the Russian-American Long-term Census of the Arctic (RUSALCA; Crane & Ostrovskiy, 2015) where carbonate chemistry measurements were collected in 2009 and 2012 (Bates, 2015; Mathis et al., 2009, 2015a; Cross et al., 2018). Building on this legacy, NOAA has recently initiated a long-term monitoring project for the Pacific Arctic called the Distributed Biological Observatory (DBO). The DBO is a field-based program that makes biological, physical, and chemical observations at a series of sites along a latitudinal gradient from the Bering to Beaufort seas to link biological observations to ongoing environmental changes (Moore & Grebmeier, 2018). While the DBO was formally established in 2010, some time-series observations in DBO regions date back decades. OA observations were added to the DBO portfolio in 2017, with some regional observations also initiating in 2015 (**Figure 4.1**).

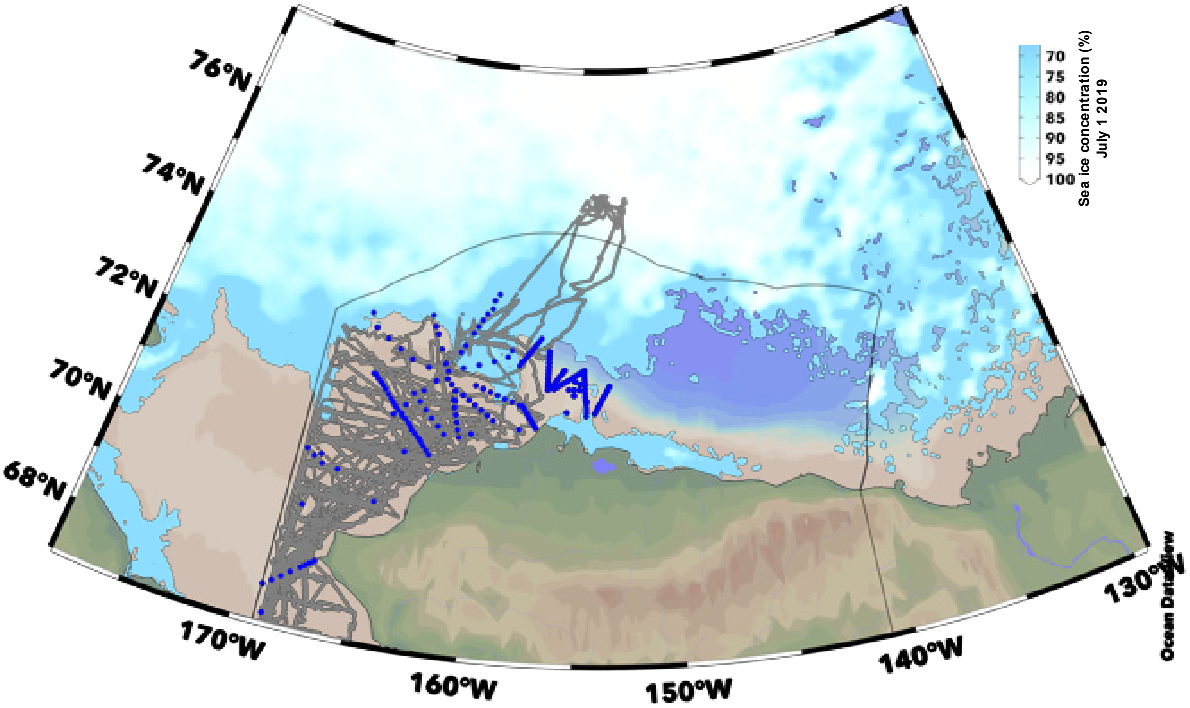

Figure 4.1. Ocean observing system for the Chukchi Sea between 2015 and 2020, as supported by the NOAA Ocean Acidification Program and Arctic Research Program. Shown here in blue dots are discrete sampling stations occupied during the Distributed Biological Observatory missions. Gray tracklines indicate surface observations collected from autonomous vehicles. Background shading indicates the MASAM2 daily sea ice concentration (%) from July 1 2019, as a proxy showing how observations fit into typical sea ice conditions. While the saildrone tracklines extend well into the basin, an area typically covered by ice as shown, note that these measurements were collected in open water conditions.

Across the research community, OA observations in the U.S. Arctic are also relatively new. In the U.S. Pacific Arctic, carbon cycle sciences have been periodically studied only since the early 1980s (1982: Chen et al., 1985), with the first large-scale carbonate chemistry mapping programs implemented only over the last few decades (e.g., SBI: Bates & Mathis, 2009, Anderson et al., 2010; ICESCAPE: Bates et al., 2014b; RUSALCA: Bates, 2015; BLE LTER: Lougheed et al., 2020). In part, this lack of observing data is due to unique environmental hazards encountered in the Arctic. Sea ice is a clear infrastructure challenge for surface and bottom moorings, as sea-ice drafts can reach the ocean bottom in many coastal regions. Year-round, long-term monitoring of OA in the Arctic occurs only off the shelf in deeper waters, where protection from sea ice is more predictable, as in Iceland (north of which NOAA maintains an OA buoy, Olafsson et al., 2009) and the Beaufort Sea (Cross et al., 2018). A lack of infrastructure also creates substantial barriers to winter time series and process studies. Accordingly, most of the understanding of OA in the Arctic environment is based on observations made during the summer, open-water period, which can bias observational climatologies (e.g., Evans et al., 2015).

To meet some of these technological challenges, NOAA scientists have recently explored new platforms and sensors specifically for Arctic deployments (Cross et al., 2016). Since 2017, a new autonomous vehicle (the saildrone) has collected seasonal surface CO_2 flux measurements in an effort to supplement those collected by ships (Cross et al., 2016; Sabine et al., 2020). NOAA is also exploring new sub-surface sensors that may be able to seasonally collect autonomous measurements of total alkalinity (TA) from moored platforms. Importantly, collecting TA measurements may help identify OA impacts, including acidification-mediated dissolution. Sensors that measure dissolved inorganic carbon (DIC) are also currently under development. Combining readily available $p\mathrm{CO}_2$ sensor data with developing DIC or TA sensor data will also help to generate extended carbonate system data in a time-series setting.

NOAA has recently supported regional OA modeling efforts in the Bering Sea and the Gulf of Alaska (Siedlecki et al., 2017; Pilcher et al., 2019), however carbonate chemistry modeling in the Chukchi and Beaufort seas remains limited. While global models can presently be used to study the Arctic system, they often simplify complex processes that can be especially important leading to misrepresentation of their total impact (e.g., freshwater balances and biogeochemical interactions between land and ocean, sea and ice, and within benthic habitats: Manizza et al., 2011; Carmack et al., 2016; Steiner et al., 2016).

Saildrones, capable of making autonomous ocean measurements, waiting at the dock in Dutch Harbor, Alaska before their multi-month NOAA research mission. Credit: Saildrone, Inc.

By contrast, regional models offer finer spatial resolution and can incorporate high-resolution coastal processes. Process studies and long-term monitoring can be used to help build and validate regional models. Once developed, these validated models will be used to project multi-decadal trends in OA and test model performance for seasonal forecasts of corrosive water conditions. Furthermore, historical hindcasts can provide context to long-term ecological time series in the region, illuminating potential links between ecosystem variability and OA.

Research Objective 4.1: Targeted observations and process studies to increase understanding of OA dynamics and impacts

Given the limited number of observations in the historical record, time-series and process studies can help to resolve key unknowns in the Arctic carbonate cycle.

Activity 4.1.1: Quantify anthropogenic CO_2 concentrations through coastal and open ocean cruises in order to constrain rates of anthropogenic coastal acidification versus contributions from other processes such as advective transport, changing river inputs, upwelling rates, source water advection, or locally enhanced air-sea exchange.

Activity 4.1.2: Sustain long-term monitoring of carbonate chemistry observations linked to biological sampling, which will increase our understanding of ecosystem impacts of OA.

Activity 4.1.3: Design process studies to help the scientific community target key uncertainties in carbonate cycling, such as wintertime cycles and seasonal respiration rates.

Research Objective 4.2: Build high-resolution regional models able to simulate fine-scale OA processes

Limited infrastructure and harsh conditions can make a spatially extensive carbonate monitoring system in the Arctic impractical and cost-prohibitive. High-resolution regional models will provide a broader spatial and temporal context for observations.

Activity 4.2.1: Use process studies to generate new observations that can be used to validate regional models and test their predictive capability.

Activity 4.2.2: Use validated models to project OA trends on multi-year to multi-decadal time frames and develop historical hindcasts of OA variables that can be used to provide context to existing decadal scale ecological time series, such as those that underpin the DBO.

Activity 4.2.3: Use validated models to pursue short-term seasonal forecasts of corrosive water conditions and other decision support products for NOAAs stakeholders in the Arctic region.

Biological Sensitivity in the Arctic Region

Few studies have quantified species-specific responses of Arctic taxa to OA. Some Arctic zooplankton species are negatively affected in laboratory studies (e.g., *Euphausia superba*, Kawaguchi et al., 2013; *Euphausia pacifica*, Cooper et al., 2016, and McLaskey et al., 2016; *Pseudocalanus acuspes*, Thor & Oliva, 2015) while at least the juvenile stages of a critical forage fish species (Arctic cod, *Boreogadus saida*) appear resilient to acidified conditions (Schmidt et al., 2017; Kunz et al., 2016). Note that potentially more sensitive larval stages have not been examined yet. There is evidence that some species may express an adaptive capacity to cope with OA either via phenotypic plasticity or selective responses (e.g., *Pseudocalanus acuspes*, Thor & Dupont, 2015; De Wit et al., 2016). However, U.S. commercial, protected, and subsistence species have not been evaluated for OA sensitivity and resilience. Following the blueprint set by the NOAA Alaska OA Enterprise, studies that focus on OA sensitivity of taxa in the U.S. Arctic region appear to be the consensus next step.

In order to quantify the effects of OA on protected and managed species and on the ecosystems on which they depend, it is imperative to initiate targeted, Arctic-specific laboratory and field acidification studies. Highest priority species are those for which there is a federal management plan (snow crab, *Chionoecetes opilio*; Arctic cod, *Boreogadus saida*; and saffron cod, *Eleginus gracilis*) and species important in the food web such as *Hyas coarctatus* and *Ophiura sarsi* (NPFMC, 2009). Species of secondary import include forage shellfish that are important prey for protected species such as walruses and bearded seals (Lowry & Frost, 1981). Given the rapid pace of environmental change in the Arctic, it is also imperative that these studies explore multiple stressors (Breitburg et al., 2015). Given that many species in Arctic regions are stenothermic, temperature is a critical co-stressor that must be investigated. Additionally, as the timing and location of sea ice breakup changes, pelagic-benthic linkages that depend on ice algae may also shift, altering the quality and quantity of food to the benthos. Thus, experiments examining the effects of food quality and quantity in differing OA scenarios will also be important. Finally, changes in freshwater input are predicted with climate change and so salinity may also be an important costressor to consider for some species. Gene expression, metabolomic, and proteomic measurements, especially once initial response experiments have been performed, will be important for understanding the physiological and molecular responses to OA in these species. The critical importance of multi-stressor experiments in the Arctic region make additional NOAA investment in laboratory infrastructure essential. Complex experimental tank setups and intricate control systems are required to assess multiple stressors with scientific rigor.

Zooplankton collected by researchers in the Chukchi Sea, a marginal sea of the Arctic Ocean. Credit: Lindsey Leigh Graham/ NOAA

Understanding ecosystem level responses to OA is critical to help co-develop fisheries management and human adaptive strategies in the Arctic. Establishing reference points via surveys of biological resources and quantifying changes under ecosystem change are critical next steps. The Chukchi Ecosystem Observatory (CEO) is collecting co-located biological and carbonate data for a moored platform (Hauri et al., 2018). From a broad-scale approach, the DBO is an excellent framework for studying ecosystem-level OA sensitivity. DBO sites are already focused on locations of high productivity, biodiversity, and biological rates of change. NOAA investment in the DBO efforts will help to establish reference levels to quantify change in the Arctic and link those changes to physical parameters, including OA. In addition, the DBO will help to focus research efforts on species particularly vulnerable to change. Similar partnerships should also be established with other groups involved in ecosystem-level research to leverage such data in exploring the role of OA in the Arctic ecosystem. Further, process studies, such as quantifying ice and pelagic primary production and linking that to carbon flux to the benthos will be important in understanding carbon cycles and predicting ecosystem-level changes in reduced ice conditions.

As data on species-specific vulnerabilities become available, it will be important for modelers to incorporate this perspective. It is likely that a suite of modeling techniques, including single-species models, multispecies models, and qualitative models will be needed to predict how the ecosystem is likely to change in response to these vulnerabilities. For example, incorporating data into modified stock-assessment models (e.g., Punt et al., 2016) will help inform adaptation strategies for fisheries management, subsistence users, and local communities. In contrast, multispecies ecosystem models such as the Atlantis model should be used to predict indirect effects on important species and guilds under changing conditions (e.g., Marshall et al., 2017). Finally, qualitative models may be useful, especially in data-limited situations, to make large scale predictions and to focus research efforts on critical species and linkages in the system (e.g., Reum et al., 2015).

Research Objective 4.3: Conduct laboratory studies of OA impacts in economically and ecologically important species

In order to quantify the effects of OA on protected and managed species and the resulting impacts on ecosystems, it is imperative to conduct targeted, Arctic-specific laboratory and field OA studies.

Action 4.3.1: Conduct laboratory studies on high-priority species such as potential fisheries species (snow crab, *Chionoecetes opilio*; Arctic cod, *Boreogadus saida*; and saffron cod, *Eleginus gracilis*), species important in the food web such as *Hyas coarctatus* and *Ophiura sarsi*, and species that are important food resources for protected species.

***Action 4.3.2*:** Examine OA and temperature interactions in laboratory and field experiments to quantify potential synergistic responses to co-stressors.

***Action 4.3.3*:** Conduct laboratory experiments on effects of OA and concurrent stressors, such as salinity and food quality/quantity, using species likely to encounter these environmental conditions, which exhibit potential vulnerabilities to such conditions, and meet qualifications listed in *Action 4.3.1*.

***Action 4.3.4*:** Use gene expression, metabolomic, and proteomic measurements to understand the physiological pathways affected by OA, particularly for species identified in initial response experiments as vulnerable to OA.

Research Objective 4.4: Conduct ecosystem-level studies to evaluate OA impacts

Characterizing baseline physical and biological conditions, monitoring changes in these ecosystem attributes, and performing process studies on key species will provide foundational information that can be used by the scientific community to model and predict ecosystem-level effects of OA.

Action 4.4.1: Establish reference conditions for Arctic ecosystems and invest in sustained ecosystem monitoring of important Arctic species and zooplankton.

Action 4.4.2: Perform targeted process studies to quantify important ecosystem pathways.

Research Objective 4.5: Biological projection and forecast development

Models will be needed to integrate sensitivity studies and oceanic observations in order to predict effects of OA on Arctic species and ecosystems and to understand the impacts on, and guide the adaptation of, human communities.

Action 4.5.1: Use appropriate modeling techniques, including single-species, ecosystem, and qualitative models, to understand the likely effects of OA in the Arctic.

Human Dimensions in the Arctic Region

Commercial fisheries in the Arctic Ocean account for a tenth of the world's total fish catch (AMAP, 2013; CAFF, 2013). Additionally, many of the region's residents rely on these fisheries for food, economic security, and cultural benefits. While no commercial fisheries or Marine Protected Areas (MPAs) currently exist in U.S. Arctic waters, a number of conservation management activities have been enacted to ensure the protection of sustainable fisheries across the Arctic in the event that fisheries or MPAs emerge, as noted in NOAA's Arctic Action Plan (NOAA, 2014). The U.S. Arctic Fisheries Management Plan limits commercial harvests in U.S. Arctic waters until sustainable management practices can be devised (NPFMC, 2009).

This conservation practice has spread across the Arctic region. In 2017, the U.S. and four other nations with waters adjacent to the High Seas portion of the Central Arctic Ocean (CAO) agreed to interim measures for the prevention of unregulated commercial fishing in the CAO High Seas (US ARC, 2019; Hoag, 2017). The agreement included a 3-year mapping program, to be followed by a long-term monitoring initiative, exploring the distribution of species with a potential for future commercial harvests.

The Arctic is home to ice floes that can pose challenges to conducting research in the Arctic, but also yield unique ecosystems and ocean conditions. Credit: Jessica Cross/NOAA

The science and implementation plan for this agreement developed by the Fifth Meeting of Scientific Experience on Fish Stocks in the Central Arctic Ocean (FiSCAO) includes mapping data on carbonate chemistry, while developing management practices that incorporate OA stresses. Although there will be both winners and losers in acidified ecosystems, the magnitude and rate of changes anticipated in Arctic carbon chemistry combined with other habitat changes are likely to impact ecosystems and human communities (AMAP, 2018). In U.S. sub-Arctic regions, previous work has indicated that early actions to support sustainable fisheries in the face of OA will be critical for managing future outcomes (Punt et al., 2016; Seung et al., 2015). Even where OA is not the primary environmental stressor, it could interact with or amplify other stressors like warming, hypoxia, and loss of sea ice.

In addition to threatening the growth of Arctic commercial fisheries, OA also has the potential to impact subsistence and cultural resources, including indirect effects on marine mammals. While permafrost thaw, sea-level rise, and coastal erosion are likely to represent the greatest challenge to these communities (e.g., Berman & Schmidt, 2019; Hjort et al., 2018), research findings of OA effects may help inform further human adaptation strategies (Metcalf, 2015). Previous work has shown that the most pronounced OA exposure occurs in areas that also support critical populations of seabirds, walrus, and bowhead whales (Cross et al., 2018). The communities that rely on these populations have emphasized the need to understand and adapt to coming changes in the marine environment (Mathis et al., 2015a; ICCA, 2015; Lam et al., 2016), with these goals expressed in NOAA's Arctic Action Plan (NOAA, 2014). Here we emphasize two objectives that focus on supporting human communities through sustainable fisheries management, in the event that an Arctic commercial fishery does emerge, as well as other forms of community adaptation support.

Research Objective 4.6: Support NOAA's contributions to U.S. Arctic fisheries management

NOAA should provide relevant OA products and data to fisheries management and conservation efforts in the Arctic. These products should be designed with managers and stakeholders in mind in order to maximize beneficial outcomes.

Action 4.6.1: Design targeted carbonate chemistry products that support the U.S. Arctic Fisheries Management Plan and the FiSCAO Science Plan.

Action 4.6.2: Include OA risk information when designing fisheries management strategies for the U.S. Arctic region.

Research Objective 4.7: Assess regional adaptation strategies to OA coupled with environmental change

Many Arctic communities are already struggling with impacts to subsistence harvests. Most notably, reduced and destabilized sea ice is limiting access to large marine mammals for traditional subsistence hunting practices. Additional risks from OA could compound these stresses.

Action 4.7.1: Survey commercial, local, and indigenous communities to better understand stakeholder and decision maker needs for OA information and integrate traditional knowledge and perspectives into decision support products.

Action 4.7.2: Work with organizations that have links to communities, including the Arctic Waterways Safety Committee, Adapt Alaska, and the Alaska Ocean Observing System's (AOOS) Alaska OA Network (AK-OAN) to develop and transition decision support products.