3. Alaska Region Acidification Research

Thomas P. Hurst[1], Jessica N. Cross[2], W. Christopher Long[3], Darren J. Pilcher[4], Michael Dalton[5], Kirstin K. Holsman[5], James T. Thorson[5], Robert J. Foy[6], Jennifer M. Mintz[7]

[1]NOAA/NMFS, Alaska Fisheries Science Center, Newport, OR

[2]NOAA/OAR, Pacific Marine Environmental Laboratory, Seattle, WA

[3]NOAA/NMFS, Alaska Fisheries Science Center, Kodiak, AK

[4]NOAA/OAR, Joint Institute for the Study of Atmosphere and Ocean, University of Washington, Seattle, WA

[5]NOAA/NMFS, Alaska Fisheries Science Center, Seattle, WA

[6]NOAA/NMFS, Alaska Fisheries Science Center, Juneau, AK

[7]NOAA/OAR, Ocean Acidification Program, Silver Spring, MD

Abstract

The Alaska Region includes the waters of the Gulf of Alaska, Eastern Bering Sea and surrounding the Aleutian Islands (*for information on the Chukchi and Beaufort seas refer to Chapter 4: Arctic Region*). Acidification in this region is driven by relatively high incorporation of atmospheric carbon due to high solubility in cold waters, as well as a number of regional processes such as seasonal productivity and sea ice melt pulses. Major fisheries exist in this region, some of which have proven to be sensitive to changes in ocean pH. Alaska communities also depend heavily on marine resources for subsistence, cultural identity, and well-being. The following research plan outlines the scientific rationale, research objectives and actions for the Alaska Region focusing mainly on the following regional goals:

- Expand ocean acidification (OA) monitoring with both oceanographic and shore-based based observing networks to characterize seasonal cycles, regional vulnerabilities, and future regional trajectories;
- Assess sensitivity and resilience of critically important ecosystems and commercial species and use this knowledge to model and predict ecosystem-wide impacts of acidification; and
- Evaluate the sensitivity of nutritionally and economically important subsistence and industry species to assess socioeconomic impacts.

Acidification in the Alaska Region

OA poses unique economic, nutritional, and societal concerns to Alaska communities. With a greater area of Exlusive Economic Zone (EEZ) waters and a longer coastline than that of the entire contiguous U.S., monitoring ongoing OA and understanding ecological and social consequences of OA in Alaska represents a major challenge. Alaska fisheries accounted for more than 60% of total U.S. harvests by weight in 2016 (Fissel et al., 2017), supporting an estimated 36,800 full-time jobs and $5.2 billion in total output for the U.S. economy (McDowell Group, 2017). In addition to these economic benefits, the harvest of marine resources plays a critical role in the identities and well-being of Alaska communities. More so than any other Americans, Alaskans rely upon subsistence harvests of marine resources to meet their daily nutritional needs (Fall, 2012).

In order to continue evaluating, understanding, and responding to the threat of OA to Alaska, NOAA will continue to maintain and build partnerships with regional academic institutions, other federal and state agencies, local industries, communities, and tribal members and governments. Here, we discuss the ongoing monitoring efforts and scientific understanding of OA on Alaska marine ecosystems in the Gulf of Alaska and Eastern Bering Sea. To learn more about NOAA's work along the northern Alaska coast, refer to *Chapter 4: Arctic Region Acidification Research Plan*.

Research conducted over the last decade has shown that Alaska waters are especially vulnerable to OA. Due to long-term preconditioning that results in naturally elevated carbon dioxide (CO_2) in water masses delivered to the region and increased CO_2 solubility of cold seawater, even small accumulations of anthropogenic CO_2 can produce relatively large changes in carbonate chemistry (Fabry et al., 2009; Carter et al., 2017, 2019a). Regional and seasonal processes that influence acidification patterns include advective transport, riverine discharge loaded with organic carbon, seasonal sea ice cycles that can dilute alkalinity impacting buffering capacity, and the strong biological pump that can amplify long-term signals. Because the effects of OA are expected to be observed first in these high latitude seas, they have been considered critical "bellwethers" of the OA impacts on a global scale (Fabry et al., 2009).

Direct calculations of anthropogenic CO_2 absorbed by seawater surrounding Alaska indicate concentrations ranging from 50-55 $\mu mol\ kg^{-1}$ in surface waters as of 2015 (Carter et al., 2017, 2019a). Some evidence suggests that seasonal conditions amplified by anthropogenic CO_2 have resulted in the dissolution of marine carbonates in the Bering Sea (Cross et al., 2013; Mathis et al., 2015a), although the contribution of anthropogenic CO_2 to this dissolution—and the source of carbonate minerals being dissolved (terrestrial, sedimentary, biogenic)—remains unclear.

In the past ten years, significant progress has been achieved in understanding the spatial and temporal variability of OA in Alaska waters and its potential consequences to organisms, ecosystems, and Alaska communities. NOAA research on important commercial crab fisheries and groundfish is critical for preparing commercial fisheries for the progression of OA in the region and developing strategies to mitigate the impacts of OA on communities and economies. For example, many years of research at NOAA's Kodiak Laboratory has demonstrated that the young stages of commercially important red king crab (*Paralithodes camtschaticus*) and tanner crab (*Chionoecetes bairdi*) are sensitive to OA, whereas young snow crab (*Chionoecetes opilio*) appear to be more resilient (Long et al., 2013a,b, 2016). The sensitivity of red king crab and tanner crab is expected to alter the production and profitability of crab fisheries in Alaska as OA progresses in the region (Punt et al., 2014, in review). Work on Alaska groundfishes at NOAA's laboratory in Newport, Oregon has shown similar variation in vulnerability across species and life stages. While negative impacts of OA were observed in Pacific cod (Hurst et al., 2019) and northern rock sole (Hurst et al., 2016) research has suggested that many fish species will be most vulnerable to indirect effects such as OA-induced loss of shelled prey species (Hurst et al., 2017). The impact of OA is expected to be felt most severely in those Alaskan communities that have a significant reliance on the subsistence harvest of crabs and other invertebrates, as well as those with predominantly fisheries-related economies and community well-being (Mathis et al., 2015a).

Environmental Monitoring in the Alaska Region

Given Alaska's expansive territory and extreme fine-scale variability with respect to the carbonate system (e.g., at least 6 sub-domains in the Bering Sea; Cross et al., 2014), developing an expansive observation system in Alaska is a particular challenge. To meet the challenge, targeted observational data must be used in conjunction with model, projection, and forecast studies that can increase the temporal and spatial footprint of OA products used by NOAA's stakeholders (**Figure 3.1**). To support un-

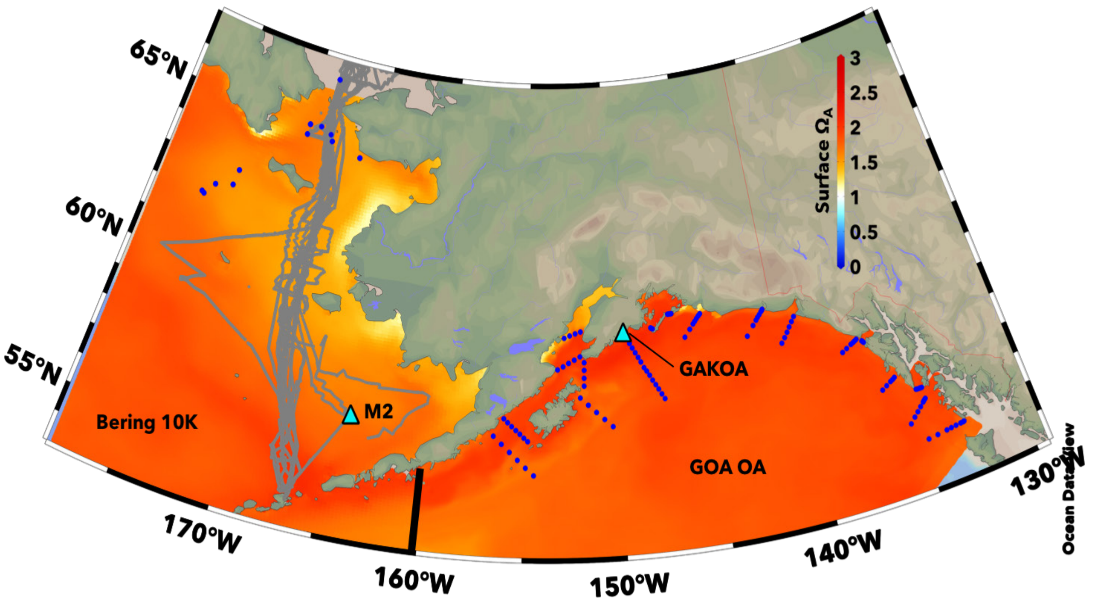

Figure 3.1. Ocean observing and forecasting system for the Gulf of Alaska and the Bering Sea between 2011 and 2019, as supported by the NOAA Ocean Acidification Program. Blue dots are discrete sampling stations occupied during 2015 and (projected) 2021. Blue triangles denote the location of two long-term moorings measuring sea-air exchange of $p\mathrm{CO_2}$. Gray tracklines indicate surface observations collected from autonomous vehicles. The background shading indicates model outputs for annual average surface aragonite saturation state in the Gulf of Alaska (GOA OA model) and the Bering Sea (Bering10K model). The Gulf of Alaska model output is for the year 2009 and the Bering Sea model output is averaged over 2003–2012.

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derstanding of chemical, physical, and biological interactions and maximize application to management concerns, observations on commercially and culturally valuable habitats are prioritized. Using observations and models together in this region will help provide important context to species response studies, economic forecasts, and resilience building.

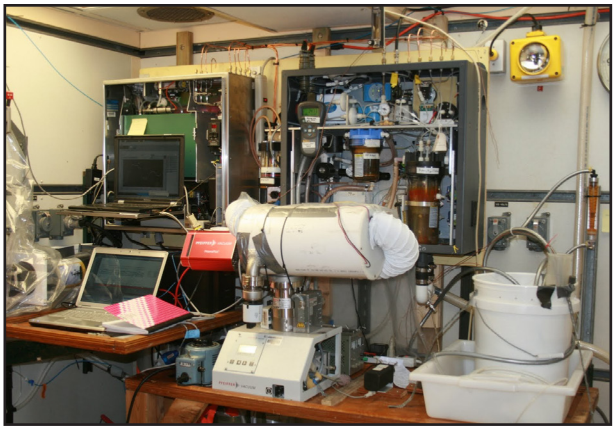
Research Objective 3.1: Characterize seasonal cycles of OA and regional vulnerabilities

Species response studies rely on an understanding of the intensity, duration, and extent of OA exposure across organismal life cycles. Collecting the data to support the species and ecosystem sensitivity analyses requires use of multiple observational tools that assess variability of ocean carbonate chemistry in both time and space.

Action 3.1.1: Maintain fixed-site moored observation network including existing moorings such as M2 and GAK. These moorings provide information on the seasonal cycle and interannual variation of OA parameters currently experienced by important habitats in the Gulf of Alaska and Bering Sea. Expansion of the mooring network should target additional important fishing habitats, such as Bristol Bay or Southeast Alaska.

Action 3.1.2: Conduct ship-based surveys that identify spatial and regional variability in carbonate parameters across important fisheries habitats. This should include sampling efforts co-located with fisheries population surveys in order to elucidate potential relationships between OA data and fisheries population data.

Action 3.1.3: Conduct ship-based process studies to improve fundamental understanding of OA drivers including impacts of advective transport, riverine discharge, seasonal ice melt, pulses of primary productivity, benthic respiration, and biological responses. Process studies help evaluate the rates and fluxes that are critical to reducing uncertainty in models.



An experimental set up for measuring seawater carbon dioxide (CO_2) aboard the R/V Thomas G. Thompson. Credit: Jessica Cross/NOAA

Research Objective 3.2: Characterize future OA trajectories at local to regional spatial scales

Projections and forecasts from regional models help identify the future impacts of OA on commercial and subsistence fishing in Alaska over a broad spatial scale.

Action 3.2.1: Support and validate existing regional ocean models for short and long-term forecasting. Regional model projections of OA quantify changes in carbonate parameters at high-spatial resolution under multiple climate emissions scenarios, which can inform species response studies. Seasonal forecasts provide an estimate of OA exposure on the short timeframes relevant for fishery communities.

Action 3.2.2: Develop OA indicators that link ecosystem exposure to OA and fisheries population dynamics. Historical and forecasted trends in key ecosystem indicators are routinely used by fishery managers. Development of an OA indicator will improve forecasts of OA ecosystem impacts and create a management-focused OA product for Alaska.

Research Objective 3.3: Develop a distributed, community-level coastal monitoring network

Alaska communities are distributed along a vast coastline, many of which are isolated from surrounding communities, accessible only by air or sea. The impacts of OA on many of these communities will result from the local impacts on subsistence harvest fisheries and community-level industries (e.g., aquaculture operations). However, current oceanographic models are not sufficiently resolved to predict the OA conditions in these highly variable coastal regions. Therefore, understanding and mitigating the localized impacts of OA will require localized monitoring at multiple sites along the Alaskan coastline. In order to address these needs, an evolving network of coastal sites with regular sampling and carbonate system analysis has been established through the cooperation between NOAA, local communities, and shellfish growers.

Action 3.3.1: Develop information networks and data management procedures to ensure accurate and timely reporting of OA conditions.

Action 3.3.2: Work with local communities and shellfish growers to identify local monitoring needs. Provide training and technical expertise to sustain and further develop Alaska's coastal OA monitoring network through establishment of additional OA monitoring sites.

Action 3.3.3: Provide high spatial and temporal resolution data from this network to meet real-time monitoring needs of local communities and to improve our understanding and forecasting of coastal acidification throughout Alaska.

Biological Sensitivity in the Alaska Region

Over the last decade, research at the Alaska Fisheries Science Center has examined the sensitivity of commercially important Alaska crab and groundfish species in the Gulf of Alaska and Bering Sea (**Figure 3.2**). These results have demonstrated important differences in sensitivity between species and among life stages within species. They have also demonstrated variation in the primary mechanisms by which OA will affect the productivity of specific fishery species. Laboratory studies have shown that crab species differ in their sensitivity to OA with Tanner crab (Long et al., 2013a, 2016; Swiney et al., 2016) and red king crab (Long et al., 2013a,b; Swiney et al., 2017) being the most sensitive, whereas blue king crab (Long et al., 2017) and snow crab appear to be more resilient (W.C. Long, unpublished data). Among groundfishes, larval and juvenile walleye pollock didn't appear to suffer negative effects of OA in the lab (Hurst et al., 2012, 2013), but young northern rock sole and Pacific cod were impacted (Hurst et al., 2016, 2019). These results provide critical decision support information for the management of Alaska fisheries and the communities that rely upon these resources.

While significant advances have been achieved in quantifying the responses of Alaska marine species to OA, many unknowns still exist and hinder the scientific capability of fully predicting OA impacts on critical species. To date, most of the research has focused on commercial crab and selected groundfish species; there are many other species that have not yet received sufficient research attention. In particular, salmon are critical in Alaska as commercial, sport, and subsistence species and sensitivity to acidification has yet to be examined across this species group. Although bivalves are known to be sensitive to OA (Harvey et al., 2013), there are many bivalve species including weathervane scallops (*Patinopecten caurinus*), razor clams (*Siliqua patula*), geoduck (*Panopea generosa*), and littleneck clams (*Leukoma staminea*) that have commercial or subsistence value and need to be investigated. More recent efforts to evaluate the sensitivity of salmon and bivalves have begun in partnership with universities in the northwest and Alaska.

OA is also expected to impact lower trophic level (LTL) species, but there has been little LTL OA research to date in Alaska. Some of these lower trophic level species are food web "bottlenecks," critical prey species that funnel energy from phytoplankton up to larger organisms. Impacts on these bottleneck species (e.g., krill, pteropods, copepods, and shrimp) will quickly spread throughout the food web potentially disrupting population productivity of commercially important fish and crabs as well as protected and culturally important species. Food web disruptions are expected to be the primary mechanism of OA effects on marine mammals and some fish species in Alaska (Mathis et al., 2015a; Hurst et al., 2016). Therefore, understanding the sensitivity to OA of key, lower trophic level species will be critical to predict the consequences of OA to the Alaskan economy and communities.

To date, research has largely focused on the effects of OA on physiological responses such as growth and reproductive success, but other responses, such as changes in the sensory functions can also

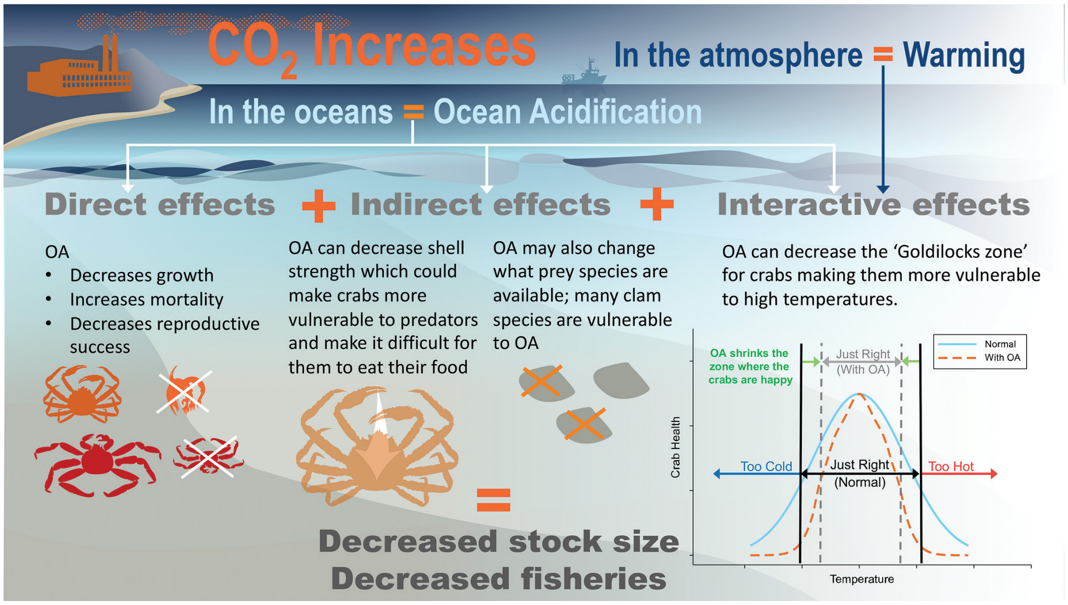


Figure 3.2. Ocean acidification is expected to impact crab and other marine resources through direct effects of elevated CO₂ and reduce pH, indirect effects on predators and prey, and through interactions with other environmental factors and stressors. Graphics: Rebecca White/NOAA

be affected (Clements & Hunt, 2015), and could have implications for foraging, predator avoidance, or mate-finding behaviors. Negative effects of OA may be partially ameliorated by acclimation and adaptation. This can be partially addressed by identifying the mechanisms behind the physiological responses to OA using gene expression analysis and proteomics, and by quantifying inter- and intra-specific differences in those responses. Further, carryover effects, transgenerational effects, and evolutionary potential must be explored using experiments that extend over multiple life-history stages and generations and via targeted breeding. This will allow researchers to estimate the extent to which species will be able to adapt to changing oceanic pH. Recent research has been initiated to explore the detailed physiological effects of OA on marine species (specifically crabs), including the effects on the immune system (Meseck et al., 2016) as well as shell structure and function (Coffey et al., 2017). In fishes, OA is expected to have the biggest impact on the sensory and behavioral systems that drive feeding and predator avoidance. Work examining these effects has, so far, been conducted only for larval Pacific cod (Hurst et al., 2019) and juvenile pink salmon (Ou et al., 2015).

Finally, OA is not occurring in isolation, declining ocean pH is co-occurring with large-scale changes in temperatures, oceanic oxygen levels, sea ice cover, and freshwater inputs in addition to localized habitat modifications. Very little work has been done on the interaction between OA and these stressors. These interactions can be complex and identifying which stressors are mostly likely to co-affect key species and performing experiments to elucidate the response is critical (Breitburg et al., 2015). Such experiments will require investment in laboratory infrastructure as maintaining experimental conditions becomes exponentially more challenging as additional factors are examined.

Increasing research focus on the ecosystem-wide effects of OA will enhance understanding of the cumulative effects on ecosystems and fisheries. In the region this will be critical to informing protection and management of fisheries, protected species, and ecosystems and to identify risk and evaluate adaptation measures. New and existing food-web models can be modified to include climate and OA drivers. Recent advances in climate-informed modeling include ongoing efforts to couple food web models (e.g., CE-size-spectrum; Reum et al., 2019, 2020), climate-enhanced groundfish assessment models (Hollowed et al., 2020) and individual based models for snow crab (Stockhausen et al., *in prep*) to environmental indices derived from high resolution ROMS-NPZ models (Hermann et al., 2019). Inclusion of mechanistic OA linkages are now possible through the incorporation of carbonate dynamics in ROMS models, which reveal distinct seasonal and spatial patterns in OA (Pilcher et al., 2019), and which can be projected to evaluate future changes in exposure across space and time. Such projections, linked statistically or deterministically to key processes in biological models (e.g., physiology, predation, behavior, distribution, growth) could help reveal sensitive species and interactions, emergent non-intuitive outcomes of cascading impacts, and potential attenuation/amplification of cumulative effects of multiple stressors (e.g., warming, OA, fishing). Management strategy evaluations that evaluate the degree to which spatial and harvest management tools can counter OA and climate-driven impacts will further help reveal inherent tipping points and thresholds under various adaptation goals and provide climate-informed scientific advice for decision making (Holsman et al., 2019; Karp et al., 2019; Gaines et al., 2018).

Alaska brown bears depend on salmon that are potentially vulnerable to acidification as a food source. Credit: Crew and Officers of NOAA Ship Fairweather

Research Objective 3.4: Characterize sensitivity and adaptive potential of critical resource species to OA and other stressors

Species response research should evaluate the multi-stressor impacts of OA combined with warming, hypoxia and other environmental variables. Species response research should also include consideration of the effects of natural variation in environmental conditions (e.g., temperature, salinity, dissolved oxygen) on species responses to OA.

Action 3.4.1: Conduct experiments to understand the range of life-stage responses of OA and associated environmental stressors.

Action 3.4.2: Conduct experiments on potential for organismal acclimation and transgenerational adaptation to future environments.

Action 3.4.3: Expand research to include under-studied species including Alaska salmon and bivalves that have commercial and subsistence value.

Action 3.4.4: Expand experimental system capabilities to incorporate time-varying environmental conditions and expand capacity for multi-stressor experiments.

Research Objective 3.5: Examine sensitivity of critical lower trophic level "bottleneck" species to OA

Improving the fundamental understanding of LTL species that are critical to Alaska ecosystems to estimate the indirect impact on commercial and subsistence value species.

Action 3.5.1: Conduct OA-sensitivity studies on regionally important ecosystem drivers such as krill, bivalves, echinoderms, copepods, pteropods, and shrimps.

Action 3.5.2: Apply phylogenetic and trait-based analyses to identify sensitive species that have broad impact on the food web.

Action 3.5.3: Use these analyses to help identify species that may serve as bio-indicators of OA impacts in the region.

Research Objective 3.6: Identify the ecosystem-wide impacts of OA

A better understanding of the multi-faceted impacts of OA across species groups and trophic levels will improve understanding of the cumulative effects on ecosystems and fisheries. This is critical to informing protection and management of fisheries, protected species, and ecosystems and to identify risk and scope of adaptation measures.

Action 3.6.1: Conduct laboratory experimental studies to quantify the effects of OA and *in situ* field observations to validate and parameterize OA impacts to biological couplings (predator-prey interactions) in food web and climate-enhanced models.

Action 3.6.2: Improve understanding of responses to OA by incorporating consideration of environmental and ecosystem variability including episodic warming, harmful algal blooms, and mass mortality events.

Action 3.6.3: Develop integrated climate-biological-socioeconomic models that link the physiology, growth, behavior, and distribution of species to spatial and temporal patterns of corrosive water exposure will allow for evaluation of direct and cascading effects of OA on the social-ecological system.

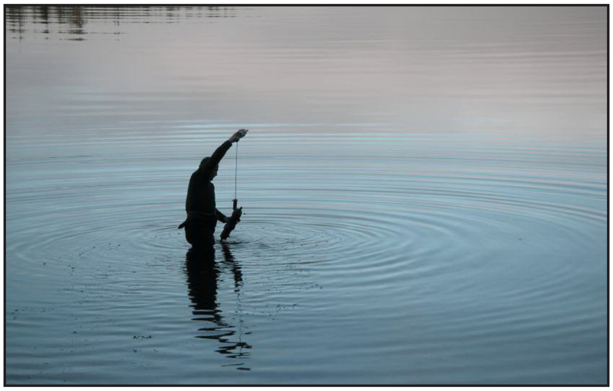
Human dimensions in the Alaska Region

The seafood industry is a major source of employment in Alaska, employing more than 50 thousand workers earning $2 billion in total annual income (McDowell Group, 2017). The nation's largest, and most valuable, crab fishery occurs in waters off the coast of Alaska and is potentially susceptible to impacts from OA. Over the last decade, the primary goal of research regarding the socioeconomic impacts of OA in the Alaska region has been to forecast biological and economic effects on commercially important Alaska crab and fish stocks. To evaluate potential impacts, prior research developed bioeconomic models that relate direct effects of OA to future changes in stock productivity, measured in terms of declining yields and income over time. Moreover, direct effects of OA on the fishing industry create indirect effects for other industries,

Commercial fishing is a major component of the economy throughout Alaska's coastal communities. Credit: NOAA

which were evaluated using a regional economic model for Alaska (Seung et al., 2015). In present value terms, the welfare loss for Alaskan households from cumulative impacts of OA in the coming decades on one crab stock, Bristol Bay red king crab, could exceed a billion dollars. Bioeconomic models were also developed for Tanner crab and snow crab, in the Eastern Bering Sea. The next phase of research on human dimensions of OA in the Alaska region will expand focus to include impacts on non-commercial activities, such as subsistence use, through the development of coupled social-ecological models.

Localized and species-specific responses to OA may lead to changes in the composition and yields of harvested species, plus the location and accessibility of harvestable resources. Direct and indirect climate-driven changes in the productivity and distribution of species can affect bycatch risk and interactions among fisheries, as well as other sectors in ways that may differentially perpetuate risk across coastal communities and limit the scope for adaptation to climate change (Himes-Cornell & Kasperski, 2015; Barange et al., 2014, 2018). Integrated modeling of OA effects on the coupled social-ecological system, such as technical interactions between industries, can help reveal cumulative impacts on marine resource-dependent communities. An example that demonstrates the importance of these interactions is bycatch of Tanner crab in the eastern Bering Sea snow crab fishery, the largest and most valuable Alaska crab fishery. Snow crab are insensitive to direct effects of OA, but indirect effects arising from technical interactions with Tanner crab, which are sensitive, could constrain future yields of snow crab (Punt et al., in review). Further, interest has been growing in commercial mariculture of seaweeds and shellfish in south-central and southeast Alaska. It is currently unknown how OA will impact this growing industry. In recognition of the importance of spatial heterogeneity and dynamic feedbacks within and between social and ecological systems (Holsman et al., 2017), coupled social-ecological models will be developed that are community-specific to evaluate impacts on individual ports, fleets, industry sectors, and the communities they support.



Researcher collects water sample to measure dissolved carbon dioxide levels. Credit: NOAA

Finally, to date, research to forecast effects of OA in Alaska has prioritized commercially important species based on the potential for state-wide economic impacts. However, to many Alaska communities, subsistence use and cultural association with marine resources is as important as local economic benefit. Subsistence communities harvest a range of marine species and rely on these local resources for commerce, cultural identity, and the subsistence way of life. Forecasting effects of OA on subsistence species is essential for monitoring and responding to future impacts of OA in the Alaska region.

Research Objective 3.7: Improve assessment of socioeconomic impacts of OA on fisheries-dependent communities

Developing coupled social-ecological models that are community-specific will be important to evaluating the impacts on individual ports and the fishing fleets they support.

Action 3.7.1: Use food web models to account for direct and indirect OA effects on multiple species and incorporate these effects in spatial bioeconomic models that represent biological and technical interactions among species and stocks.

Action 3.7.2: Analyze direct and indirect effects of OA and develop and apply a new framework for biological and bioeconomic reference points with multiple species that includes aggregate maximum sustainable yield (MSY) and multispecies maximum economic yield (MEY).

Action 3.7.3: Consider OA ontogenetic effects on growth and survival of animals in order to assess tradeoffs and potential co-benefits of various management interventions that target different life-history stages and population productivity bottlenecks.

Action 3.7.4: Use integrated assessment models to inform stock assessment status and recovery plans.

Research Objective 3.8: Assess community sensitivity and resiliency to OA impacts on critical nutritional and cultural resources

To more comprehensively understand the societal and cultural impacts of OA on Alaska communities, assessments of OA will be expanded to include sensitivities of critical nutritional and cultural resource species. Research will also directly evaluate the impacts of OA-induced changes in marine ecosystems to well-being of coastal communities.

Action 3.8.1: Work with local communities including indigenous peoples to identify locally-important species for additional OA sensitivity analyses and work with community leaders to disseminate the findings of these analyses.

Action 3.8.2: Analyze the economic and sociological effects of OA-induced food web alterations that may impact the harvest of nutritionally and culturally important species including large marine mammals.

Action 3.8.3: Support community awareness of OA impacts and work with local stakeholders to identify economic and sociological sensitivities and evaluate and implement adaptive responses.

4. Arctic Region Acidification Research

Jessica N. Cross[1], W. Christopher Long[2], Darren J. Pilcher[3], Thomas P. Hurst[4], Richard A. Feely[1], Carol Stepien[1]

[1]NOAA/OAR, Pacific Marine Environmental Laboratory, Seattle, WA

[2]NOAA/NMFS, Alaska Fisheries Science Center, Kodiak, AK

[3]NOAA/OAR, Joint Institute for the Study of Atmosphere and Ocean, University of Washington, Seattle, WA

[4]NOAA/NMFS, Alaska Fisheries Science Center, Newport, OR

Technical contributors: Joseph E. Salisbury[1], Wei-Jun Cai[2]

[1]College of Engineering and Physical Sciences, University of New Hampshire, Durham, NH

[2]College of Earth, Ocean and Environment, University of Delaware, Newark, DE

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**).

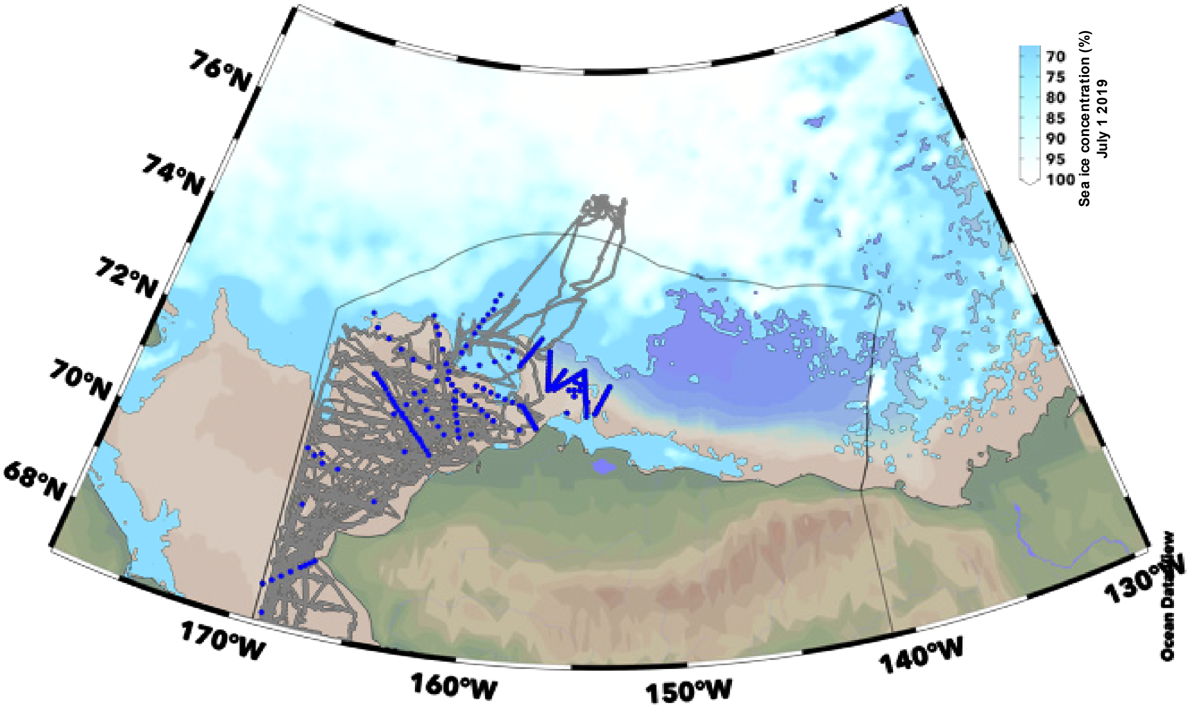


Figure 4.1. Ocean observing system for the Chukchi Sea between 2015 and 2020, as supported by the NOAA Ocean Acidification Program and Arctic Research Program. Shown here in blue dots are discrete sampling stations occupied during the Distributed Biological Observatory missions. Gray tracklines indicate 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 pCO₂ 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.

References

[INTRO] = Introduction;

[NAT] = National Ocean & Great Lakes;

[OO] = Open Ocean Region;

[AK] = Alaska Region;

[ARC] = Arctic Region;

[WC] = West Coast Region;

[PAC] = U.S. Pacific Islands Region;

[SAG] = Southeast Atlantic & Gulf of Mexico Region;

[FLC] = Florida Keys and Caribbean Region;

[MAB] = Mid-Atlantic Bight Region;

[NE] = New England Region;

[GL] = Great Lakes Region

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