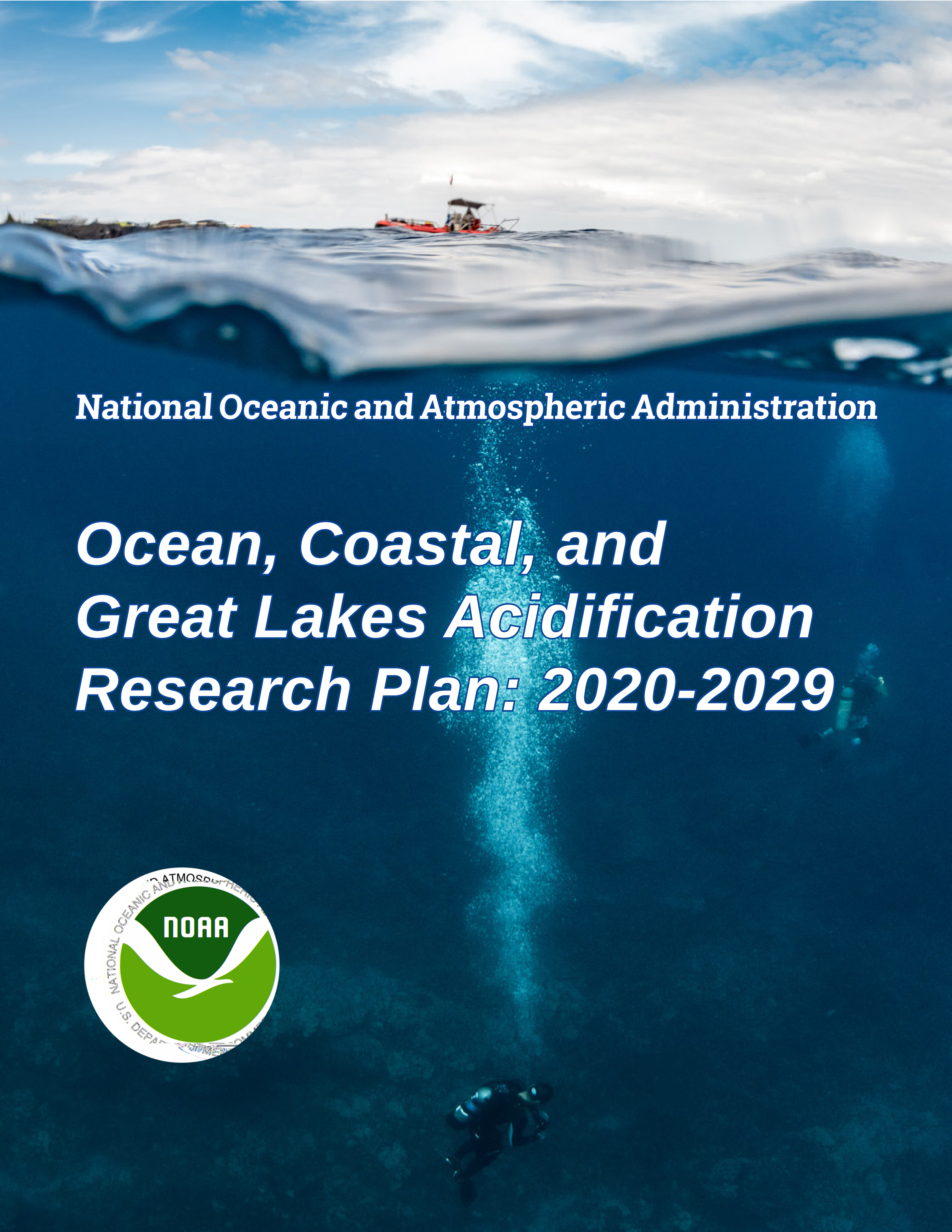

National Oceanic and Atmospheric Administration

Ocean, Coastal, and Great Lakes Acidification Research Plan: 2020-2029

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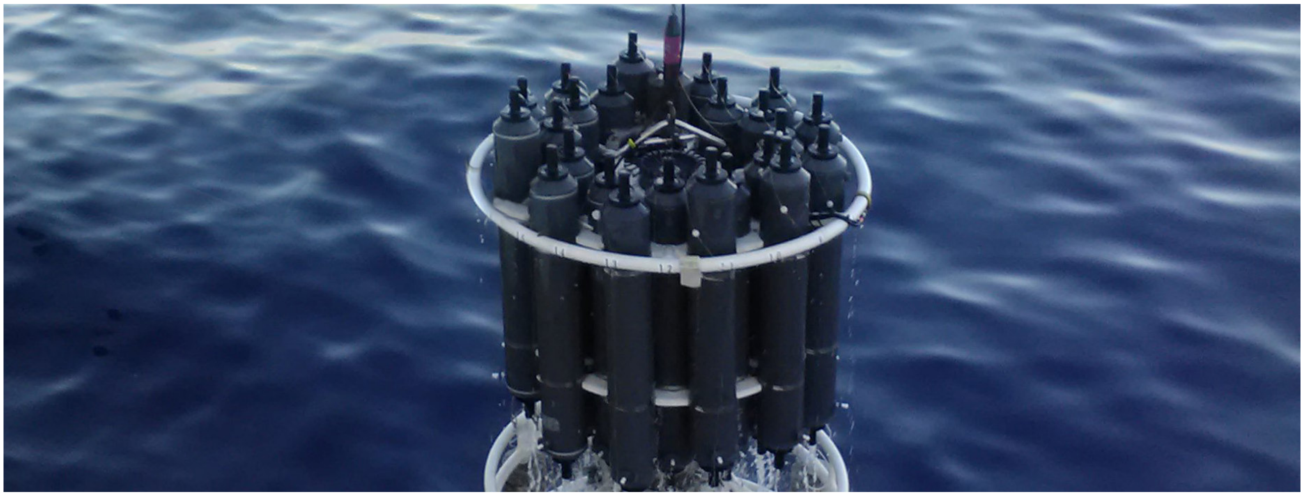


Executive Summary

Ocean Acidification (OA), driven predominantly by ocean uptake of atmospheric carbon dioxide (CO_2), is resulting in global-scale changes in ocean chemistry with predictions of broad-scale ecosystem impacts. Coastal acidification, which refers to the pH decline over decade or longer time scales resulting not only from atmospheric CO_2, but also from other coastal chemical additions and subtractions, is recognized as the coastal manifestation of OA. Impacts from coastal acidification are already present in ecosystems and fisheries. Acidification in the Great Lakes is projected to progress at a rate similar to the oceans as a result of increasing atmospheric CO_2 concentrations and enhancement by regional air quality, acid deposition via precipitation, and lower buffering capacity. Acidification of the open ocean, coasts, and Great Lakes continues to raise concerns across the scientific, resource management, and coastal communities given the ecological impacts and resulting social and economic effects. In many instances throughout the plan, the term "OA" is used to represent both ocean and coastal acidification processes described above.

In response to legislative drivers and scientific concerns, NOAA's research mission is to understand and predict changes in ocean ecosystems as a consequence of continued acidification of the oceans, coasts, and Great Lakes; conserve and manage marine organisms and biomes in response to such changes; and share that knowledge and information with others. The Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM; 33 U.S.C. Chapter 50, Sec.3701-3708) requires that NOAA has a monitoring and research program to determine the potential consequences for marine organisms and ecosystems; to assess the regional and national ecosystems and socioeconomic impacts; and to identify adaptation strategies and techniques for conserving marine ecosystems.

The 2010 NOAA Ocean and Great Lakes Acidification Research Plan has guided research at the agency over the last decade and provides a framework for the updated research plan. The 2020-2029 Research Plan builds upon accomplishments made and responds to newly emerging science and requirements. In coordination with international, interagency, and external academic and industry research partners, the present Research Plan aims to support science that produces well-integrated and relevant research results, tools, and products for stakeholders.

The Research Plan is framed around three themes:

1) **Document and predict environmental change via monitoring, analysis, and modeling;**
2) **Characterize and predict biological sensitivity of species and ecosystems; and**
3) **Understand human dimensions of ocean, coastal, and Great Lakes acidification impacts.**

These research themes can collectively be used to understand, predict, and reduce vulnerability to ocean, coastal, and Great Lakes acidification. Environmental change research and monitoring are critical to documenting acidification and collecting data that can be used to understand natural and anthropogenic influences and enhance predictive capabilities. Enhancing the understanding of biological sensitivity is foundational to characterizing species and ecosystem response, as well as adaptive capacity, which are both integral to developing ecosystem models and management practices. Understanding the potential human impacts of acidification requires translating and synthesizing physical environmental change and biological sensitivity knowledge to assess the vulnerability of human communities and economies to ocean, coastal, and Great Lakes acidification.

The Research Plan includes regional chapters that encompass the coastal zones around the U.S., including its territories and the Great Lakes, an Open Ocean Chapter focusing on deep ocean regions beyond the continental shelf, and a National Chapter. The National Chapter draws upon the regional and open ocean needs to present high-level, collectively relevant research objectives. Each chapter is framed around the research themes (environmental change, biological sensitivity, and human dimensions).

NOAA's national-level ocean, coastal, and Great Lakes acidification research goals are to:

1) **Expand and advance observing systems and technologies to improve the understanding and predictive capability of acidification trends and processes;**
2) **Understand and predict ecosystem response and adaptive capacity of ecologically and economically important species to acidification and co-stressors; and**
3) **Identify and engage stakeholders and partners, assess needs, and generate products and tools that support management, adaptation, and resilience to acidification.**

Implementation of the Research Plan will require continued collaboration across the agency and with interagency and international partners, including the Interagency Working Group on OA (IWG-OA) and the Global OA Observing Network (GOA-ON). In addition to internal research capacity at NOAA's laboratories, science centers, regional Integrated Ocean Observing System (IOOS) associations, and cooperative institutes, the extramural support of academic, non-governmental, and industry research partners will enhance NOAA's capacity for conducting cutting edge research. Data management and synthesis efforts laid out in the plan ensure that scientific data are more widely utilized and transitioned into products that will increase education, awareness, and preparedness of U.S. citizens to ocean, coastal, and Great Lakes acidification.

Introduction

Motivation for NOAA's Ocean, Coastal, and Great Lakes Acidification Research

The uptake of carbon dioxide (CO_2) by the global ocean has resulted in a worldwide phenomenon termed "Ocean Acidification" or OA (e.g., Caldeira & Wickett, 2003; Feely et al., 2004, 2009; Orr et al., 2005). OA is defined as a reduction in the pH of the ocean, accompanied by other chemical changes (primarily in the levels of carbonate and bicarbonate ions), over an extended period, typically decades or longer (IPCC, 2011, **Figure 1**). OA is caused primarily by uptake of CO_2 from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean. Anthropogenic OA refers to the component of change in the marine carbonate system that is caused by human activity (IPCC, 2011). The ocean has served as an important "sink" for anthropogenic CO_2 emissions, significantly curtailing the observed, human-induced atmospheric CO_2 accumulation (Sabine et al., 2004; Khatiwala et al., 2013; Le Quéré et al., 2015, 2018; Gruber et al., 2019a). Within the coastal zones, acidification is often driven by a combination of ocean uptake of atmospheric CO_2 and other coastal chemical additions and subtractions, driven by natural or anthropogenic processes, which cause change on decadal or longer timescales. In many instances throughout the plan, the term "OA" represents both ocean and coastal acidification processes as indicated above. Acidification also occurs in freshwater systems such as the U.S. Great Lakes, where pH is projected to decline at a rate similar to the oceans (Phillips et al., 2015).

The present rates of CO_2 release and OA are likely unprecedented, exceeding the rates of change over the last 56 million years (Gingerich, 2019). At present, OA is resulting in pole-to-pole change in ocean carbonate chemistry that has the potential to impact a range of biological processes and ecosystems and pose a challenge to coastal communities and marine-dependent economies. The OA signal caused by human activities, the so-called anthropogenic OA signal, has very likely emerged in over 95% of the surface open ocean (IPCC Special Report on Oceans and Cryosphere in a Changing Climate, 2019).

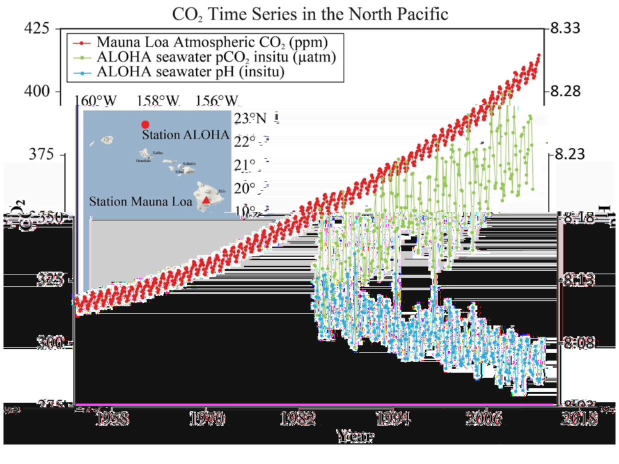


Figure 1. The longest time-series (1958 to present) of atmospheric CO_2 concentration (ppm) measured at the Mauna Loa Observatory in Hawai'i. Ocean chemistry measurements of seawater pCO_2 and pH at neighboring Station ALOHA began in 1988. These time-series show that seawater pCO_2 concentrations increase in tandem with atmospheric concentrations, but with much greater annual variability, while seawater pH declines.

The International Panel on Climate Change (IPCC) reported that it is virtually certain that by absorbing more CO_2, the ocean has undergone increasing surface acidification ([IPCC Special Report on The Ocean and Cryosphere in a Changing Climate, 2019]()). The oceans have absorbed approximately 25-30% of the total emitted anthropogenic carbon, which has caused an estimated 0.1-unit reduction in global mean surface ocean pH since the Industrial Revolution (Feely et al., 2004, 2008, 2009; Orr et al., 2005; Khatiwala et al., 2013; Gattuso et al., 2015; Le Quéré et al., 2015, 2018; Gruber et al., 2019a). The IPCC concluded that changes in the oceans such as warming, acidification, and deoxygenation are affecting molecular processes of marine life, to organisms and ecosystems, with major impacts on the use of marine systems by human societies (Pörtner, 2012).

OA results in four chemical changes that can affect marine species: increases in dissolved CO_2 and bicarbonate ion concentrations, and decreases in pH (an increase in acidity) and the concentration of carbonate ions (**Figure 2**). Calcifying species, which include many ecologically, recreationally, and commercially important marine species, are thought to be especially sensitive to OA as they use carbonate ions as chemical building blocks to create their shells, skeletons, and other hard parts. Laboratory and mesocosm studies on some calcifying corals, shellfish, and zooplankton (i.e., pteropods, coccolithophores, and foraminifera) show calcification decline and/or dissolution as a result of exposure to conditions expected with further OA (Feely et al., 2004; Fabry et al., 2008; Busch et al., 2014; Gattuso et al., 2015; Riebesell et al., 2017; Osborne et al., 2016, 2019). Field collections from high-CO_2 locations provide evidence of species impacts of such exposure (e.g., Enochs et al., 2015a; Bednaršek et al., 2017b). Laboratory studies have also shown that physiological processes of finfish can be sensitive to OA conditions, in some cases impacting growth, survival, fertilization, embryonic and larval development, and behavior (e.g., Hurst et al., 2016, Clements & Hunt, 2018; Williams et al., 2019). OA may also pose indirect impacts to an even broader range of marine species by, for example, reducing the abundance and nutritional quality of food sources (e.g., Meyers et al., 2019) or altering food web dynamics (e.g., Busch et al., 2013; Marshall et al.,

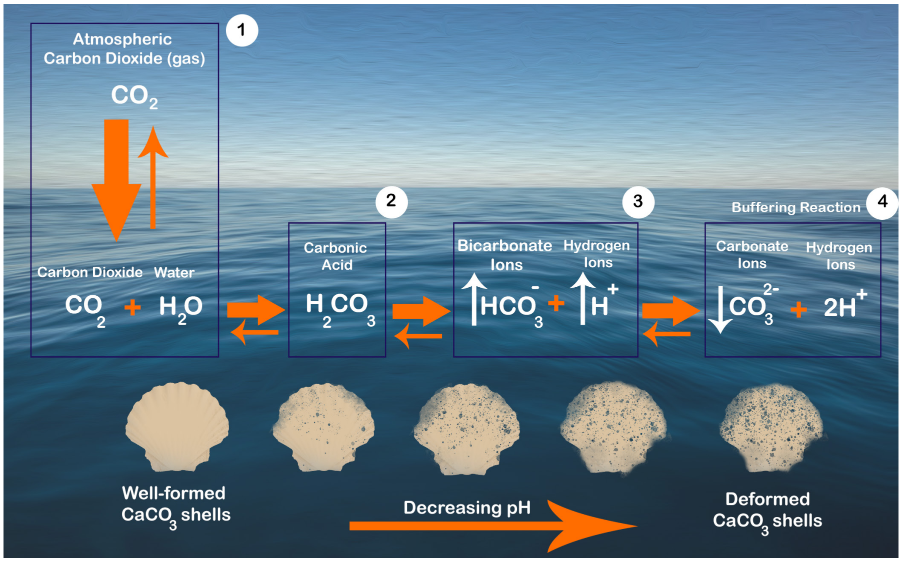


Figure 2. Ocean acidification is driven by uptake of increasing atmospheric CO_2. The introduction of CO_2 into seawater results in a series of chemical reactions that ultimately increases hydrogen ion (H^+) concentration (which by definition lowers seawater pH) and redistributes the relative concentrations of dissolved inorganic carbon (DIC) species in seawater. The net changes in DIC are an increase in bicarbonate ion concentration (HCO_3^-) and a decrease in carbonate ion concentration (CO_3^{2-}), which occurs as a result of a buffering reaction with H^+. The decline in CO_3^{2-} (and pH) notably impacts marine species that depend on this ion to build their hard parts (e.g., shells and skeletons); however, there are other direct and indirect impacts that have been observed across a range of marine species.

2017). While some time-series examinations find signatures of OA impacts on marine species (e.g., de Moel et al., 2009; Meier et al., 2014), it is important to note that other studies fail to do so (e.g., Beare et al., 2013; Thibodeau et al., 2019). Across the numerous observations of species sensitivity to OA conditions, some marine organisms and genetic strains within populations have shown resilience and adaptation, and merit future research (e.g., Hurst et al., 2013; Barkley et al., 2015; Towle et al., 2015; Putnam et al., 2017).

An oyster found in the Dosewallips Delta of Hood Canal, Washington. Credit: Simone Alin/NOAA

NOAA's Ocean, Coastal, and Great Lakes Acidification Research Mission

The Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) is one of the U.S. Federal agency leads for OA research and monitoring. NOAA's agency-wide mission is "to understand and predict changes in climate, weather, oceans, and coasts; to share that knowledge and information with others; and to conserve and manage coastal and marine ecosystems and resources." NOAA's research and development goals with respect to OA are to reduce societal and economic impacts from environmental phenomena such as OA. NOAA seeks sustainable use and stewardship of ocean and coastal resources as OA and other environmental changes challenge the resilience of coastal communities and change habitats, distribution, and abundance of marine species. NOAA's researchers aim to improve the ability to understand, protect, manage, and restore ecosystems that support healthy fisheries, increase opportunities for aquaculture, and balance conservation with tourism and recreation. In supporting OA science, NOAA informs decisions on sustainable use and stewardship of ocean and coastal resources that balance the sometimes conflicting demands of economic and environmental considerations (NOAA Research and Development Vision Areas 2020-2026).

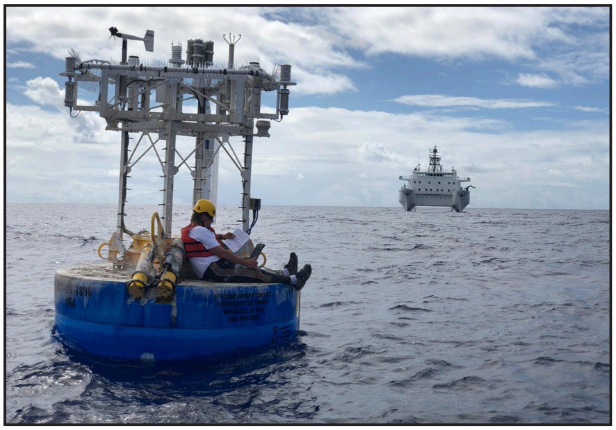
OA research is happening in five of NOAA's six Line Offices: Ocean and Atmospheric Research (OAR); National Marine Fisheries Service (NMFS); National Ocean Service (NOS); National Environmental, Satellite, and Data Information Service (NESDIS); and Office of Marine and Aviation Operations (OMAO). Each Line Office has a unique mission and a distinct contribution to the agency's collective work on ocean, coastal, and Great Lakes acidification science. OAR programs, including the Ocean Acidification Program (OAP), support foundational research that investigates the marine environment, detects changes in the oceans, improves forecast capability, and drives innovative science and technological development (Oceanic and Atmospheric Research Strategy 2020-2026). OAP and OAR Laboratories conduct sustained monitoring of OA conditions and research that improves our understanding of how OA is impacting organisms and ecosystems. NMFS provides science-based conservation and management for sustainable fisheries and aquaculture, marine mammals, endangered species, and their habitats. Researchers at several of NOAA's Fisheries Science Centers study the sensitivity of regionally important fish and shell to OA. study the sensitivity of regionally important fish and shellfish to OA. NOS supports U.S. coastal communities by translating science, tools, and services into action and addressing threats to coastal areas such as climate change and OA to work toward healthy coasts and economies. NOS programs look at specific impacts of OA on coral ecosystems and collect coastal OA data within the broader OA regional observing networks in collaboration with National Marine Sanctuaries (NMS) and the National Estuarine Research Reserve System (NERRS). NOS also funds competitive research toward the development of ecosystem models to meet management needs. NESDIS supports satellite-based science that gathers global data to monitor and understand our dynamic planet and provides data services for all of NOAA's environmental data. NESDIS' National Centers for Environmental Information (NCEI) coordinates the data stewardship for all NOAA OA data, providing support for the complete lifecycle of data, from collection, to archive, to dissemination. NOAA's OMAO plays a critical role in supporting and carrying out OA observing by administering the NOAA fleet of ships and training divers to safely facilitate ocean observations.

While ocean, coastal, and Great Lakes acidification research at NOAA responds to numerous legislative mandates and policy drivers (Appendix 1), the primary acidification-related legislation is the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM; 33 U.S.C. Chapter 50, Sec. 3701-3708). This law specifies that NOAA conduct research to understand and predict changes in the environment as a consequence of continued OA and to conserve and manage marine organisms and ecosystems in response to such changes.

The FOARAM Act also established a cross-agency coordinating body, the Interagency Working Group on OA (IWG-OA) under the auspices of the White House Office of Science and Technology Policy (OSTP). The IWG-OA is charged with tracking and coordinating OA research and monitoring efforts across the Federal Government and providing the President and Executive Office scientific advice on OA issues. The IWG-OA includes members from more than a dozen federal agencies, all of which have mandates for research and/or management of resources and ecosystems likely to be impacted by OA. The group meets regularly to coordinate OA activities to fulfill the goals of the FOARAM Act and is currently operating under the 2014 Strategic Plan for Federal Research and Monitoring of Ocean Acidification and the Implementation of the Strategic Plan for Federal Research and Monitoring of Ocean Acidification (2016).

NOAA's Ocean Acidification Research over the Last Decade

NOAA has carried out research guided by the 2010 NOAA Ocean and Great Lakes Acidification Research Plan. Research under this plan has focused on developing coordinated ocean monitoring networks, sensitivity studies, model frameworks and projections, development of data information products, vulnerability assessments of organisms and ecosystems (including people) to enable the development of innovative methods to mitigate and adapt to acidification, and the underlying data management infrastructure needed to support the ocean, coastal, and Great Lakes acidification research at NOAA. The present plan serves as an update that identifies research objectives for the next decade of acidification science at NOAA and lays a framework for building upon accomplishments made and responding to newly emerging requirements.



The R/V Kilo Moana and Woods Hole Oceanographic Institution Hawai'i Ocean Time-series buoy at Station ALOHA. Credit: Dan Sadler/Hawai'i Ocean Time-Series

The interdisciplinary nature of OA science has forged many important partnerships across NOAA program, laboratory, and line office boundaries needed to achieve the research objectives proposed in the 2010 Research Plan. Research accomplishments achieved by the agency since 2010 are detailed in the biennial reports that detail federal OA research and monitoring activities prepared by the IWG-OA: Initial, Second (FY10-11), Third (FY12-13), Fourth (FY14-15) and Fifth (FY16-17). Accomplishments specific to the OAP since its inception through 2017 are further detailed in a technical memorandum, NOAA Ocean Acidification Program: Taking Stock and Looking Forward (Busch et al., 2018).

Programs supporting acidification science at NOAA over the last decade have done so both internally by conducting research at NOAA's laboratories and re-

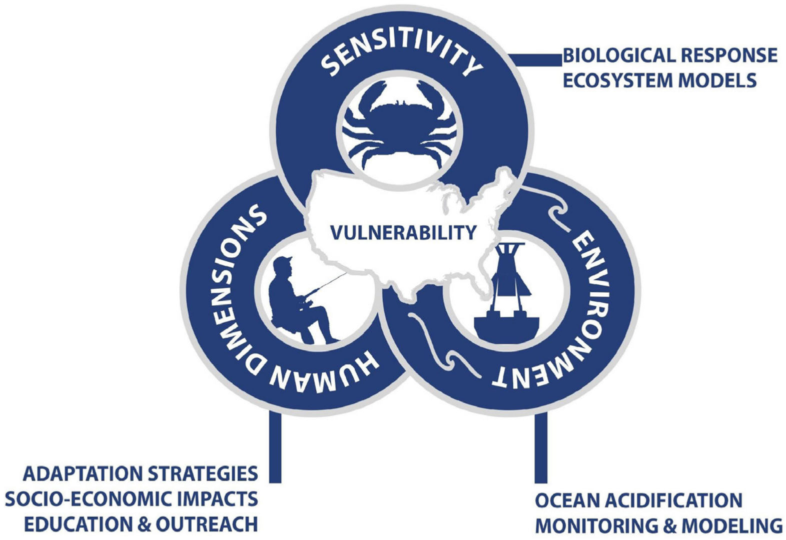


Figure 3. Assessing the vulnerability of the U.S. Blue Economy to ocean, coastal, and Great Lakes acidification demands a transdisciplinary approach that simultaneously combines an understanding of how conditions are changing (*Environment*), how living marine resources respond to the changes (*Sensitivity*), and how such changes affect dependent human communities (*Human Dimensions*). This includes monitoring and modeling environmental change; conducting research to constrain biological response and sensitivity to develop ecosystem models; and understanding the socioeconomic implications of these changes.

gional science centers, as well as externally through extramural funding opportunities for non-federal entities, including IOOS Regional Associations, Cooperative Institutes, Sea Grant programs, and other academic institutions. Extramural funding, awarded through grant competitions to both academic and industry partners, has been instrumental in developing new technologies and conducting cutting-edge research that complement NOAA's internal research and development capacity. In order to coordinate the many research endeavors occurring across the agency, NOAA formed a cross-line office body, the NOAA Ocean Acidification Working Group (NOAWG). The purpose of the NOAWG is to provide programmatic, scientific, and policy representation and input from the line offices to the strategic planning and operation of agency-wide OA research efforts. The NOAWG is facilitated and maintained by the staff of the OAP, and members include Federal researchers and program managers from NOAA programs that are actively engaged in OA-related activities.

In addition to ongoing support of OA research, NOAA took early initiative in recognizing the importance of OA data management, stewardship, and archival. This initiative was realized at a data management workshop held by the OAP in 2012, wherein the framework was established to guide OA data management, including OA metadata and archiving to facilitate OA science. NCEI established the OA Data Stewardship (OADS) and the Ocean Carbon Data System (OCADS) projects that serve the data management needs of the OA research community. These projects use a rich metadata template that was developed using a bottom-up approach by working with OA scientists around the world, with long-term archiving support, version control, stable data citation, and controlled vocabularies, meeting all NOAA Public Access to Research Results (PARR) requirements. In the coming years there are plans to merge the OADS and OCADS into a unified project called Ocean Carbon and Acidification Data System. Other data management successes since 2010 include developing metadata and data format guidance for OA data, establishing a rich metadata management system tailored to the OA community, and establishing data access portals for OA data. These actions set the foundation for the next phase of implementation, ensuring improved efficiencies in data sharing so that all OA data are findable, accessible, interoperable, and reusable (FAIR).

The Research Plan Framework and Themes

The national research plan and subsequent regional chapters integrate the themes of *environmental change, biological sensitivity, and human dimensions* to understand and, ideally, reduce vulnerability to ocean, coastal, and Great Lakes acidification. Collectively, these themes respond to NOAA's mission directive to understand and predict environmental change, to share knowledge, and to conserve and manage coastal and marine ecosystems and resources (NOAA Research and Development Plan 2020-2026). Environmental change research is critical to document and detect the progression of acidification and develop predictive numerical models and enhance predictive capabilities. Developing an understanding of biological sensitivity is foundational to characterizing species and ecosystem response, as well as adaptive capacity, which are both integral to developing robust ecosystem models and management. Investigating human impacts requires translating environmental change and biological sensitivity knowledge into useful information for studying the implications of acidification and specifically the vulnerability of communities and economies to acidification (**Figure 3**). Vulnerability is defined as the propensity or predisposition to be adversely affected.

The plan framework includes a national chapter, which outlines high-level scientific needs across the U.S. and its territories, as well as nine regional chapters, which provide scientific context and objectives for understanding acidification and assessing vulnerability on a regional scale (**Figure 4**). The goal of the plan is to align environmental change, biological sensitivity, and human dimensions research with the research needs of the regions and open ocean. The agency continues to make major progress on developing OA education and outreach tools and programs (Theme 6 of the 2010 NOAA Ocean and Great Lakes Acidification Research Plan). The goal of the present research strategy is to be carried out in tandem with the NOAA Ocean Acidification Education Implementation Plan to ensure that scientific findings are transitioned to communication and education tools and translated to stakeholders.

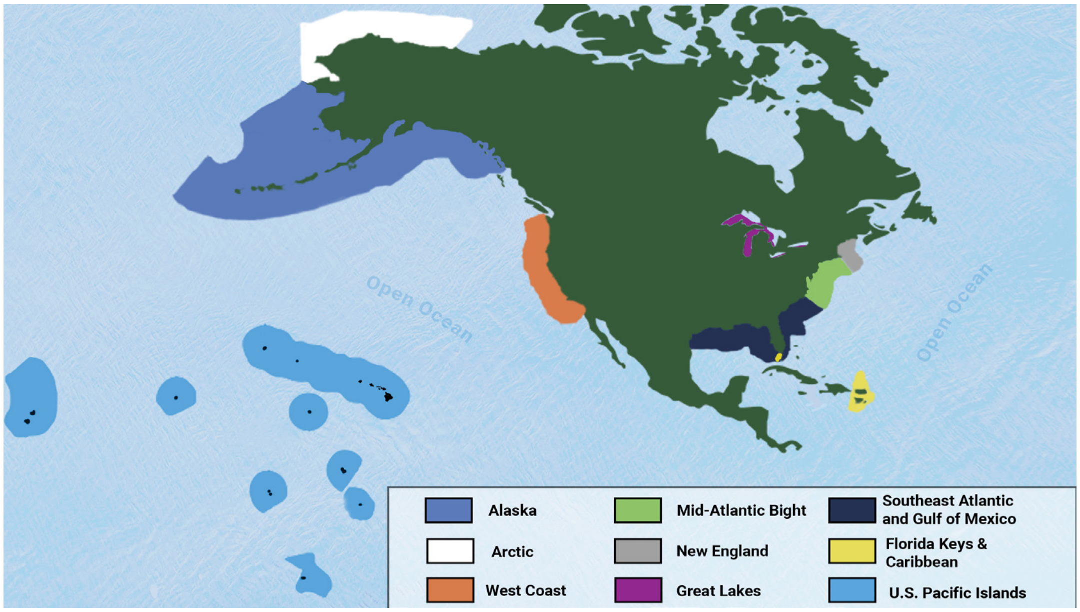
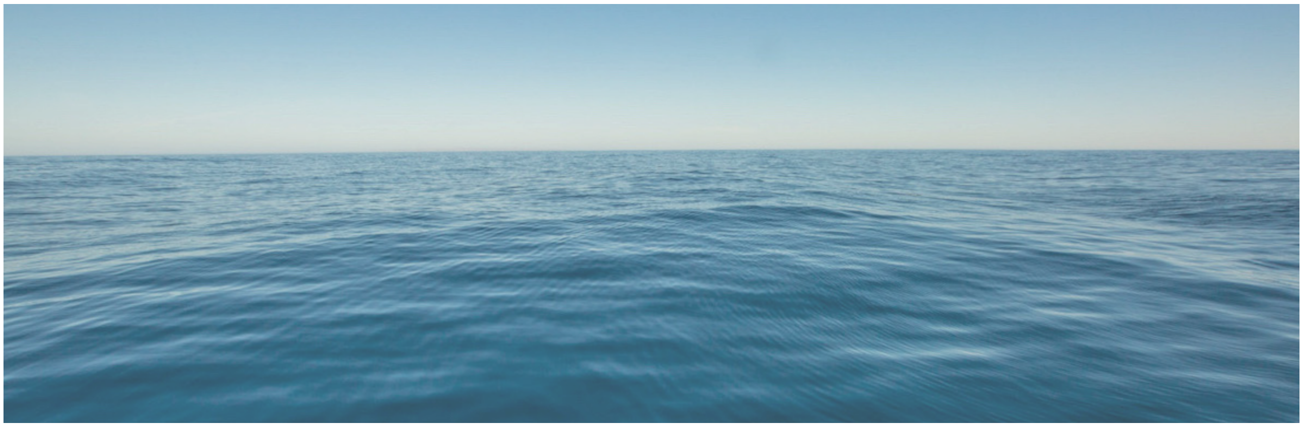


Figure 4. A map outlining the eight U.S. coastal regions that are represented in the NOAA Ocean, Coastal, and Great Lakes Acidification Research Plan (note, Southeast Atlantic and Gulf of Mexico form a single region). Coastal regions are closely based on the geographic extent of the Large Marine Ecosystem (LMEs), which represent areas of coastal oceans delineated on the basis of ecological characteristics that serve as suitable organizational units to support ecosystem-based management.



1. National Ocean, Coastal, and Great Lakes Acidification Research

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Abstract

The National Chapter includes acidification research objectives that are collectively relevant to the open ocean, the continental shelves, and coastal zones of the U.S, its territories, and the Great Lakes region. Acidification is driven primarily by the anthropogenic carbon dioxide absorbed and dissolved in the upper ocean and Great Lakes, and is causing wide-scale changes in the chemistry and biology of these systems. In addition, a number of important regional processes influence regionally unique ecosystems, and impact human communities. NOAA's national ocean, coastal, and Great Lakes acidification research goals are to:

- Expand and advance observing systems and technologies to improve the understanding and predictive capability of acidification trends and processes;
- Understand and predict ecosystem response and adaptive capacity of ecologically and economically important species to acidification and co-stressors; and
- Identify and engage stakeholders and partners, assess needs, and generate products and tools that support management, adaptation, and resilience to acidification.

Ocean, Coastal, and Great Lakes Acidification

Ocean Acidification (OA) is driven predominantly by ocean uptake of atmospheric carbon dioxide (CO_2) and results in global-scale changes in the pH of the oceans, accompanied by other chemical changes (primarily in the levels of carbonate and bicarbonate ions), that occur over long time periods (decadal to millennial time-scales; IPCC, 2011). OA has been observed in Earth's geologic record in relation to a number of natural processes that result in atmospheric CO_2 fluctuations, including but not limited to enhanced volcanic activity and glacial-interglacial climate shifts. Anthropogenic ocean acidification specifically refers to the component of pH reduction and associated shifts in the marine carbonate system that are a direct result of human activities (namely fossil fuel combustion; IPCC, 2011). In both cases, acidification exceeds the natural buffering rate by continental weathering resulting in a major perturbation of the ocean carbonate system.

Acidification occurring along coastlines, commonly referred to as “coastal acidification”, represents a combination of ocean uptake of atmospheric CO_2 and other coastal chemical additions and subtractions that can be driven by natural or anthropogenic processes. Some coastal processes that have been observed to cause such chemical alterations include, but are not limited to, organic matter respiration, freshwater influx (e.g., riverine influx and ice-melt), advection of allochthonous water masses (upwelling and lateral transport), anthropogenic nutrient loading and microbial degradation, and deposition of coastal atmospheric pollution. The combination of these processes has the potential to modify the local rate of and/or susceptibility (e.g., alter buffer capacity) to ocean acidification observed over time-scales that are typically decades or longer. Coastal acidification processes can be characterized as high-frequency or episodic events (i.e., seasonal ice melt, upwelling events, and severe rain events), but the term coastal acidification is applied when an increase in frequency and intensity of such processes lead to an overall trend or shift in the state of the coastal marine carbonate system toward more acidic conditions over time. In many instances throughout the subsequent marine-focused chapters of the Research Plan, the traditional term "OA" is collectively used to describe both ocean and coastal acidification occurring as a result of processes described above.

Continued acidification over the coming century will result in a further decline of 0.3-0.4 pH units in the global surface ocean by the year 2100 if CO_2 emissions continue unabated (Orr et al., 2005; Feely et al., 2009). The Great Lakes will continue to acidify at a similar rate and magnitude as the ocean (Phillips et al., 2015). Climate modes, such as El Niño–Southern Oscillation and Pacific Decadal Oscillation, are proving to be important determinants of the state of the marine carbon system and represent an emerging field of research (e.g., Feely et al., 2006; Nam et al., 2011; Osborne et al., 2019). Sub-global scale processes are occurring and driving the regional progression and variability of acidification, which are particularly important within coastal zones. The following research objectives are designed to facilitate our understanding and predict future responses of marine and Great Lakes biota, ecosystem processes, and biogeochemistry to acidification.

Developing partnerships with other federal agencies; academia; the private sector; state, local and tribal governments; and the international community is critical. In order to engage more broadly across the interagency, research, and stakeholder communities, the IWG-OA created a web-based communication forum called the OA Information Exchange. The OA Information Exchange has a membership of over 1000 individuals, including scientists, educators, resource managers, fishermen, aquaculturists, tribal representatives, and citizens from all over the globe.

Beyond federal and U.S.-based OA research endeavors, NOAA represents an important voice in international OA research. NOAA and the international research community are building wider connections to establish common and interdisciplinary international observing program, and data management systems. The Global OA Observing Network (GOA-ON), established in 2013 and co-founded by NOAA, is an international collaboration body on OA research. Its goals are to document the status and progress of OA in open ocean, coastal, and estuarine environments; to understand the drivers and impacts of OA on marine ecosystems; and to provide spatially- and temporally-resolved biogeochemical data necessary to optimize modeling for OA. These national and international collaborations promote informed-decision making and provide achievable solutions.

Environmental Change

Ocean, coastal, and Great Lakes acidification are affected by regionally-unique processes. Observing systems, which include moorings and mobile platforms such as research ships and autonomous vehicles, have been paramount in monitoring the progression of acidification. In addition to *in situ* observations, remote sensing assets such as satellites, provide data streams and are powerful tools for studying global surface ocean carbonate dynamics. Satellite sensors are able to detect a broad range of surface physical and biological phenomena that influence carbonate system dynamics and can sometimes be used to derive carbon parameters (Salisbury et al., 2015; Shutler et al., 2020). Combining satellite observations with *in situ* observations is critical to developing global-scale observing datasets.

The present *in situ* NOAA ocean observing system is oriented toward monitoring of the physical and chemical system (temperature, salinity, oxygen, nutrients, $p\text{CO}_2$, pH, Total Alkalinity (TA), Dissolved Inorganic Carbon (DIC)), but lacks coverage of the Great Lakes, and has limited inclusion of biological variables that are measured concurrently. Technological advances have greatly expanded non-ship-based monitoring capabilities of observations of fundamental OA variables (e.g., pH and $p\text{CO}_2$) on ocean moorings and autonomous vehicles, including profiling floats. Adoption of sustained biological measurements requires further development; as such, the field of ‘omics research, which uses molecular markers as biological indicators, presents promise for autonomous biological sampling capabilities (NOAA ‘Omics Strategy). Development of such technologies will be key to expanding the existing observing system.

An ocean acidification buoy located off the central Washington coast is serviced by researchers aboard the NOAA Ship Fairweather in 2012. Credit: Richard Feely/NOAA

Continued development and optimization of OA observing systems coordinated through GOA-ON is central to the national research objectives laid out for the coming decade. NOAA has played an important role in the formation of GOA-ON, and the objectives of both GOA-ON and this national research plan are aligned. The objectives of GOA-ON are to (1) identify and document the global-scale progression of OA, (2) determine the fraction of anthropogenic carbon content in the surface ocean, (3) provide data needed for global biogeochemical model projections, and (4) measure the biological response to OA as technology and protocols become available. Optimization of NOAA’s observing assets will be achieved if they are strategically deployed spatially and temporally in a manner that best responds to GOA-ON requirements. GOA-ON has made vast progress toward developing a truly global OA observing system via the collaborative international design of a coordinated, international, interdisciplinary program of ship-based hydrography, time-series moorings, floats, and gliders. Sustained support of GOA-ON is thus central to the enhancement of global OA observing.

Regional observing system configurations will be based on the needs of a specific geographic area, and must be configured to provide for change detection, inform regional biogeochemical models, and/or inform a specified end-user requirement. In coastal systems this demands capturing a complex interplay of processes driving coastal acidification. Regional-scale models, which have been developed for some but not all U.S. regions, are important to understanding and forecasting regional impacts to economically important fisheries or managed resources. The integration and linkage of regional ecosystem models with biogeochemical model frameworks is critical to predicting impacts to economically-important species and critical habitats. Such ecosystem forecast models incorporating OA already exist in some limited regions (e.g., Chesapeake Bay, Pacific Northwest) and can inform management actions. However, such models do not yet exist for most regions, representing an important area of further research that is needed to better predict the impact of OA on the U.S. Blue Economy.

OA research investments have generated a large number of physical, biogeochemical, ecological, and model datasets. Quality controlled and fully-integrated datasets will be instrumental in utilizing and analyzing the full breadth of OA data. Data management and stewardship will continue to be an integral part of OA research support to ensure that data are optimally used and transitioned into useful data products. The transition of scientific data to information products with minimal human interaction and ensuring that machine-to-machine services are available will be central to ease integration of data into regional and global models. Special emphasis will also be placed on ensuring that data collected by the OA observing system are findable, accessible, interoperable, and reusable (FAIR; Tanhua et al., 2019; Wilkinson et al., 2016).

Synthesis efforts provide useful products that include: integrated time-series of chemical, biological, and ecological parameters affected by OA; mapped products utilizing proxies and remote sensing (Salisbury et al., 2015; Shutler et al., 2020; Wanninkhof et al., 2020); predictions at local and regional scales through integration of models and observations; and informational materials based on OA observations and interpretation. Past synthesis efforts have been focused on the open ocean; however, many of the nation's marine resources, including over 90% of its fisheries, are found in the coastal ocean. Concerted efforts are needed to better inform the impacted industries, including aquaculture, and the U.S. population in terms of OA mitigation and adaptation efforts. Such synthesis products could make it possible to produce products that can be used by the general public to access information about OA conditions in their coastal areas, and annual U.S. national OA reports.

Research Objective 1.1: Expand and advance observing systems and technologies to improve the understanding and predictive capability of acidification trends and processes

Expanding and optimizing configuration of observing assets is central to understanding the variability and progression of acidification in the open ocean, coastal zones, and Great Lakes. Maximizing utilization of observational data streams in model simulations is critical to generating the best predictions and informing management choices.

Action 1.1.1: Sustain, improve, and adopt robust physical, chemical, and biological analytical systems, sensors, and autonomous technologies to observe the full water column and benthic environments and transition R&D technologies to serve as operational elements.

Action 1.1.2: Increase sampling of nearshore waters in sensitive and economically important areas and improve observing connectivity between coastal and open ocean to explicitly characterize the anthropogenic carbon content present in these environments.

Action 1.1.3: Sustain long-term acidification *in situ* time-series to monitor the progression of acidification and determine the impact and importance of regional and climate-related processes.

Action 1.1.4: Improve the use of satellite and other remote sensing tools and applications to observe and characterize the open ocean, coastal, and estuarine environments.

Action 1.1.5: Conduct observational and numerical simulation experiments to inform strategic deployment of NOAA OA Network observing assets for optimal spatial and temporal coverage.

Action 1.1.6: Develop and expand coverage of regionally linked biogeochemical-ecosystem models, with a focus on timescales of days to decades, capable of resolving conditions most relevant to local living marine and Great Lakes resources and dependent communities.

Action 1.1.7: Continue leadership of and support for the enhancement of the GOA-ON.

Action 1.1.8: Ensure all data collected by observing systems comply with FAIR data principles.

Action 1.1.9: Support synthesis activities to ensure environmental data are transitioned to useful products for modelers and other audiences.

Biological Sensitivity

Over the last decade, controlled laboratory and field studies have illuminated the response of marine species, populations, and ecosystems to acidification in combination with the influence of other co-occurring stressors such as elevated temperature, hypoxia, and added nutrient concentrations. Laboratory experiments allow researchers to control multiple variables to mimic future or extreme conditions in order to clearly observe species responses. Field studies can verify laboratory studies under real-world oceanographic conditions. Challenges remain in applying laboratory findings to real-world impacts, and field observations are complicated by an inability to attribute observed effects of acidification vs. co-occurring stressors (e.g., temperature, oxygen) in the environment.

Vibrant coral reef ecosystems like this one are threatened by acidification and other environmental changes. Credit: Richard Feely/NOAA

While hundreds of species sensitivity studies have been conducted to date, the number of species whose sensitivity has been well-characterized is small in comparison to the overall diversity of marine and Great Lakes life. Notably, many species that are important to ecosystem function or to commercial and subsistence harvests have yet to be examined (see regional chapters). Researching these critical species is central to understanding and predicting the impacts acidification may have on dependent human communities and economies. In addition to direct impacts (e.g., reduced calcification efficiency, impacts to larval development), indirect impacts are important to consider for an even wider range of species. Indirect impacts include altering food web and predator-prey relationships, and potential influences on the spread of invasive species. Altered food webs can result in reduced quality and/or availability of food sources due to acidification sensitivity of lower trophic-level species. Such indirect impacts demonstrate the importance of understanding ecosystem vulnerability by developing ecosystem assessments.

Understanding biological impacts benefits from co-location of biological observations with physical and biogeochemical observing assets in order to collect a suite of variables that can aid in understanding species and multi-stressor interactions. Monitoring approaches that integrate biological sensitivity and surveys with routine physical observations have the capacity to greatly expand the understanding of exposure and environmental history at a site. Concurrent measurements of three of five marine carbonate system variables (e.g., DIC, pCO_2, TA, CO_3^{2-}, and pH), will better facilitate attribution of a species' physiological response to a specific change in the carbonate system. For example, fully characterizing the marine carbonate system is important to understanding a nuanced calcifier response to individual carbonate species.

Recent developments in 'omics science and sample collection technologies have the potential to provide powerful new qualitative tools and sensors that can routinely and non-invasively monitor presence (genomics) and health or sensitivity to change (proteomics and metabolomics) of marine species (NOAA 'Omics Strategy). Such observing approaches will greatly expand the coverage and frequency of biological system sampling. Developments in 'omics science also provide the ability to conduct experiments that genetically evaluate and monitor a species' propensity to adapt or acclimate to stress-inducing environments. Such studies have been used to identify resilient species' genotypes and isolate molecular mechanisms that confer resilience with the aim to restore ecosystems.

There will be emerging and unanticipated phenomena as a result of acidification and environmental change. Examples includes the emerging relationship between OA and increased growth and toxicity of harmful algal blooms (e.g., Raven et al., 2020), and OA and hypoxia (Sunda & Cai, 2012). Such cross disciplinary multi-stressor, research to understand unusual and developing phenonomena will be important in the coming decade.

Research Objective 1.2: Understand and predict ecosystem response and adaptive capacity of ecologically and economically important species to acidification and co-stressors

Ocean, coastal, and Great Lakes acidification is occurring in tandem with a number of environmental stressors, including ocean warming and deoxygenation, which collectively influence biological response. The impact of acidification and multi-stressor environments on a number of economically and ecologically important marine and Great Lakes species have yet to be examined. Building upon our current species, community, and ecosystem response knowledge will be central to predicting future ecosystem-level change. Further, assessing sensitivity and adaptive capacity of species and populations will be important to developing effective mitigation, adaptation, conservation, and restoration plans.

Action 1.2.1: Assess acidification and multi-stressor sensitivity among species, particularly ecologically and economically important species, to build understanding, provide important information to ecosystem modeling efforts, and inform management decisions.

Action 1.2.2: Collect, integrate, and synthesize co-located physical, chemical, biological, and ecological data to study species and ecosystem response to acidification and multi-stressor environments.

Action 1.2.3: Promote the full characterization of the marine carbonate system to facilitate attribution of species' physiological response and resulting community and ecosystem responses.

Action 1.2.4: Foster new research to study emerging and unanticipated ecosystem changes, including but not limited to multi-stressor interactions and harmful algal blooms.

Action 1.2.5: Use new knowledge to further refine existing ecosystem models that can be linked to biogeochemical models and inform scenarios of future acidification and environmental change.

Action 1.2.6: Assess sensitivity within species and populations to evaluate potential for biological capacity to adapt and acclimate to acidification and multi-stressor environments.

Action 1.2.7: Explore feasibility and benefits of identifying genetic resistance and resilience to acidification and environmental change within species in order to apply active mitigation strategies, foster resilient marine communities, and improve habitat conditions, and restoration success.

Human Dimensions

Ocean, coastal, and Great Lakes acidification has the potential to cause fundamental changes to a number of commercial fisheries, subsistence harvests, recreational fishing, aquaculture, and eco-tourism, as well as the way of life for some coastal communities. This clear connection between acidification and affected human communities makes human dimension research critical to the ocean, coastal, and Great Lakes acidification mission at NOAA.

A man harvests oysters in Yaquina Bay, Oregon. Credit: NOAA

According to laboratory studies, a number of valuable commercial fisheries may be directly impacted by OA. Such fisheries and their U.S. landing values (based on the [Fisheries of the United States, 2018 Report]) include West Coast Dungeness crab ($239.3 million across California, Oregon, and Washington in 2018), Alaska king crab ($67.2 million in 2018), and New England Atlantic sea scallop ($532.3 million in 2018) along with myriad other bivalve species found around the U.S. including mussels ($11.1 million in 2018), clams ($244.1 million in 2018), and oysters ($258.7 million in 2018). OA has also been shown to negatively impact coral reef ecosystems, which have an estimated total economic value based on combined U.S. coral reef services of $3.4 billion per year (Edwards, 2013). One coral reef ecosystem service, shoreline protection, is declining as a result of coral bioerosion in regions such as the Caribbean and Pacific Islands (see subsequent chapters), making coastal zones more vulnerable to severe storms and waves that are typically dissipated by the presence of coral structures. The annual value of estimated flood risk reduction by coral reefs in the U.S. alone is more than 18,000 lives and $1.805 billion in 2010 (Storlazzi et al., 2019).

The FOARAM Act of 2009 calls for educational and public outreach opportunities to improve public awareness and understanding of the current scientific knowledge of OA and impacts on marine resources. Over the last decade, NOAA has been dedicated to working with the regions across the U.S. to develop OA education toolkits and to provide workshops and webinars on platforms such as the OA Information Exchange to communicate about ocean change and potential response strategies. The agency published its first NOAA Ocean Acidifiation Education Implementation Plan in 2014. The present research plan aims to sustain the efforts being carried out under the education implementation plan, and to guide environmental change and biological sensitivity science that can be applied to socioeconomic research, and generate meaningful information and products for stakeholders and partners. Resources and products include open ocean, coastal, and Great Lakes region education and outreach resources such as visualizations and other information products targeting diverse stakeholders.

Socioeconomic research will be framed based on the needs of and conducted in consultation with relevant stakeholders and partners in order to ensure actionable and relevant research results. It will be important to systematically identify acidification-vulnerable stakeholders and partners to build relationships and to understand their acidification needs and concerns in the context of the broader environmental change they are facing. Established national and regional networks such as the Coastal Acidification Networks (CANs) that are part of the IOOS Regional Associations, Sea Grant Extension Agents, National Marine Sanctuaries, and National Estuarine Research Reserves have built long standing relationships and collaborations that can facilitate relationship building and identification of need. Building partnerships with communities may also lend itself to community-based observing and the integration of local knowledge into research efforts. Such partnerships have the potential to greatly expand the spatial and temporal coverage of monitoring and provide valuable insights to supplement ongoing monitoring of ocean, coastal, and Great Lakes acidification.

Managers at the state, local, tribal, and regional levels need targeted social and economic research results to be able to best anticipate and prepare for acidification impacts by developing suitable and region-specific strategies to address the threats of climate and ocean change. The integration of environmental understanding, biological sensitivity and socioeconomic results in models to forecast regional acidification effects on communities and economies will be essential to prepare for future impacts of ocean, coastal, and Great lakes acidification and environmental change. Considering future impacts, an important next step will be to support research that evaluates and develops effective local communication, mitigation, and adaptive strategies to support resiliency of communities.

Research Objective 1.3: Identify and engage stakeholders and partners, assess needs, and generate products and tools that support management, adaptation, and resilience to acidification

Integrating scientific knowledge into social, cultural, and economic frameworks is central to understanding the vulnerability of communities to ocean, coastal, and Great Lakes acidification and environmental change. Research and associated communication products, tools, and technologies that are relevant or useful to stakeholders and partners should be framed to directly address their needs and concerns.

Action 1.3.1: Identify and build relationships with vulnerable communities, stakeholders, and partners to identify needs and concerns, exchange knowledge, and understand how acidification fits within their decision making contexts.

Action 1.3.2: Develop a strategy for engaging indigenous governments and communities to exchange knowledge and integrate indigenous and scientific knowledge sources.

Action 1.3.2: Model economic, cultural, and social impacts to evaluate intervention actions and explore adaptive strategies that build resilience, empower communities, and inform policy-making.

Action 1.3.4: Encourage research partnerships and two-way dialogues with stakeholders to ensure that science is aligned with local to regional level priorities, by supporting networks that are engaging in outreach, communication, and research, such as the OA Information Exchange and Coastal Acidification Networks.

Action 1.3.5: Develop and operationalize data synthesis, visualization tools, and communication products with robust stakeholder and partner input to ensure products are responsive to needs.

Action 1.3.6: Create education and outreach resources in partnership with researchers, educators, and community partners based on regional needs and real data products to promote understanding and awareness of ocean, coastal, and Great Lakes acidification and possible adaptation, mitigation, and resilience strategies.

Action 1.3.7: Monitor trends in community awareness and perceptions of acidification impacts and participation in stewardship activities across diverse stakeholders.

2. Open Ocean Region Acidification Research

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Abstract

The primary goals of the open ocean research plan are to determine how anthropogenic carbon and pH changes interact with natural variability to collectively act on ocean carbonate chemistry and biology, and to continue to support and enhance the NOAA contribution to the Global Ocean Acidification Observing Network (GOA-ON) with new sensors, autonomous platforms, and biological measurements to be co-located with the physical and chemical studies. The observations will be utilized to validate models and calibrate satellite data synthesis products. Global maps and data synthesis products will be developed to provide information for national and international policy and adaptive actions, food security, fisheries and aquaculture practices, protection of coral reefs, shore protection, cultural identity, and tourism. The Open Ocean Region's research goals are to:

- Maintain existing observations and continue developing and deploying autonomous vehicles and biogeochemical (BGC) Argo floats to measure surface and water column carbon parameters, nutrients, and other Essential Ocean Variables (EOVs);
- Conduct biological sampling (e.g., Bongo net tows) during GO-SHIP cruises to determine the biological impacts of OA and other stressors on planktonic communities;

- Develop data management systems and synthesis products including visualizations of key chemical and biological parameters to quantify anthropogenic carbon dioxide (CO_2) buildup, rates of change of global ocean OA conditions, and biological rate processes; and
- Support data synthesis activities to provide validation of biogeochemical models.

Ocean Acidification in the Open Ocean Region

This chapter evaluates how anthropogenic changes and natural variability collectively act on ocean carbonate chemistry and determine the vulnerability to future ocean acidification (OA) conditions within the open ocean regions in deep waters beyond the continental shelf. Natural carbonate chemistry variability results from the combined actions and interactions among many different processes (e.g., air-sea exchange, circulation and transport, upwelling, production, remineralization, carbonate mineral dissolution, etc.). OA is an anthropogenic process, rooted in natural seawater carbonate chemistry, but is also influenced by regional and temporal variations and processes. Natural variability in carbonate chemistry is compounded by OA changes that have the capacity to create particularly extreme conditions in some regions of the global ocean. For example, high latitudes are particularly vulnerable to decreasing aragonite state conditions because of the combined effects of the anthropogenic CO_2 input, low temperature, and lower buffer capacity (Hauri et al., 2015; Zhang et al., 2020).

Models indicate that with continued atmospheric CO_2 absorption, the ocean is likely to undergo rapid changes in calcium carbonate saturation state, affecting calcifying organisms and leading to large-scale ecological and socioeconomic impacts (Feely et al., 2009; Orr et al., 2005; Steinacher et al., 2009;

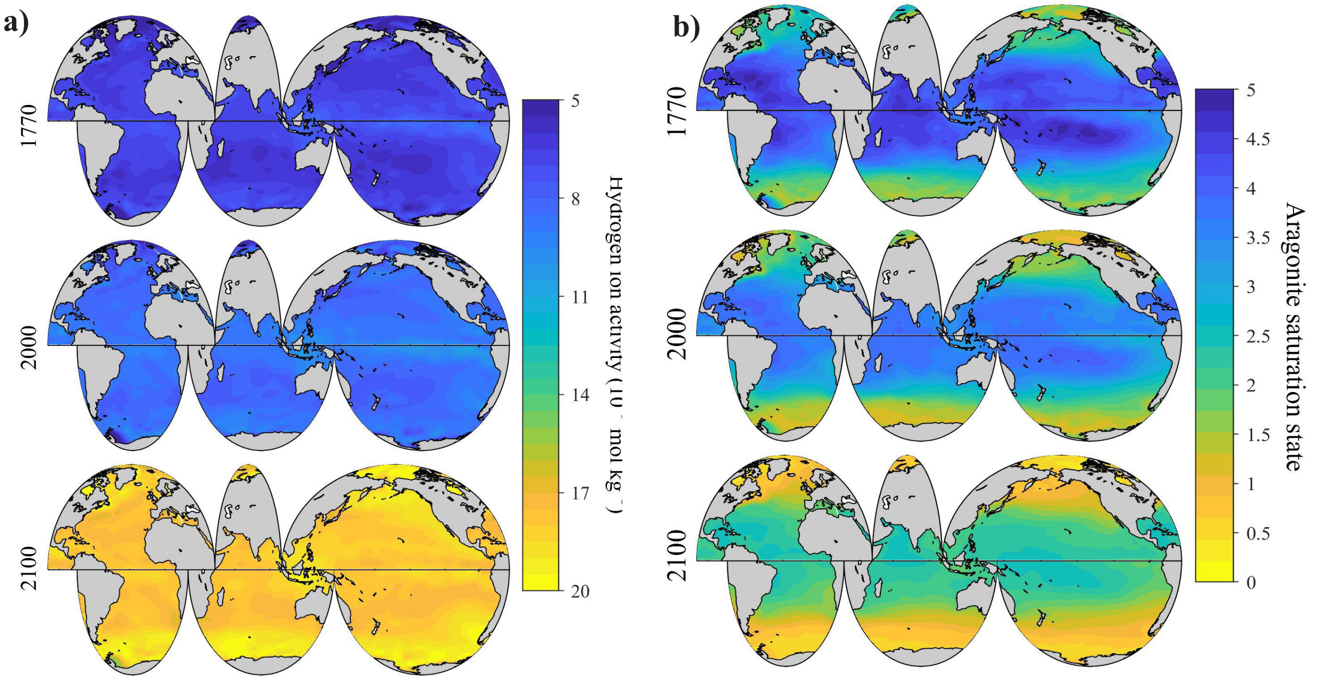


Figure 2.1. Model output of past, present, and future: a) hydrogen ion activity changes and b) aragonite saturation state based on global surface ocean pCO$_2$ observations normalized to the year 2000. The hydrogen ion activity distributions for 1770 and 2100 are reconstructed by extracting the temporal changes of pCO$_2$ and SST at individual locations of the global ocean from the Geophysical Fluid Dynamics Laboratory (GFDL)'s ESM2M Model and converting the data to hydrogen ion activity using CO2SYS. This provides a regionally varying view of the historical and future surface ocean H^+ simulations given by the Intergovernmental Panel on Climate Change (IPCC) Assessment Report (AR5) for the Representative Concentration Pathway 8.5 scenario (adapted from Jiang et al., 2019).

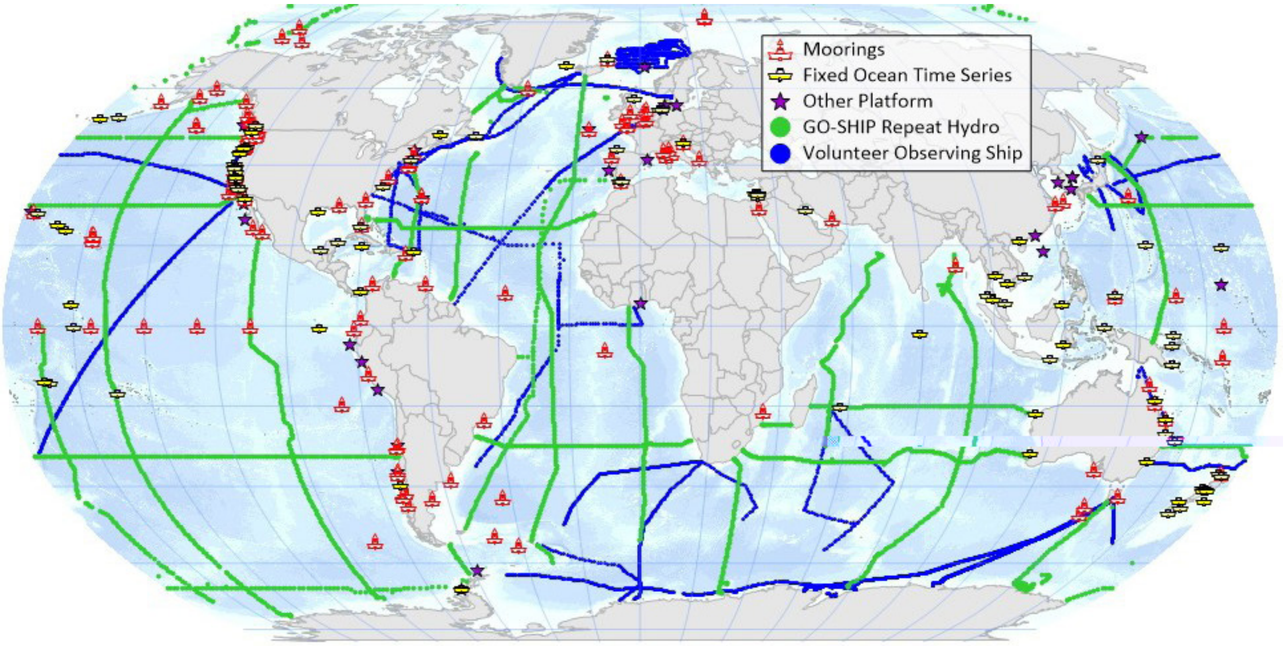


Figure 2.2. Present-day Global Ocean Acidification Observing Network, which is collaborative with the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) surveys, the Surface Ocean CO_2 Observing NETwork (SOCONET), the Ship of Opportunity Program (SOOP) volunteer observing ships, and the Ocean Sustained Interdisciplinary Time-series Environment observation System (OceanSITES) , and other open ocean and coastal observing networks (after Tilbrook et al., 2019).

Gattuso et al., 2015; see also Chapter 6; **Figure 2.1**). Quantifying the relative magnitude of natural variations provides useful context for determining the tolerance levels of organisms, which evolved before the influence of human-caused CO_2 emissions. The most important indicators for OA are pH (-log *a*(H^+)), *p*CO_2, carbonate ion concentrations ([CO_3^{2-}]), and calcium carbonate mineral saturation states, with significant increases in surface ocean pH and downward trajectories of surface ocean [CO_3^{2-}] and carbonate saturation states expected throughout this century with increasing atmospheric CO_2 (e.g., **Figure 2.1**). However, attempts to synthesize pH and other carbonate data for the open ocean have largely been limited by available high-quality data, since pH and other carbonate parameter measurements require great care, calibration, and metadata validation (Feely et al., 2009; Takahashi et al., 2014; Jiang et al., 2015; Olsen et al., 2016; Carter et al., 2017; Gruber et al., 2019a,b; see also **Figure 6.2** in Chapter 6: U.S. Pacific Islands Region). In this chapter we recommend future research objectives, activities, and priorities for the open oceans for the next decade of NOAA OA research.

Environmental Change in the Open Ocean Region

After launching the GOA-ON in 2013, the current observing network is comprised of several observing networks deployed around the world—including moorings, repeat hydrography lines, ships of opportunity, and fixed ocean time-series (**Figure 2.2**). The existing large-scale global oceanic carbon observatory network, supported by the NOAA Global Ocean Monitoring and Observing (GOMO) Program, which includes the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) surveys, the Surface Ocean CO_2 Observing Network (SOCONET), the Ship of Opportunity Program (SOOP) volunteer observing ships, and the Ocean Sustained Interdisciplinary Time-series Environment Observation System (OceanSITES) time-series stations in the Atlantic, Pacific, and Indian oceans have provided a backbone of carbonate chemistry observations needed to understand OA (**Figure 2.2**). Indeed, much of the present understanding about long-term changes in the carbonate system is derived from these repeat surveys and time-series measurements in the open ocean (Feely et al., 2004, Sabine et al., 2004; Carter et al., 2017, 2019a; Sutton et al., 2019; Gruber et al., 2019b). At present, many of the existing moored carbon observatories only measure *p*CO_2 in surface waters, which is insufficient to effectively monitor and forecast OA conditions and concomitant biological effects. Future efforts will require additional platforms with an enhanced suite of physical, chemical, and biological sensors in the ocean interior.

Efforts to observe and predict the impact of OA on marine ecosystems must be integrated with an understanding of both the natural and anthropogenic processes that control the ocean carbonate system (**Figure 2.3**). Biogeochemical cycling leads to remarkable temporal and spatial variability of carbon in the open ocean. Long-term, high-quality observations are critical records for distinguishing natural cycles from climate change. There are several methods by which anthropogenic carbon can be distinguished from natural carbon, but all rely on the repeated, high-quality, spatially dense, synoptic, coast-to-coast records of nutrients, ventilation tracers, carbonate system measurements, dissolved gases, and physical properties provided by the GO-SHIP cruises (e.g., Sabine et al., 2004; Khatiwala et al., 2013; Carter et al., 2017, 2019a; DeVries, 2014; Gruber et al., 2019b). Recent research has shown that there are significant regional and decadal variations in anthropogenic CO_2 storage (e.g., Landschützer et al., 2016; DeVries et al., 2017; Gruber et al., 2019a,b), indicating that repeat hydrographic surveys will remain critical for quantifying ocean carbon storage in the coming decades. Feely et al. (2016) extended the open ocean anthropogenic carbon estimates to the California Current Large Marine Ecosystem, allowing the impacts of OA to be separated from natural processes over a two-decade-long time span. This is a critical application for anthropogenic carbon estimates that should be applied in other regions, as coastal regions play disproportionate roles in fisheries and ocean primary production compared to their small (~8% of total) ocean area, and because theseregions with air-sea *p*CO_2 disequilibria typically lack means to directly quantify the overall anthropogenic impact.

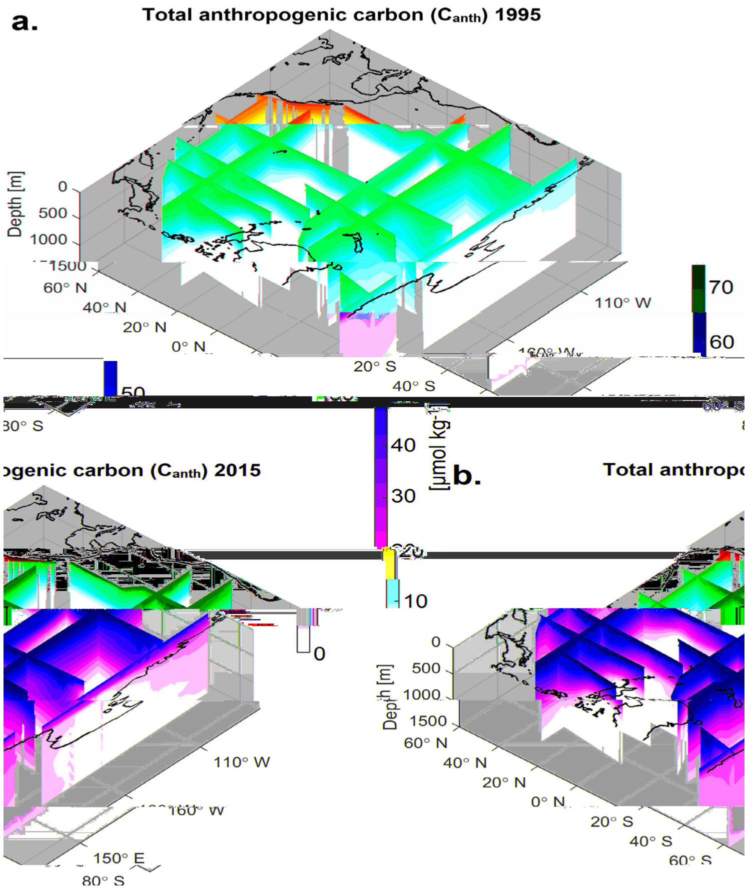


Figure 2.3. Anthropogenic dissolved inorganic carbon concentrations in μmol kg-1 along Pacific Ocean repeat hydrographic sections, estimated for (a) 1995 and (b) 2015. Darker colors indicate that higher concentrations are found near the surface, and extend deeper into the water column in the subtropical gyres. This figure is adapted from Carter et al. (2019a).

Open ocean time-series observations now exist in nearly all oceanic regions and show that the inorganic carbon chemistry of the surface ocean is currently changing at a mean rate consistent with the atmospheric CO_2 increase of approximately 2.0 µatm yr-1 (Bates et al., 2014a; Sutton et al., 2017, 2019). However, enhanced variability in high-latitude regions can complicate and, at times, obscure detection and attribution of longer-term ocean carbon changes. Recent work suggests it will require decades of observations to detect an anthropogenic signal at many coastal time-series stations (Carter et al., 2019a; Sutton et al., 2019; Turk et al., 2019). High-quality, open ocean time-series observations represent critical components of GOA-ON and provide a critical constraint of offshore processes influencing coastal systems, and we recommend their adoption at a larger scale. Open ocean time-series are a powerful way to quantify the United Nations Sustainable Development Goal 14.3 to minimize and address the impacts of OA, including tracking rates of change of OA globally.

Autonomous platforms have demonstrated their potential for revolutionizing the quantity and coverage of OA-related information retrievable from remote regions in all seasons (Bushinsky et al., 2019; Meinig et al., 2015). These surface vehicles and profiling floats possess the capacity to quantify OA and biogeochemical seasonal cycling across traditionally inaccessible regions and timescales. The advent of BGC-Argo profiling floats, with pH as one of the six BGC sensors, offers enormous opportunity to obtain greatly expanded datasets in the open ocean that will provide seasonal resolution of trends and processes that lead to a better understanding of the evolution of marine chemistry and biology conditions as they pertain to OA (**Figure 2.4**). Aside from directly determining OA parameters and processes from these programs, the data are increasingly used

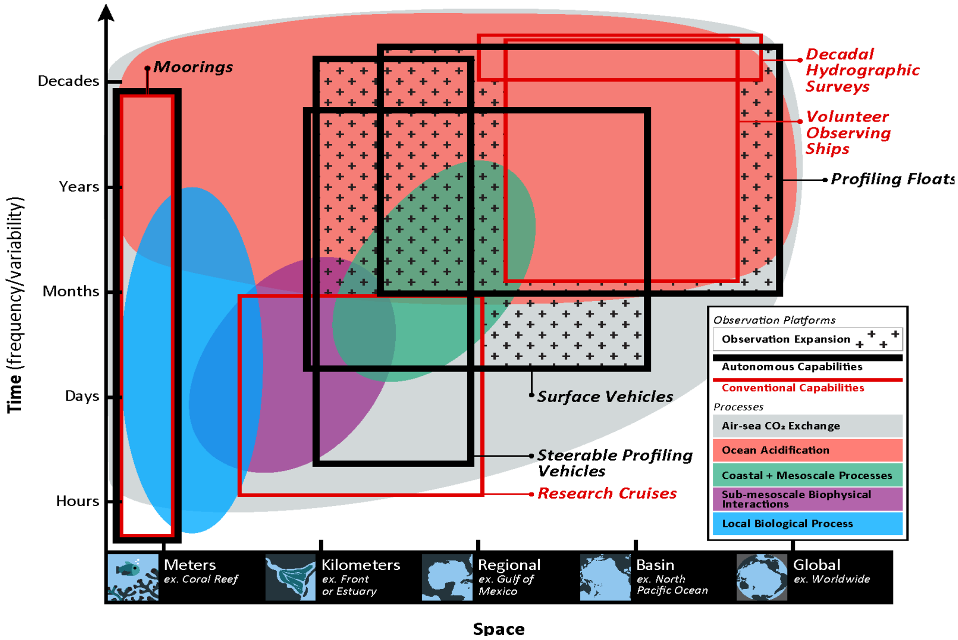


Figure 2.4. Carbonate system processes and autonomous vehicle observational capabilities as a function of time and space. Ocean processes that affect the carbonate system (solid colored ovals with labels in the legend) are depicted as a function of the temporal and spatial scales over which they must be observed to capture important scales of variability and/or long-term change. The ability of platforms, including conventional approaches (red boxes) and autonomous arrays (black), to capture carbonate system processes is superimposed over the characteristic time and space footprints of important carbon cycle processes. The mooring box includes both open-ocean observatories and compact, fixed observatories deployed in coastal and benthic regions. Box boundaries that are directly adjacent to one another (i.e., the upper boundaries of profiling floats, decadal hydrographic surveys, and ships of opportunity) indicate the same temporal or spatial boundary, but are offset for clarity (after Bushinsky et al., 2019). Satellite remotely sensed surface ocean observations (ranging from sub-km to global and from sub-days to decades in some cases) can be assimilated into carbonate and ocean physics models and used as validation for some model outputs.

to validate models including ingestion into novel assimilation schemes such as ocean state estimates. However, as an emergent autonomous technology, the uncertainties associated with their use and lack of *in situ* calibrations are still being quantified, and extensive work remains to be completed before the promise of this observation strategy can be fully realized (Johnson et al., 2017; Williams et al., 2017). On autonomous surface vehicles, seawater $p\mathrm{CO_2}$, and pH can be directly measured, with *in situ* calibration of CO_2 providing high-quality data equivalent to moored $p\mathrm{CO_2}$ time-series (e.g., Saildrone). However, even the highest-quality $p\mathrm{CO_2}$ and pH sensors in combination do not meet GOA-ON climate-quality goals for tracking OA, and sensor development efforts must address this challenge. Research must continue to determine how best to implement new observing platforms and sensors, use the data they retrieve, and quality control and manage their sensor outputs.

Research Objective 2.1: Continue leadership and support for GOA-ON (coordinated with Pacific Islands Region Chapter 6 Research Objective 6.2)

GOA-ON provides a framework to knit together information from ship-based hydrography; time-series moorings, floats, and gliders with carbon system, pH, and oxygen sensors; and ecological surveys and associated biological responses. Support will assure continuation of the ongoing international observing programs, support augmentation of observation with key biological Essential Ocean Variables (EOVs) and encourage further development of novel platforms.

Action 2.1.1: Build upon the existing NOAA-supported GOA-ON activities and expand the global network with new sensors and observing platforms that provide important information on the changing physical, chemical, and biological conditions in open ocean environments.

Action 2.1.2: Ensure OA relevant measurements are included on all Surface Ocean CO_2 Observing Network (SOCONET) and Ship of Opportunity Program (SOOP) volunteer observing ships.

Action 2.1.3: Enable the development of globally accessible, high-quality data and data synthesis products, including assessments of OA status and trends, which facilitate research and new knowledge on OA, communicate the status of OA and biological response, and enable forecasting of OA conditions.

Research Objective 2.2: Separate natural and anthropogenic CO_2 signals and elucidate feedbacks on seasonal to decadal scales

Quantifying the vertical and horizontal distributions, temporal variability, and long-term trends of anthropogenic carbon will provide critical information for determining the biogenic responses of organisms and communities to OA.

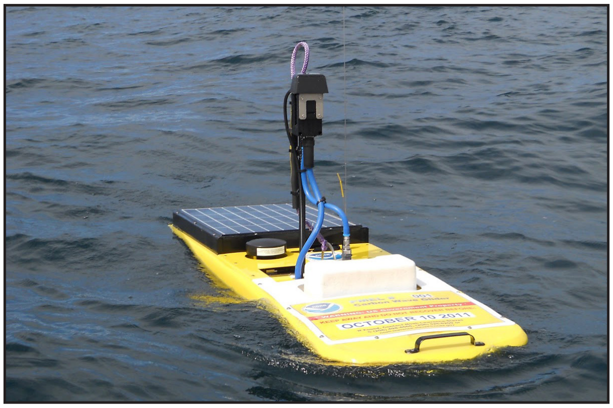
Action 2.2.1: Link open ocean and coastal cruises for tracking the distribution and trends of anthropogenic carbon increases in the ocean.

Action 2.2.2: Expand time-series observations in open ocean and coastal waters (see *Chapters 3–11*) to characterize rates of ocean carbon change over time, which is necessary to reduce uncertainties in future projections of OA.

Action 2.2.3: Continue the development of sensors on autonomous platforms that can measure carbon parameters, nutrients, and other biogeochemical EOVs, especially those meeting climate- quality standards of GOA-ON.

Developing global synthesis and modeling products and maps of OA indicators

Repeat coast-to-coast cruises are the chief means through which we understand rates of decadal ocean uptake of anthropogenic CO_2 and resulting global inventories (Sabine et al., 2004; Gruber et al., 2019b), as well as the ensuing ocean carbonate chemistry changes that are underway in the global ocean (e.g., Byrne et al., 2010; Feely et al., 2004, 2012; Carter et al., 2016, 2017; Jiang et al., 2015, 2019). Sustained support for decadal reoccupation of open ocean repeat hydrography lines is critical to ensure that we can continue to estimate ocean uptake and inventories of anthropogenic carbon into the future, as well as providing high-quality datasets for global ocean model validation. These in turn support accurate and reliable generation of boundary conditions for regional coastal models (e.g., Feely et al., 2016; Carter et al., 2017, 2019a).



A wave glider makes ocean carbon dioxide (pCO_2) measurements in Washington coastal waters while deployed by researchers aboard the R/V Wecoma. Credit: Richard Feely/NOAA

Open ocean transects provide valuable insight into source water evolution relevant to coastal acidification trajectories, although their decadal resolution provides infrequent snapshots of such conditions and must be cross-referenced to more frequent coastal observations to gain insight into rates of change in shelf environments (cf. Feely et al., 2012, 2016; McClatchie et al., 2016). Global Earth System Models of coupled carbon and climate are also key sources of information on past trends and future projections for OA. Currently available model data include a suite of simulations from the 5th Coupled Model Intercomparison Project (Taylor et al., 2012; https://esgf-node.llnl.gov/projects/cmip5/), including simulations from NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) with two state-of-the-art Earth System Models, GFDL-ESM2M and GFDL-ESM2G (Dunne et al., 2012a, 2013; ftp://nomads.gfdl.noaa.gov/CMIP5/output1/NOAA-GFDL/). The global modeling community continues to advance on this frontier and has commenced an ongoing 6th phase of the Coupled Model Intercomparison Project (Eyring et al., 2016), which includes a vastly more comprehensive suite of experiments, in which GFDL is fully engaged. Public access to the next-generation Earth System Models will be provided by the global modeling community over the coming years.

New autonomous platforms such as autonomous surface vehicles and profiling floats offer an enormous opportunity to obtain greatly expanded datasets that will provide daily to seasonal resolution of trends and processes, especially in traditionally inaccessible regions. However, there are considerable data management tools that must be developed before these observations can be integrated with established observations in global data synthesis products and used to validate models. Intercomparisons between established and new observations can help determine uncertainty of new technologies, but a data integration system is also critical to support these new approaches now and into the future. Research must continue to determine how best to implement these observing platforms, use the data they retrieve, and quality control and manage their sensor outputs. Support for the continuation of the ongoing observing programs, support augmentation of observations with key biological EOVs such as plankton, assure maintenance of the high quality of the data, and encourage further development of these new platforms.

Global seasonal-to-interannual prediction of acidification anomalies requires reliance on large- scale physical and biogeochemical data assimilation that is dependent on *Research Objective 2.2* above. These forecasts are in a state of development and require a better understanding of data assimilation methods, especially considering the new observational assets coming online in the next few years. Global historical and future scenarios of decadal to centennial acidification using fully coupled carbon-climate earth system models are in continued development as described in *Research Objective 2.3*. When run in physical data-assimilation mode, these models show much early promise with respect to predictability of carbon uptake and acidification (Li et al., 2016; Park et al., 2018) on seasonal to decadal timescales, and earth system prediction is possible using the GFDL MOM6 model. An essential part of this development on all timescales includes multi-decade retrospective analysis of acidification patterns compared with observations to test the skill and improve the forecast and projection systems. Key observations for this activity include those that characterize the ocean ecosystem and biogeochemical cycles at the process level and their sensitivity to multiple stressors including the physiological role of acidification on plankton growth and behavior and its consequences for biodiversity and controls on calcite, aragonite, and high Mg-calcite formation and dissolution. The cycling of calcium carbonate has been recently identified as a potentially important process that is not consistently simulated (Dunne et al., 2012b; Buitenhuis et al., 2019); and thus remains poorly constrained and requires further improvements in understanding.

Research Objective 2.3: Observe the evolution of marine chemistry and biology to provide model initial conditions and validation

Quantifying OA impacts requires the development of global and regional data products from observational data such as open ocean observations from GO-SHIP, BGC Argo, and SOCONET to provide initialization data for model runs and validation datasets for testing model predictive capabilities (*in coordination with Pacific Islands Region Chapter 6 Research Objective 6.3*).

Action 2.3.1: Develop synthesis products including maps and sections of key chemical and biological parameters to quantify the buildup of anthropogenic CO_2, rates of change in global ocean OA conditions, and impacts of OA on key species.

Action 2.3.2: Continue the development of data management and quality control systems for autonomous sensors on autonomous surface vehicles and biogeochemical (BGC) Argo profiling floats in order to incorporate these new observations in data products and validate models.

Action 2.3.3: Continue development of regional-to-global scale prediction BGC models focused on acidification extremes spanning timescales from seasonal to interannual to decadal.

Satellite Observations for Understanding Open Ocean Acidification

Satellite observations offer a powerful tool for studying surface ocean carbonate dynamics either by deriving CO_2 parameters via satellite sea surface temperature and salinity, or by inferring large-scale patterns from physical parameters that can be remotely-sensed and validated using observations obtained from *in situ* observing assets (e.g., ships and time-series stations). While satellite sensors are not capable of actual direct carbonate parameter measurements, they are able to sensibly detect a broad range of surface physical and biological phenomena that influence carbonate system dynamics (Salisbury et al., 2015; Shutler et al., 2020). By quantifying changes in parameters through time and space, satellite data together with *in situ* observations can provide reasonable rate proxies for the effects of mixing and community metabolism on the carbonate system (Hales et al., 2012). Beyond the direct study of OA, ocean satellite data can also support other activities detailed throughout this plan ranging from cruise planning to model validation. Robust, sustained, internally consistent access to ocean satellite products that are fit-for-purpose (e.g., near-real-time and delayed science quality products) remains a critical need.

Recognizing that many satellite-based empirical or semi-empirical algorithms relating observable parameters to OA are regionally specific (i.e., Gledhill et al., 2015), there remains a requirement to objectively establish discrete domains where uniquely defined algorithms can be robustly parameterized. One promising approach in recent years has been the development of dynamic seascape classification products (i.e., Kavanaugh et al., 2014, 2016). Thus, there is much opportunity for improvements that include, but are not limited to, the addition of new variables, methodological comparison, and global validation.

Surface ocean gridded data synthesis products of satellite remote sensing outputs can provide surface ocean-specific algorithms to be applied to remotely sensed products to produce gridded fields of monthly global sea surface pCO_2. These fields can then be coupled to total alkalinity (TA) fields derived from salinity data (e.g., ESA- SMOS; NASA SMAP), which can be used in conjunction with pCO_2 and temperature to derive monthly dynamics for global surface ocean carbonate saturation states and pH (e.g., Jiang et al., 2015, 2019).

Improved models for quantifying surface biological perturbations to the carbonate system from space are needed. The predominant perturbation arises from net community production (NCP), or the balance between gross primary production (GPP) and community respiration (CR). Several existing strategies for retrieving satellite-derived NCP include a space-time accounting of the change in organic carbon inventories (Jönsson et al., 2011; Jönsson & Salisbury, 2016), satellite estimates of organic carbon export (e.g., Siegel et al., 2014; Li et al., 2018), and satellite-derived NPP (e.g., Saba et al., 2011) versus CR (Zhai et al., 2010). To facilitate these efforts, repeated hydrographic surveys should facilitate *in situ* optical measurements that include apparent and inherent optical properties, particle-size distributions, and multispectral fluorescence, in conjunction with ship-based rate measurements (NPP, NCP, and CR). Additional measurements may be required to optimally relate optical data to rate estimates, including but not limited to chlorophyll (and associated pigments), particulate organic carbon, and phytoplankton functional-type enumerations.

Research Objective 2.4: Derive global statistical or quasi-mechanistic algorithms to infer surface ocean carbonate dynamics and underlying biological processes to be acquired from remotely sensed data

Satellite observations can be used to determine surface ocean carbon distribution either directly or by synoptically scaling up discrete surface observations obtained from *in situ* observing assets.

Action 2.4.1: Derive seascape-specific multivariate algorithms for predicting global surface ocean $p\mathrm{CO}_2$ at suitable spatiotemporal scales (e.g., monthly, 0.5 degree).

Action 2.4.2: Incorporate measurements supporting satellite algorithm development and determination of net biological productivity into ongoing OA surveys.

Biological Sensitivity in the Open Ocean Region

Large-scale hydrographic studies crossing major biogeographical provinces are of fundamental importance for understanding short- and long-term biological and ecological responses associated with OA and other climate change-related stressors in the open ocean (e.g., Bednaršek et al., 2014, 2017a; Engström-Öst et al., 2019). Each province is characterized by a set of baseline conditions, and additionally is affected by seasonal and 'event-scale' variability. On large scales, the transitions between adjacent provinces are often characterized by strong OA gradients. When accompanied by gradients in other environmental factors, such as temperature, nutrients, dissolved oxygen, and food availability, they create the potential for multiple drivers to provoke strong biological responses (Bednaršek et al., 2018).

Planktonic communities likely are some of the most vulnerable to OA and comprise key prey items for larger pelagic and benthic invertebrates, fishes, and marine mammals. Plankton are unevenly distributed across oceanic ecosystems, with their numbers, composition, and survival being highly sensitive and responsive to environmental conditions. Related species often respond differently to OA and other stressors, and have different spatial and temporal dynamics that may substantially affect food availability for larger organisms, and in turn for ecosystem services and seafood resources. Changes in biodiversity and lower and higher trophic level species composition are ultimately dependent upon species vulnerability versus adaptation potential. So far, OA gradients have been used as natural laboratories for detection of sensitive responses across various levels of biological organization.

There is a fundamental need for integration of physical, chemical, and biological data into a biogeographic framework to be able to develop OA-related species-distribution models. The assessment of OA-related impacts is currently limited because synoptic information about species distributions, their physiological limitations, and the physical-chemical characterization of local environments are not always recorded together. More specifically, Habitat Suitability Indices (HSIs) can be used as statistical approaches using multiple regression methods to define an envelope of optimal conditions in which an organism may persist (Bednaršek et al., in review). Continuous Plankton Recorder (CPR) data have been collected over time, and some of them now represent unique time-series that could be used with gridded products generated by large hydrographic surveys to define species' niches and construct species-distribution models related to prognostic shifts in OA properties. Future CPR studies should add OA sensor measurements to the observational effort.

Large-scale OA gradients in the open ocean represent transition zones where enhanced biodiversity potentially harbors important genetic variability. However, many taxa are difficult to distinguish and identify to the species level, and most can only be identified to higher taxonomic levels in their early life history stages (e.g., as eggs and larvae). Advances in new metagenomic technology (barcoding, eDNA, etc.) will allow for the evaluation of the relationships among community-level biological diversity and physical and chemical ocean parameters, in order to understand responses to OA and enable the establishment of linkages using molecular identification tools for rapid monitoring and assessment of climate change effects on pteropods and other planktonic species in the future (Stepien et al., 2019).

Research Objective 2.5: Research impacts on lower trophic levels in oligotrophic waters

Biological and biogeochemical studies on hydrographic surveys can delineate biological responses to OA gradients across biogeographic province boundaries in the open ocean (in coordination with *Pacific Islands Region Chapter 6 Research Objective 6.4*).

Action 2.5.1: Utilize Bongo and Continuous Plankton Recorder tows during OA cruises to determine the biological impacts of OA and other stressors on planktonic communities.

Action 2.5.2: Develop statistical tools for assessing the impacts of OA and other stressors on marine organisms.

Action 2.5.3: Develop biogeochemical and phylogenetic tools for assessing impacts of OA and other stressors on marine organisms.

Humpback whale fluke spotted off the northern California coast. Credit: Richard Feely/NOAA

Research Objective 2.6: Research impact of OA on highly migratory species

Migratory species, including fishes, squids, and marine mammals are dependent on some OA-sensitive species as food. Analyses of species compositions and their food chains *in situ* and in lab experiments will help predict OA effects (in coordination with *Pacific Islands Region Chapter 6 Research Objective 6.5*).

Action 2.6.1: Develop biogeochemical tools for assessing the impacts of OA and other stressors on higher-level taxonomic groups.

Human Dimensions in the Open Ocean Region

The impacts of OA on marine ecosystems in the open ocean will likely have negative effects on ecosystem services, marine resources, and the human communities that depend on them for their livelihoods, subsistence, and social and cultural continuity (Cooley & Doney, 2009; Cooley et al., 2012, 2016; Gattuso et al., 2015; Hoegh-Guldberg et al., 2017; Leong et al., 2019). A high priority in the open ocean is identifying and projecting the effects of OA on marine resource-reliant industries, local fisheries, and human communities, and developing ecosystem-based fisheries management systems that are driven by OA-informed environmental, ecological, and socioeconomic considerations.

Much of the focus of OA impacts are in coastal regions where humans directly rely on resources such as fisheries, and natural barriers such as reefs providing storm protection. However, open ocean forcing affects these coastal resources. For example, climate variability such as El Niño Southern Oscillation and large-scale extreme events such as the northeast Pacific marine heatwave of 2014-2016 have direct impacts on coastal resources and coral reefs (Di Lorenzo & Mantua, 2016; Kleypas et al., 2015; Peterson et al., 2017; Sanford et al., 2019). Improved global projections of OA combined with warming and sea level rise are also necessary for informing coastal zone managers and policymakers. The connections between open ocean events and the coastal zone must be better understood to project OA impacts.

Another critical open ocean process that could be impacted by OA is the biological pump (Passow & Carlson, 2012; Boyd et al., 2019). Additional research and model development are needed to understand how ocean warming and OA will affect the ability of the biological pump to sequester carbon, which is necessary for predicting future atmospheric CO_2 concentrations and the resulting carbon cycle changes.

An important objective to mitigating future OA impacts will be securing coordinated national and international investments to develop effective adaptation strategies and solutions for affected communities. Metrics of impact due to changes in open ocean forcing and processes will be required for decision-makers to understand how effective local adaptation strategies can be in the face of global ocean and climate change. These impacts must be effectively communicated to decision- makers and the public to describe potential OA impacts to environmental, biological, economic, and social systems. Open ocean researchers should pursue efforts to create visualization and educational products and outreach resources targeting diverse stakeholders to promote understanding and awareness of OA.

Research Objective 2.7: Assess direct and indirect effects of OA on communities

Coupling open ocean forcing, coastal environmental and ecological dynamics, and human-use sectors in ecosystem models will support assessment of OA impacts on marine resource-reliant industries and communities, including impacts to human well-being and ecosystem services (in coordination with *Pacific Islands Region Chapter 6 Research Objective 6.7*).

Action 2.7.1: Identify relationships among key social, cultural, and economic drivers to biophysical, fishery, and ecosystem parameters along the open ocean to coastal continuum to predict potential responses from future OA scenarios.

Action 2.7.2: Create regional economic impact and behavioral models for marine resource-reliant industries that include open ocean forcing to inform consideration of benefits and costs of alternative management strategies to mitigate impacts from OA.

Action 2.7.3: Develop management objectives related to human-use sectors, ecosystem services, and well-being, and derive indicators to monitor effectiveness of management strategies.

3. Alaska Region Acidification Research

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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-

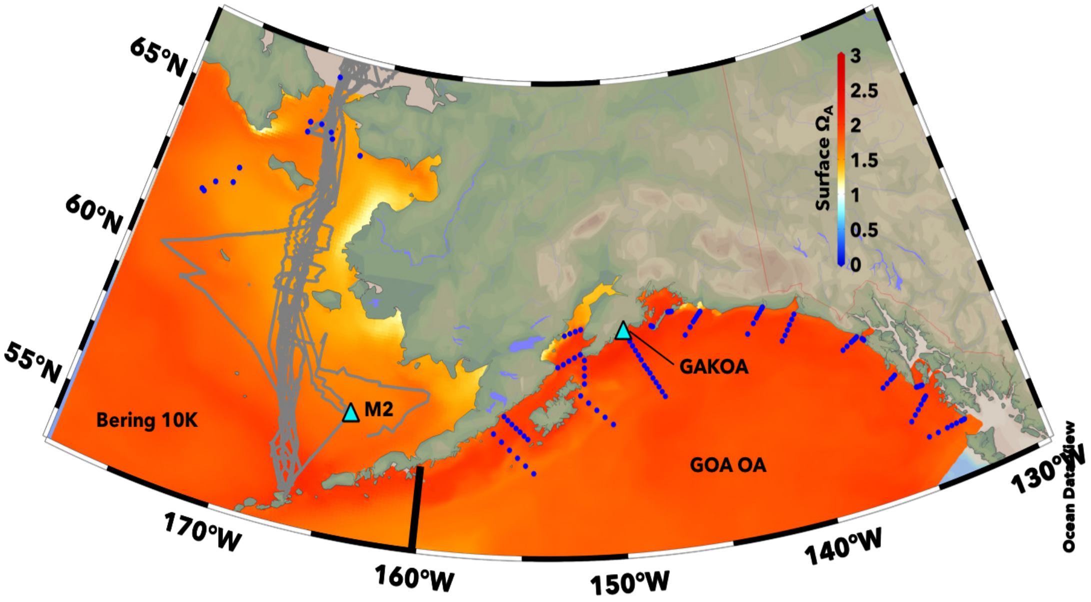


Figure 3.1. Ocean observing and forecasting system for the Gulf of Alaska and the Bering Sea between 2011 and 2019, as supported by the NOAA Ocean Acidification Program. Blue dots are discrete sampling stations occupied during 2015 and (projected) 2021. Blue triangles denote the location of two long-term moorings measuring sea-air exchange of $p\text{CO}_2$. 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.

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.

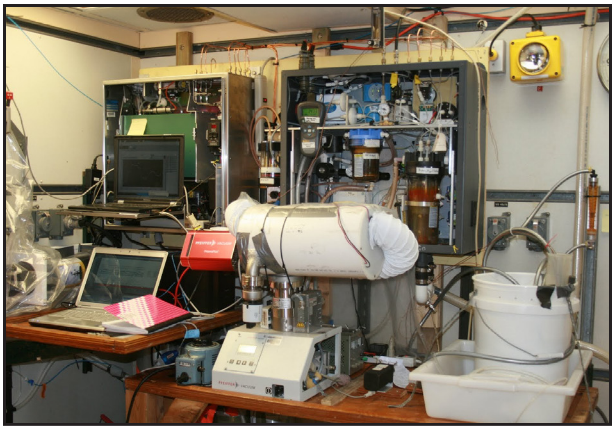
Research Objective 3.1: Characterize seasonal cycles of OA and regional vulnerabilities

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.

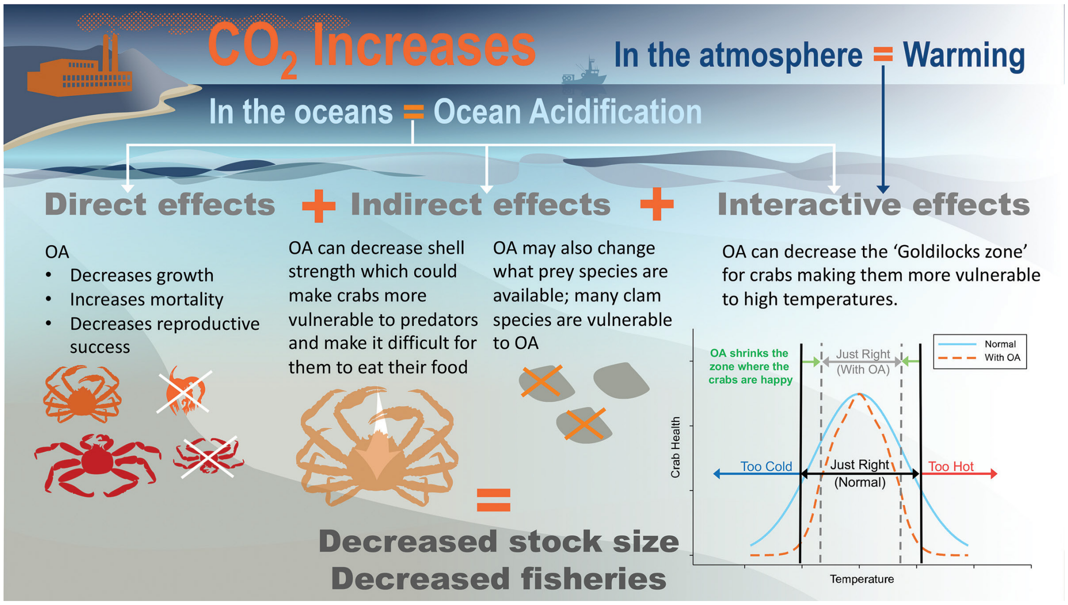
Biological Sensitivity in the Alaska Region

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



OA
- Decreases growth
- Increases mortality
- Decreases reproductive success

OA can decrease shell strength which could make crabs more vulnerable to predators and make it difficult for them to eat their food

OA may also change what prey species are available; many clam species are vulnerable to OA

OA can decrease the 'Goldilocks zone' for crabs making them more vulnerable to high temperatures.

Figure 3.2. Ocean acidification is expected to impact crab and other marine resources through direct effects of elevated CO_2 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.

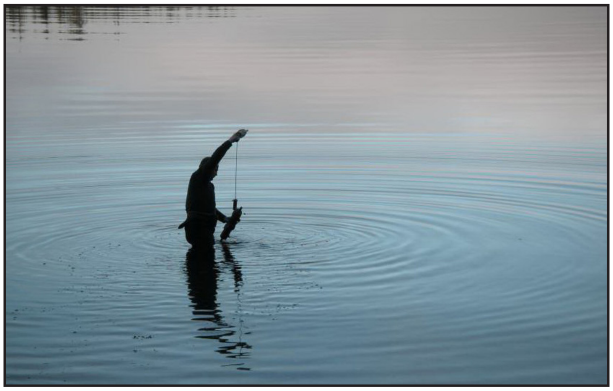
Human dimensions in the Alaska Region

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

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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**).

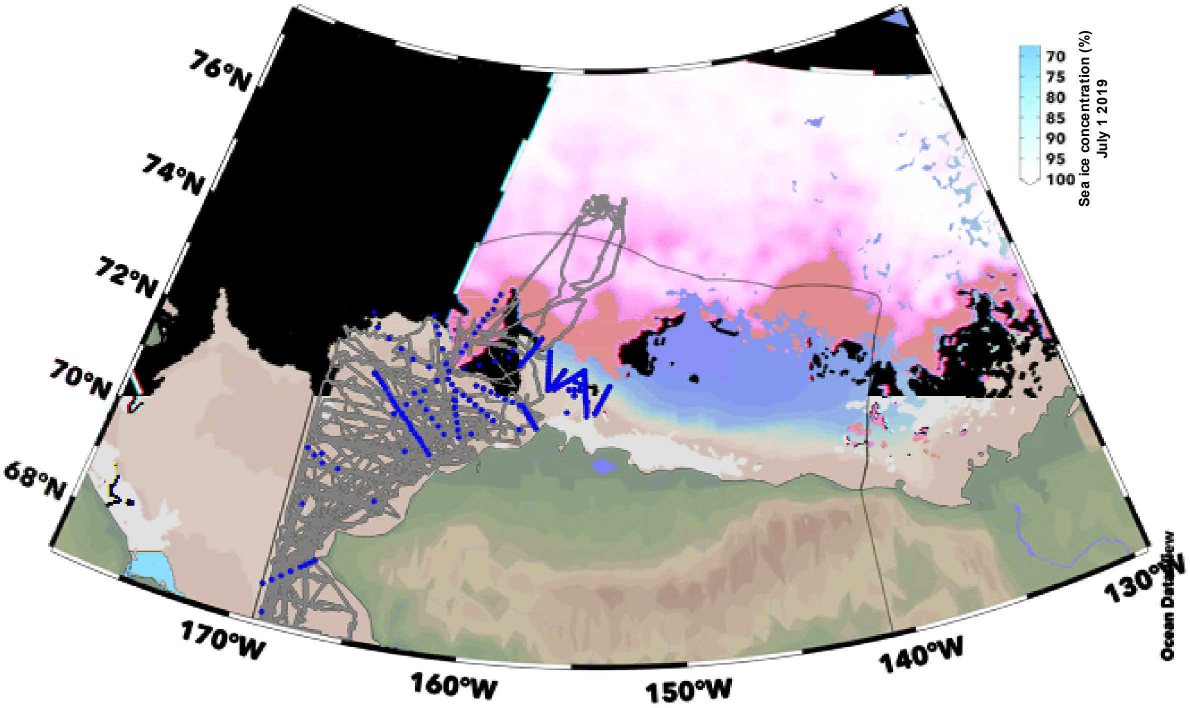

Figure 4.1. Ocean observing system for the Chukchi Sea between 2015 and 2020, as supported by the NOAA Ocean Acidification Program and Arctic Research Program. Shown here in blue dots are discrete sampling stations occupied during the Distributed Biological Observatory missions. Gray tracklines indicate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

5. West Coast Region Acidification Research

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Abstract

The West Coast Region includes the U.S. coastal waters off of Washington, Oregon, and California including the continental shelf and inland seas. These waters are influenced by adjacent regions and are collectively referred to as the California Current Large Marine Ecosystem (CCLME). This region is an eastern boundary current system marked by seasonal upwelling, which brings old, cold, and low-pH, carbon-rich subsurface waters to the ocean surface and drives significant regional pH and temperature variability. The CCLME is home to a highly productive ecosystem yielding economically and culturally significant fisheries including salmon and Dungeness crab. NOAA's West Coast Region research goals are to:

- Sustain and develop time-series that integrate carbonate chemistry and biological observations in habitats that are critical to commercially and ecologically important species, and use this knowledge to improve high-resolution regional models;
- Characterize species sensitivity to direct and indirect impacts of ocean acidification (OA) and evaluate the potential for species adaptation and acclimation; and
- Improve the understanding of the socioeconomic risk and vulnerability of fishing and coastal communities to OA in order to develop informed adaptation strategies.

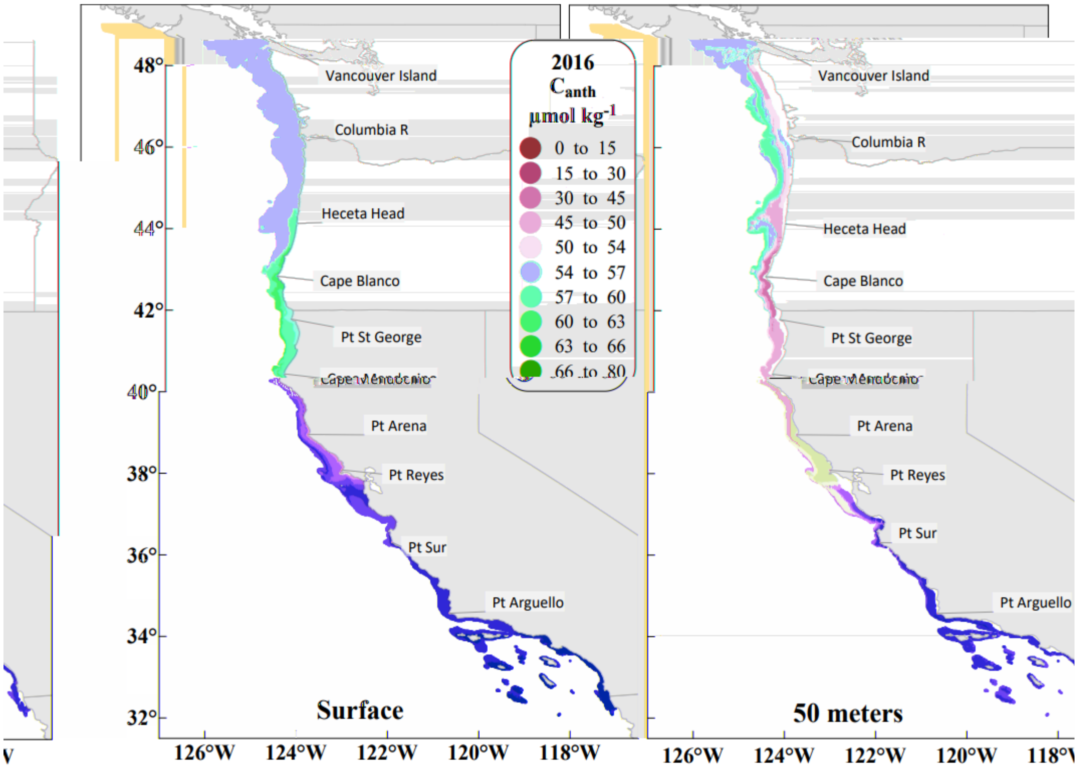


Figure 5.1. Distribution of anthropogenic carbon in surface and 50 m depth ocean waters in May-June 2016 based on the West Coast Ocean Acidification cruise. Credit: NOAA

Acidification in the West Coast Region

The North American Pacific coast from Vancouver Island to Baja California is a classic eastern boundary current upwelling region, termed the California Current Large Marine Ecosystem (CCLME) (Hickey, 1998; Chavez et al., 2017). In the CCLME, natural oceanographic processes combine with nutrient additions in some coastal areas and climate change-induced processes (i.e., enhanced upwelling); together these lead to a more rapid rate of acidification than in many other regions (Rykaczewski & Dunne, 2010; Turi et al., 2016; Carter et al., 2019a). This rapid acidification has raised concerns by people reliant on its productive living marine resources.

Seasonal winds drive a coastal upwelling circulation characterized by equatorward flow in the CCLME, with coastal jets, associated eddies, and fronts that extend offshore, particularly in the central CCLME. Climate-driven alterations in upwelling circulation result in changes in coastal acidification and spatial gradients in anthropogenic carbon (greater surface accumulation in the south than the north due to the fact that the upwelled waters more prevalent in the north do not reflect current atmospheric carbon dioxide (CO_2) concentrations, **Figure 5.1**; deeper penetration in the north), particularly with recently intensified coastal winds (Feely et al., 2016, 2018; García-Reyes et al., 2015; Jacox et al., 2014; Rykaczewski et al., 2015; Sydeman et al., 2014). Upwelling supplies deep water to the shelf, which is rich in dissolved inorganic carbon and nutrients, but oxygen-poor. OA and hypoxia are stressors that are often found together because low-oxygen and high-CO_2 conditions both result from microbial respiration of organic matter (Chan et al., 2017; Feely et al., 2016, 2018). Models project that 50% of shelf waters in the central CCLME will experience year-long undersaturation by 2050 (Gruber et al., 2012; Hauri et al., 2013; Turi et al., 2016). In addition to upwelling stress, the northern CCLME experiences strong freshwater influences, associated with large outflows from the Columbia and Fraser rivers, as well as numerous smaller mountainous rivers with more episodic discharge. This riverine input leads to both lower buffering capacity and nutrient loading in local waters.

Knowledge of marine species' OA sensitivities has substantially increased since the early recognition of the role of changing seawater carbonate chemistry in oyster hatchery production problems in the Pacific Northwest (Barton et al., 2012, 2015). Laboratory work has revealed that some West Coast species including Dungeness crabs (Miller et al., 2016), Coho salmon (Williams et al., 2019), krill (McLaskey et al., 2016), and pteropods (Busch et al., 2014) are sensitive to OA conditions. Field evidence on Dungeness crabs, pteropods, foraminifera, and copepods, important prey in food webs for finfish including salmon, supports these conclusions (Bednaršek et al., 2014, 2016, 2017a,b, 2018, 2019, 2020; Bednaršek & Ohman, 2015; Feely et al., 2016; Osborne et al., 2016, 2019; Engström-Öst et al., 2019; **Figure 5.2**). West Coast-focused meta-analyses and synthesis work suggest that sensitivity research on a broader range of species and ways to infer both sensitivity among related species and species risk are needed to effectively project OA impacts on marine ecosystems (Busch & McElhany, 2016, 2017; Davis et al., 2017; Hodgson et al., 2016; Jones et al., 2018; Bednaršek et al., 2019).

The West Coast has many ecologically, economically, and culturally significant species with important life stages that inhabit depths below the productive, sunlit surface. While the surface ocean contains the highest anthropogenic CO_2 concentration from air-sea exchange processes, the subsurface environment is subject to considerably greater stress due to the combined effects of natural and anthropogenic CO_2 sources (**Figure 5.1**; Feely et al., 2008, 2010, 2012, 2016, 2018; Bednaršek et al., 2014; Siedlecki et al., 2016). Many regionally important species, like Dungeness crab, which generated $3.6 billion in commercial landings from 1950 to 2017, occupy a variety of habitats throughout their life cycles from the coast to the shelf and from benthic to surface waters. There are five National Marine Sanctuaries and numerous Essential Fish Habitats along the West Coast, which protect water quality and benthic habitats and fishes. Better characterization of pelagic and benthic habitat conditions across these continental shelf habitats is critical to inform fisheries and sanctuaries managers about OA exposure.

Output from OA scenarios in ecosystem models of the West Coast suggests more resilience to OA than might be inferred from sensitivity studies, although notable potential impacts are projected for Dungeness crab and the human communities economically and culturally dependent on its fishery (Ainsworth

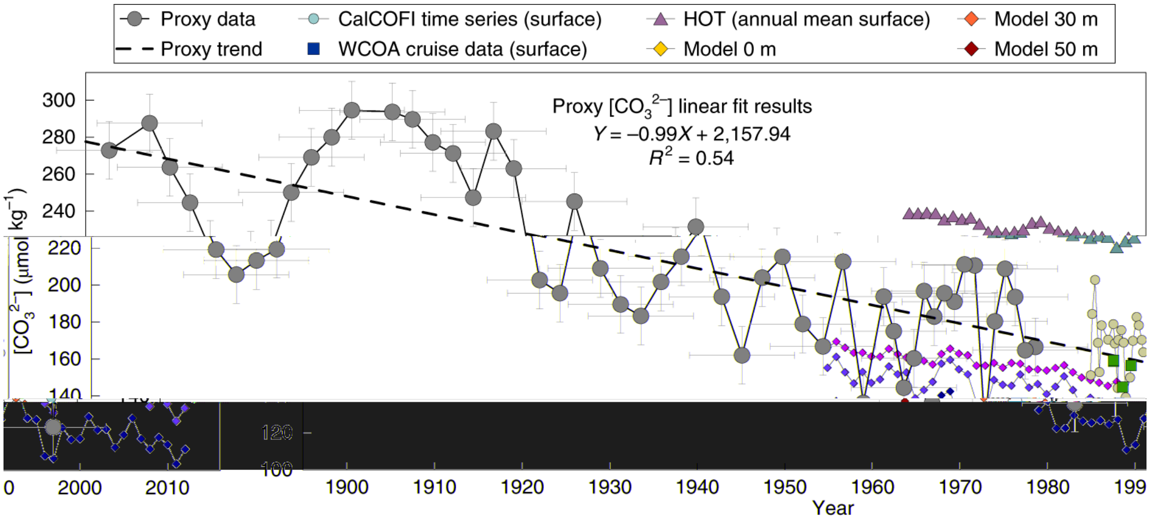


Figure 5.2. A twentieth-century proxy reconstruction of carbonate ion concentration ($[CO_3^{2-}]$) for the California Current Ecosystem (Santa Barbara Basin, CA). Proxy $[CO_3^{2-}]$ values are based on fossil planktonic foraminifera shell thickness and reveal an estimated 35% decrease in $[CO_3^{2-}]$ over the 20th century. The proxy-based $[CO_3^{2-}]$ compared to available *in situ* surface measurements and published hindcast biogeochemical model simulations and are in excellent agreement with the forward-projected trend, even if datasets do not temporally overlap. Modified from Osborne et al. (2019)

et al., 2011; Busch et al., 2013, 2014; Marshall et al., 2017; Hodgson et al., 2018). Increasingly, consideration of OA together with other stressors that co-occur with it in the region, such as hypoxia and warming, is seen as crucial for characterizing and understanding OA's influence on living marine resources in a way that is ecologically relevant to the CCLME (Bednaršek et al., 2018, 2019, 2020; Trigg et al., 2019; Reum et al., 2014, 2016).

Environmental Change in the West Coast Region

Since the publication of the 2010 NOAA Ocean, Coastal, and Great Lakes Acidification Research Plan, NOAA has supported a range of OA observations and monitoring efforts on existing and NOAA-developed platforms, which include moorings, cruises, ships of opportunity, gliders, and new autonomous platforms (**Figure 5.3**). Research cruises provide the highest quality physical and chemical measurements, particularly for subsurface observations, and yield both good estimates of cumulative OA exposure and anthropogenic CO_2 content; thus, cruises, including both coastal and open ocean repeat-hydrography cruises (GO-SHIP, Sloyan et al., 2019a), remain a strong research priority for OA (Carter et al., 2019a).

A researcher using an experimental system to study acidification impacts on marine species in the NOAA Mukilteo Research Station in Washington. Credit: Benjamin Drummond/bdsjs.com

On the other hand, sensors on time-series moorings or autonomous platforms can provide observations with high spatial and/or temporal resolution that capture the full range of carbonate chemistry variability (Carter et al., 2019b). Some sensors are mature and in regular use (e.g., Sutton et al., 2014a; Wanninkhof et al., 2019), while important work continues on improving and evaluating newer *in situ* sensors with respect to accuracy, precision, and data-processing methods for operational deployments (e.g., Bresnahan et al., 2014; Williams et al., 2017; Riser et al., 2018).

NOAA and academic scientists have partnered with shellfish growers on the West Coast to monitor OA conditions at hatcheries and grow-out sites via shore-based inorganic carbon systems and sensors in development, with real-time data accessibility (Barton et al., 2012, 2015). This has led to our ability to understand OA dynamics along a gradient from nearshore to offshore (Alin et al., 2015). West Coast environments experience a large range of marine environmental conditions over both space and time with respect to carbonate chemistry and benefit from excellent access to laboratory and ship facilities. Through partnership with the U.S. IOOS regional associations (NANOOS, CeNCOOS, and SCCOOS), OA sensors deployed on existing IOOS assets have increased West Coast observation capability substantially. National Ecosystem Research Reserves measure pH in estuaries throughout the region. In addition, National Marine Sanctuaries and areas designated as Essential Fish Habitat by NMFS provide key testbeds for ongoing assessment of the consistency, uncertainty, and reliability of new platforms and sensors, particularly those that provide insight into critical subsurface habitats and conditions. For instance, the benthic nearshore time-series observations from the Olympic Coast National Marine Sanctuary have been used with empirical relationships to calculate OA variables. Collectively, these nearshore observations show much more dynamic conditions than offshore, though seasonal upwelling is still the dominant signal. Nearshore data streams are critical for understanding impacts on coastal species and can benefit from partner platforms such as aquariums, industry, and other shoreside facilities with marine resource interests.

Economically, ecologically, and culturally important West Coast species such as Dungeness crab, geoduck, other harvested bivalves, salmon, and groundfish use a variety of different habitats throughout

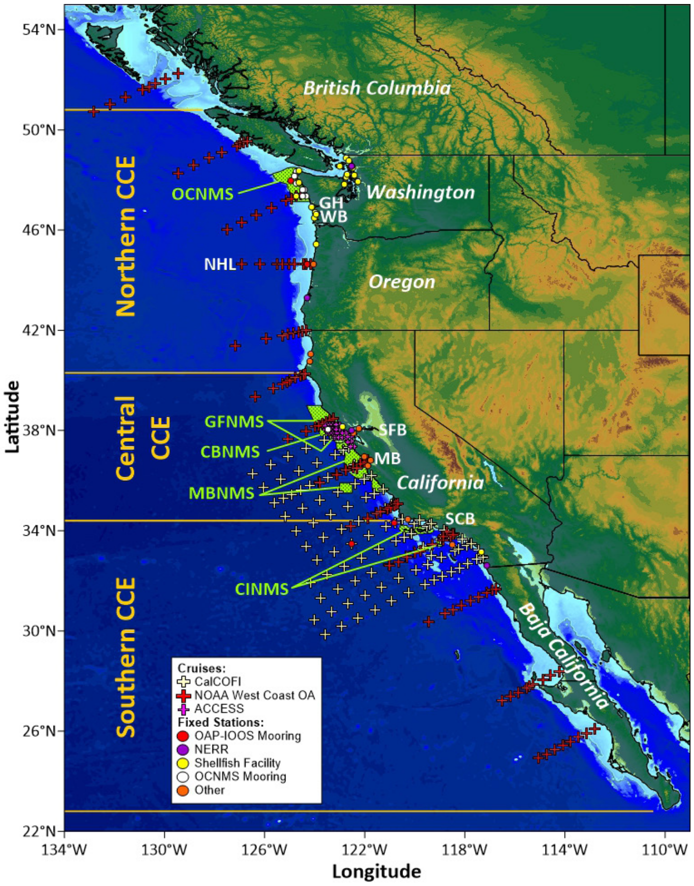


Figure 5.3. Map of the California Current Large Marine Ecosystem (CCLME) with National Marine Sanctuary boundaries (lime green) and long-term North American Pacific coast, NOAA-supported OA sampling platforms, as indicated in the legend. Abbreviations include: OCNMS = Olympic Coast National Marine Sanctuary, GH = Gray's Harbor, WB = Willapa Bay, NHL = Newport Hydrographic Line, OAP-IOOS = NOAA Ocean Acidification Program – Integrated Ocean Observing System, NERR = National Estuarine Research Reserve, GFNMS = Gulf of the Farallones National Marine Sanctuary, CBNMS = Cordell Bank National Marine Sanctuary, MBNMS = Monterey Bay National Marine Sanctuary, SFB = San Francisco Bay, MB = Monterey Bay, CINMS = Channel Islands National Marine Sanctuary, SCB = Southern California Bight. Credit: Dana Greeley/NOAA

the water column and from the shoreline to the shelf-break, making OA monitoring in a diversity of habitats critical for fulfilling NOAA's OA-monitoring-related responsibilities. Different species are sensitive to different aspects of the carbonate system (i.e., $p\text{CO}_2$, pH, aragonite or calcite saturation; i.e., Waldbusser et al., 2015); thus, full delineation of the carbonate system is important at all locations. Such measurements have enabled shellfish growers to adjust culturing practices successfully (Barton et al., 2015). Characterizing the multiple aspects of change in the ocean environment, including increasing anthropogenic CO_2 concentrations, decreasing oxygen, warming, and changing nutrient availability, is required to tease out which changes drive marine ecosystem response (Feely et al., 2016, 2018; Pacella et al., 2018; Evans et al., 2019). Integrating physical and chemical time-series with time-series of species and ecosystem indicators is a priority for oceanographic research globally (Sloyan et al., 2019b) and for the West Coast specifically. In this region, the unusual environmental conditions that have occurred over the past decade have caused unprecedented harmful algal blooms (HABs) and mass mortality events of sea stars, seabirds, and kelp (Miner et al., 2018; Gibble et al., 2018; Harvell et al., 2019; Hohman et al., 2019). Some West Coast sanctuaries and regions, such as the Southern California Bight, have developed climate action plans, identified indicator species and habitats, and detailed monitoring strategies (Duncan et al., 2014; Hutto, 2016).

To provide decision support at relevant timescales for managers of West Coast species and protected areas, improved models are needed that provide skillful estimates of environmental conditions at daily to decadal timescales and beyond. Predictability of these model systems depends on the right resolution for habitats of interest, resolving processes with the appropriate skill and understanding, and predicting processes on the correct timescale. This underscores the need to sustain OA observations across spatial gradients from nearshore to offshore, in order to verify and provide input to models. On-going model development and evaluation are needed to improve parameterizations of important processes in simulations, including short-term and seasonal forecasts. Mechanisms driving predictability of carbon variables on various timescales require further investigation, especially on decadal timescales (Turi et al. 2016; Li & Ilyina, 2018; Li et al., 2019), to provide better forecasts and predictions. These mechanisms will require a more complete understanding of the processes responsible for communication across interfaces on these timescales within the upwelling regime – between the CCLME and the North Pacific Gyre, the shelf and offshore, and the estuaries and the shelf. These processes contribute to amplification of the OA signal within this system, but the degree to which they contribute inter-annual to decadal variability is not well constrained at present. West Coast models now are skillful enough that they can attribute coastal and estuarine acidification to the relevant driver, be it inputs from air-sea exchange, and/or nutrient inputs (e.g., Puget Sound, San Francisco Bay, southern California), rivers (Washington to northern California), changing ocean circulation (e.g., upwelling), and/or biological process rates (e.g., Halle & Largier, 2011). Live Ocean and J-SCOPE, two newer modeling systems in the Pacific Northwest, now provide forecasts and projections of ocean conditions relevant for marine resources, such as sardine and Dungeness Crab (Kaplan et al., 2016; Siedlecki et al., 2016). Other decision points that model simulations can support include timing of fishery openings relative to forecasted OA or hypoxia conditions and field out-planting of shellfish within optimal temperature and carbonate chemistry windows.

Research Objective 5.1: Improve characterization of OA parameters in subsurface environments that are critical habitats to commercially and ecologically important species

Better characterization of surface and subsurface carbonate chemistry conditions will improve understanding of the risk of species and ecosystems to OA and parameterization of models used to hindcast, describe current, and forecast conditions.

Action 5.1.1: Ensure that conditions and rates of environmental change of OA and interacting stressors—particularly temperature, carbon chemistry, oxygen, nutrients, and HABs—are assessed via co-located observations in critical habitats for key species at vulnerable life stages, as well as for their food resources.

Action 5.1.2**:** Enhance moorings and profiling platforms to include additional chemical and biological sensors for subsurface waters to delineate rates of change of critical parameters.

Action 5.1.3: Continue to quantify anthropogenic CO_2 concentrations through coastal and open ocean cruises, which collect the data needed to attribute carbonate chemistry change to anthropogenic acidification versus contributions from other processes.

Action 5.1.4: Provide measured and calculated OA products necessary for validation of underlying physical and biogeochemical processes in coupled physical-biogeochemical coastal models of acidification and model output.

Research Objective 5.2: Enhance understanding of the relationships between biological systems and chemical conditions, including effective indicators of change for various habitats

Tracking biological response to OA, other long-term secular ocean changes, unusual environmental events including marine heatwaves, HABs, and mass mortality events underlies the reason for developing integrated monitoring efforts, which can help tease out environmental drivers and identify cause and effect of unusual events.

Action 5.2.1: Incorporate biological observations into physical and chemical time-series (e.g., research cruises, long-term monitoring at sentinel sites such as National Marine Sanctuaries, shellfish hatcheries, underway sampling on ships, autonomous platforms).

Action 5.2.2: Develop procedures to utilize pteropods and other species as West Coast-specific indicators of species and ecosystem status and change across different habitats.

Research Objective 5.3: Advance analytical tools that can better describe ocean conditions in the past, present, and future

Model development is critical to providing skillful estimates of environmental conditions at daily to decadal timescales and beyond and at spatial scales that vary from regional to local. Development of past-to-future, high-resolution West Coast ocean models should continue in order to provide decision support at relevant timescales for managers of West Coast sanctuaries, Essential Fish Habitat, deep-sea coral and sponge habitats, and shellfish and finfish species.

Action 5.3.1: Develop models that can be validated, parameterized, and evaluated by observational data (e.g., moored time-series, nearshore stations) and that include chemical and biological rates key for understanding the progression of OA.

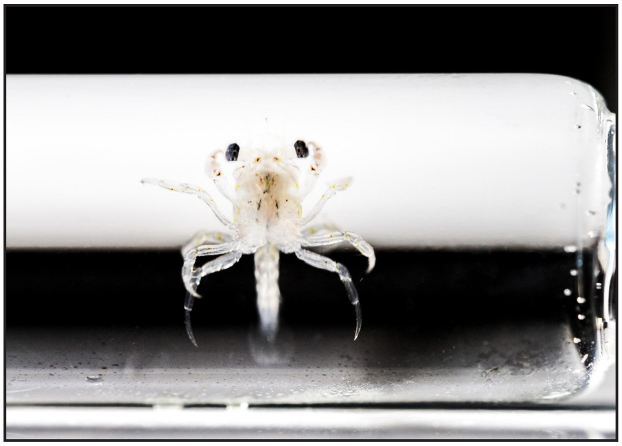
Action 5.3.2: Develop short-term and seasonal forecasts and synthesis products that can support annual industry, tribal, and management decision points and decadal predictions that support planning, policy, and adaptation among West Coast states, tribes, and stakeholders.

Action 5.3.3: Better utilize West Coast satellite observations and satellite-derived products to complement and provide independent estimates of spatially resolved current and upcoming ocean conditions from surface to benthic habitats.

Biological Sensitivity in the West Coast Region

West Coast ecosystems are highly productive and have economic and cultural value. The marine heatwave and El Niño events of 2014-2016 indicated how sensitive West Coast ecosystems and their marine resources are to the kinds of environmental conditions that are expected to become more frequent and intense in the future. The goal of this work is to project long-term ecological effects of OA to better understand the consequences of carbon emissions, provide managers the information needed to anticipate changes in marine resources, and inform potential mitigation and adaptation options.

Studies that identify the sensitivities of ecologically and socioeconomically important species yield information useful for management of wild capture fisheries, ecosystems, and aquaculture now and in the future. Species sensitivity studies can be designed to build understanding of physiological mechanisms that underlie species' responses to OA; help characterize species vulnerability; and estimate OA risks to people and community well-being. Such information underpins modeling efforts that aim to project species response to OA progression and is important for extrapolating patterns of sensitivity in species not subject to experimentation or observation. Targeted output from experiments should include functional relationships 1) across a range of pH, $p\mathrm{CO}_2$, or aragonite or calcite saturation state values, which can be used to identify response thresholds, and 2) with co-occurring environmental stressors projected to change with climate change, including temperature, oxygen concentration, and salinity. The experimental facilities at the Northwest Fisheries Science Center (NWFSC) have built in a multi-stressor (OA, dissolved oxygen, and temperature) and diurnal variability approach, and the new Mukilteo facility now under design will improve on those capabilities.



Dungeness crab megalops, a larval stage. Credit: Benjamin Drummond/bdsjs.com

The West Coast is exposed to variability in carbonate chemistry conditions over both space and time and can be used as a natural laboratory. Recently, OA events have co-occurred with marine heatwaves, hypoxic events, and HABs, exposing organisms to interactive effects of multiple stressors. Collection and analysis of field samples having defined chemical exposures, or conducting novel *in situ* experiments can inform understanding of the implications of OA under field conditions, with duration of exposure under acidified conditions longer than can usually be accomplished in the lab. In addition, experimentally derived thresholds related to species sensitivity can be tested in the field to improve the interpretation of species vulnerability in coastal environments.

To date, we have not yet been able to directly attribute population changes from existing time-series to OA, potentially due to the lack of available paired chemical and biological measurements (McElhany, 2016). However, physiological and organismal responses in field samples correlate with anthropogenic CO_2 content (Bednaršek et al., 2014, 2017a, 2020; Feely et al., 2016). As OA and co-stressors progressively increase, species tolerance thresholds will continue to be crossed, which will precipitate ecological change. Biological time-series collections, sample preservation and archival, and analyses are needed now to enable the detection and attribution of change; on-going West Coast time-series should be maintained, enhanced, and examined. Monitoring should focus on 'indicator species', selected by careful consideration of carbonate chemistry sensitivity, cost of observation, availability of existing data, likely changes in habitat conditions, ecological or economic importance, etc. Two candidate indicator taxa include foraminifera and pteropods, the latter of which is already used as indicator of OA in the Puget Sound and Southern California Bight regions.

A potential tool for defining how the natural environment may be becoming stressful to marine life is to develop habitat suitability indices (HSIs), which provide depth- and time-integrated metrics of species exposure to challenging environmental conditions, ideally based on rigorous laboratory experiments. These HSIs use sensitivity information developed in combination with the modeling efforts to give managers advance information about the likely condition or survival of marine species. It is critical to develop integrated ecosystem metrics like HSIs in partnership with states, tribes, industry, and other organizations to reflect environmental exposure of key species to multiple stressors relevant to forecast and decision-maker timescales. HSIs also provide valuable information for food web and ecosystem modeling (*Action 5.6.2*) and help guide efforts to detect biological effects of OA in the field (*Action 5.6.3*). HSI metrics need to be testable with observations and connected to monitoring activities. HSIs do not, in themselves, translate into species impact but rather serve as an indication of potential exposure.

Research Objective 5.4: Understand species sensitivity to OA and characterize underlying mechanisms

Species sensitivity studies yield information that underpins our understanding of the potential impacts of OA on human and natural systems.

Action 5.4.1: Conduct laboratory sensitivity studies on species harvested in federal, state, and tribal fisheries along the West Coast and the prey species that support them.

Action 5.4.2: Develop and implement methods to generate data on the mechanisms driving species sensitivity, including acid-base balance, 'omics approaches, and neural and behavioral functioning to elucidate sub-lethal effects of OA conditions and possible adaptation.

Action 5.4.3: Assess how knowledge of sensitivity based on laboratory studies translates to expressions of sensitivity to different carbonate chemistry conditions and multiple stressors in the field.

Research Objective 5.5: Investigate the potential for species to acclimate and/or adapt to OA

Studies that target information on species acclimation and acclimatization (i.e., recovery of function by individuals with prolonged exposure) or adaptation (i.e., genetic and epigenetic changes within a population or across populations) make possible long-term predictions for key ecologically and socioeconomically important species.

Action 5.5.1: Conduct multi-generational, complete life-cycle laboratory studies to characterize sensitivity to OA.

Action 5.5.2: Assess how OA sensitivity varies within and among individuals, strains, and populations of a species in field and aquaculture studies to improve understanding of intra- and inter-specific variance, which has enormous implications for understanding how to manage marine resources for OA

Action 5.5.3: Employ molecular techniques to better understand the influence of OA on individuals and populations.

Research Objective 5.6: Enable the detection and attribution of direct and indirect impacts of OA on managed species and ecosystems

While evidence from laboratory experiments indicates that many marine species are sensitive to OA conditions, limited understanding of how this sensitivity will influence populations or their distributions in the wild or alter food webs and ecosystems creates a critical gap in current research efforts and for sound resource management under changing ocean conditions.

Action 5.6.1: Develop Habitat Suitability Indices, which provide depth- and time-integrated metrics of species exposure to challenging environmental conditions and can be integrated into forecasts and predictions.

Action 5.6.2: Model species, food web, and ecosystem responses to OA to understand the consequences of OA and the success of management strategies for sustainable harvests and conservation. Intensive numerical models can join data and tools from various scientific disciplines in ways that conceptual models cannot.

Action 5.6.3: Conduct biological monitoring and data analysis at robust enough levels to detect species or ecosystem change attributable to OA, and specifically to anthropogenic carbon uptake.

Human Dimensions in the West Coast Region

The ocean, coasts, and estuaries of the CCLME hold vast economic, social, and cultural importance for more than 1,100 coastal and fishing communities, including tribes and indigenous communities, and other diverse populations in rural, suburban, and urban areas. Through fisheries landings data, and other data sources such as the U.S. Census, NOAA has developed some knowledge about commercial and recreational fishing activities, reliance on fishing and aquaculture, and other social and economic conditions linking people to marine systems (Harvey et al., 2018; ONMS, 2019). However, while it is generally acknowledged that healthy and productive marine ecosystems support human communities, the mechanisms that link marine species and habitats with the full array of human dimensions (e.g., livelihoods, nutritional needs, cultural heritage, and recreation benefits for coastal populations) are not well understood (Breslow et al., 2016; Kittinger et al., 2012). In addition, critical gaps exist in the quality, frequency, topical, and geographic breadth of available information. Underdeveloped conceptual models describing the relationships between various fishing and coastal communities and marine ecosystems, as well as the lack of sufficient and appropriate data to assess socioeconomic changes, create challenges to evaluating OA vulnerability of people in different places who have varied dependence on marine systems. Hence, to support decision-making at local to regional scales throughout the West Coast, there is a need to synthesize and collect new socioeconomic data in order to develop models and other tools that may be used to estimate the socioeconomic impacts of OA in the region. Improved understanding of OA risks to sociocultural and economic well-being of fishing and coastal communities are priorities for NOAA social science on the West Coast (NOAA Fisheries, 2016, 2019a).

Dungeness crab support an economically important West Coast fishery. Laboratory, field, and modeling studies suggest Dungeness crabs are negatively affected by acidified conditions. Credit: Benjamin Drummond/bdsjs.com

Improved knowledge of the vulnerabilities of socioeconomic well-being to OA, and how these vary across populations, is critical to understand and develop strategies for mitigation and adaptation. A science-based framework to support planning, policy, and responses to OA by West Coast states, tribes, and stakeholders requires deeper knowledge of adaptive capacity. For example, how do community and fisheries characteristics (e.g., labor dynamics, social services, vessel mobility, species allocations, etc.) and perceptions of OA risks shape their response strategies? Research in support of adaptation depends on information about institutional structures and policy contexts (e.g., port infrastructure and fisheries permitting systems) that either help fisheries or communities perform well in the face of change or create barriers and challenges to their adaptation. Such focus on institutional and policy contexts creates the foundation for simulating scenarios and identifying alternative management actions, including those actions expected to generate benefits to communities and increase their adaptive capacity (Aguilera et al., 2015; Evans et al., 2013). Providing decision-relevant information to managers and industry, including developing technical tools for evaluating the socioeconomic consequences of potential management actions related to OA, is critical to effective management (**Figure 5.4**). In many cases, actions taken in response to OA will create synergistic benefits for a multitude of changes facing communities. The West Coast constitutes a dynamic social-ecological system with multiple and cumulative stressors arising from changes in the ocean such as temperature, OA, hypoxia, and HABs coupled with disruptions in conditions of fishing and coastal communities such as market prices, fishing access, labor shortages, and demographic changes (Bennett et al., 2016). More comprehensive and foundational human dimensions research can help decision-makers evaluate multiple objectives and outcomes (e.g., ecological, social, and economic benefits) and model future projections and uncertainties of the social-ecological impacts of ocean change in order to maintain thriving coastal communities and economies.

Research Objective 5.7: Improve understanding of the risks to social, cultural, and economic well-being of fishing and coastal communities that are dependent on OA-sensitive species, and the associated social and economic drivers of OA vulnerability

Human vulnerability to OA can be direct or indirect through impacts to important species and ecosystems, and compounded by other (non-OA) social and ecological stressors that human communities may face. Communities and decision-makers require better information about social-ecological relationships and mechanisms of impact in order to anticipate and understand OA risks to people.

Action 5.7.1: Collect new information (e.g., through the use of surveys and interviews) and synthesize existing information (e.g., commercial and recreational fisheries data, fishing community profiles, and traditional and local knowledge) to better characterize the interactions of humans and environments and the importance of OA-sensitive species and ecosystems to people across scales.

Action 5.7.2: Develop new OA-relevant social-ecological conceptual models and use these coupled models to estimate the risks to humans and community well-being (e.g., cultural, livelihood, and health) and the distribution of risks across sectors and social and demographic factors.

Action 5.7.3: Improve models to 1) provide necessary decision support for estimating income and employment impacts of OA on commercial fisheries, aquaculture, and coastal tourism and 2) relate the economic value of recreational crab and other shellfish harvesting to estimated changes in biomass.

Action 5.7.4: Examine the synergistic, antagonistic, and cascading effects of multiple and cumulative stressors on human vulnerability to address critical gaps in our knowledge of how OA-impacts interact with other environmental and socioeconomic stressors that communities must contend with.

Research Objective 5.8: Improve understanding and communication of adaptation strategies of fishing and coastal communities

Improved knowledge and communication of how communities can reduce vulnerability, including the barriers and capacities for coping with and adapting to OA and cumulative stressors, are critical to developing policies, tools, and strategies for mitigating socioeconomic risks (*Objective 5.7*) and identifying management actions that may result in more resilient communities.

Action 5.8.1: Develop information about adaptive capacity, and specifically evaluate institutional structures and policy contexts that either help or hinder fisheries and communities in the face of change.

Action 5.8.2: Identify alternative management actions to improve resilience of communities and ecosystems under OA conditions, for example by identifying resource management actions that generate indirect and co-benefit flows to communities, reflect community priorities, and reduce potential negative consequences from management decisions to communities.

Action 5.8.3: Provide decision-relevant information to managers and industry, including developing technical tools for simulating scenarios and evaluating the socioeconomic tradeoffs of potential management actions related to OA.

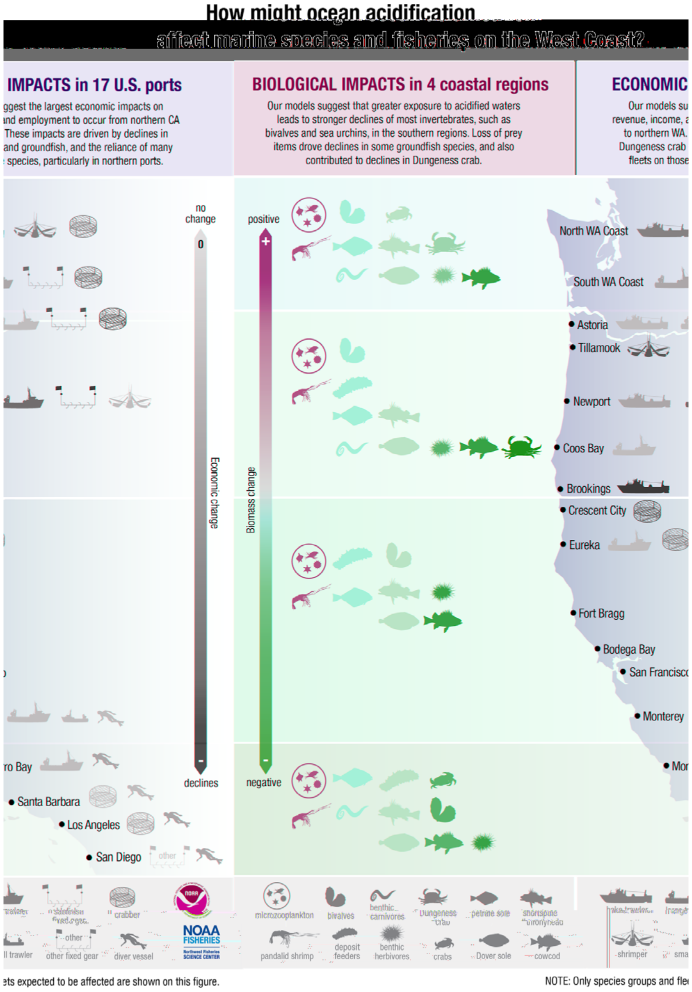


Figure 5.4. Infographic of model output on how OA could influence West Coast species and the economies of communities that participate in fisheries harvest. The infographic is based on work presented in Busch & McElhany (2016), Marshall et al. (2017), and Hodgson et al. (2018). Credit: Su Kim/NOAA

6. U.S. Pacific Islands Region Acidification Research

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Abstract

The Pacific Islands region includes the exclusive economic zones surrounding a diverse collection of islands and atolls — including the State of Hawaiʻi, the Territories of American Samoa and Guam, the Commonwealth of the Northern Marianas Islands, and the U.S. Pacific Remote Island Areas — that are widely scattered across the western and central Pacific Ocean and separated by many thousands of kilometers of vast pelagic waters. Much of the region is uninhabited and federally protected, and these ecosystems generally experience relatively low levels of local anthropogenic stress. However, the Pacific Islands are significantly impacted by global forcing, including basin-wide climate variability such as the El Niño Southern Oscillation and the Pacific Decadal Oscillation, and global climate change. This region is home to vibrant coral reef ecosystems, numerous threatened and endangered species, and economically- and culturally-significant fisheries supporting commercial industries and local communities. NOAA's Pacific Islands Region research goals are to:

- Maintain existing and develop new ocean acidification (OA) monitoring sites co-located with biological surveys of coral reef and broader marine ecosystems to improve understanding of OA progression and response to be used in real-time forecasts for risk assessment and decision making;
- Integrate physical, chemical, biological, and ecological data to assess ecosystem-wide direct and indirect impacts of OA, with an emphasis on key Pacific marine species; and
- Couple environmental, ecological, human-use, and non-use valuation models to assess OA impacts to human well-being and develop effective ecosystem-based management strategies and relevant science communication tools.

Figure 6.1. Map of archipelagic and island areas included under the U.S. Pacific Islands region and U.S. Exclusive Economic Zone boundaries.

Acidification in the U.S. Pacific Islands Region

The U.S. Pacific Islands region includes the exclusive economic zones surrounding the State of Hawaiʻi, the Territories of American Samoa and Guam, the Commonwealth of the Northern Marianas Islands, and the U.S. Pacific Remote Island Areas (**Figure 6.1**). The region encompasses biologically-diverse coral reef ecosystems; supports culturally- and economically-valuable commercial, subsistence, and recreational fisheries; and is home to numerous threatened and endangered species. The rich diversity and abundance of marine life and associated ecosystem services are vital for the health, culture, coastal protection, and economic viability of Pacific Island communities.

The Pacific Islands region covers an immense geographical area (5.82 million km^2) that spans dramatic gradients in oceanographic conditions, ranging from the relatively stable, oligotrophic North and South Pacific Subtropical Gyres to the dynamic upwelling zones of the central equatorial Pacific. Many of the islands and atolls in the Pacific Islands region are uninhabited, remote, and federally protected as National Wildlife Refuges and Marine National Monuments. As a result, these ecosystems experience relatively low levels of local anthropogenic stress, but are significantly impacted by global forcing, including climate variability and climate change (Polovina et al., 2016). Natural climate modes that exert influence in the region include the El Niño Southern Oscillation and the Pacific Decadal Oscillation, which drive large interannual and decadal shifts in ocean temperatures, winds, vertical mixing, equatorial upwelling strength, and seawater carbonate chemistry that influence the structure and function of coral reef and pelagic ecosystems (Brainard et al., 2018; Sutton et al., 2014b). Within the past several decades, the progressive acidification of open ocean surface waters has occurred in concert with rising atmospheric and surface seawater carbon dioxide (CO_2) concentrations. The 30-year Hawai'i Ocean Time-series has documented significant decreasing trends in surface seawater pH of 0.0016-0.0019 yr^{-1} in the North Pacific Subtropical Gyre (Bates et al., 2014a; Dore et al., 2009; **Figure 6.2**), and pH has declined 0.0018-0.0026 yr^{-1} in the central equatorial Pacific between 1998 and 2011 (Sutton et al., 2014b).

Coral reefs form the structural foundation for most of the island ecosystems in the region and provide substantial ecosystem goods and services to local communities through fisheries, tourism, and coastal protection (Bishop et al., 2011; Brander & van Beukering, 2013; Moberg & Folke, 1999; Storlazzi

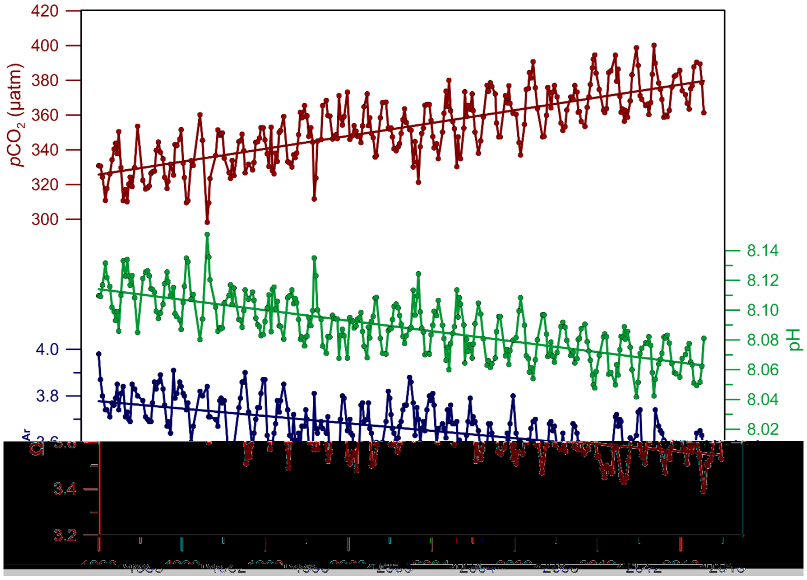


Figure 6.2. Time series of mean surface carbonate system parameters measured at Station ALOHA, 100 km north of O'ahu, Hawai'i (22.75 °N, 158 °W), 1988–2017. Partial pressure of carbon dioxide (pCO$_2$), pH (total scale), and aragonite saturation state (ΩAr) were calculated from dissolved inorganic carbon (DIC) and total alkalinity (TA). Linear regression fits are overlaid. Adapted from Dore et al. (2009)

et al., 2019). These ecosystems are among those expected to be most sensitive to OA (Hoegh-Guldberg et al., 2007; Kroeker et al., 2010). Over the past two decades, NOAA's comprehensive coral reef OA monitoring program has assessed spatial patterns and initiated monitoring of temporal trends in carbon system-related parameters and the biological and ecological components of coral reef ecosystems most likely affected by OA. NOAA data collected on U.S. Pacific coral reefs have: 1) established carbonate chemistry baselines around 38 islands (**Figure 6.3**); 2) documented spatial patterns and drivers of reef calcium carbonate accretion around 31 islands (**Figure 6.4**); 3) initiated assessments of reef bioerosion and dissolution at 13 islands; and 4) described cryptobiotia and microbial community diversity and abundance at 13 islands. The exposure to and impacts of OA within the vast pelagic and deep-sea ecosystems of the region remain much more poorly characterized.

Environmental Change in the U.S. Pacific Islands Region

Assessing spatial patterns and temporal trends in OA in coral reef and pelagic ecosystems is a high priority for NOAA's environmental monitoring in the Pacific Islands region. Since 2000, NOAA has conducted biennial or triennial coral reef monitoring at 38 Pacific Islands as part of the Pacific Reef Assessment and Monitoring Program (Pacific RAMP) and, since 2013, as part of the National Coral Reef Monitoring Program (NCRMP). In 2005, NOAA initiated monitoring of carbonate chemistry and key OA-related ecological indicators. These sampling efforts have established baseline means and spatial variability in nearshore environments across the Pacific Islands region (**Figure 6.3**). In the open ocean, the international observing collaboration established under the Global OA Observing Network (GOA-ON) has provided OA data integrated from repeat ship-based hydrography, volunteer observing ships, time-series stations, and moorings for the Pacific pelagic areas that support important commercial fisheries and highly-migratory protected species (see Open Ocean Region, Chapter 2). There is currently no comparable OA observing network for mesophotic and deep-sea coral reef environments.

Paired with spatially-broad, but temporally-sparse *in situ* sampling, moored autonomous OA sampling arrays provide near-continuous monitoring of chemical, physical, and meteorological conditions at sentinel sites. These high-resolution time series offer baseline data on diel, seasonal, and interannual variability in carbonate chemistry and can be used to detect long-term acidification trends. Sustained observations are especially important in nearshore coral reef environments, where secular trends in pH can be difficult to discern due to highly variable biogeochemical conditions (Sutton et al., 2019). In the Pacific Islands region, NOAA and the University of Hawaiʻi have maintained Moored Autonomous $p\mathrm{CO_2}$ (MA$p\mathrm{CO_2}$) buoys at several open ocean stations (WHOI Hawaiʻi Ocean Time-series, equatorial Tropical Moored Buoy Array) starting in 2004 and at four nearshore sites around Oʻahu, Hawaiʻi (Ala Wai, Kilo Nalu, Kaneʻohe Bay, CRIMP/CRIMP 2) starting in 2005. An additional buoy was deployed in Fagatele Bay, American Samoa in 2019.

Characterizing regional-scale OA patterns and trends across the broad oceanographic gradients of the Pacific Islands presents an enormous challenge. However, spatially-explicit, seasonal and annual carbonate chemistry datasets and OA forecasts (e.g., Gledhill et al., 2008) that project variability in OA exposure and identify possible hotspots or refugia can be useful management tools. Upscaling *in situ* observations, developing coupled hydrodynamic and biogeochemical models, and integrating remote sensing and model data to create hindcast and predictive OA spatial products are therefore high priority research needs for the Pacific Islands to support regional decision making and management strategy evaluation.

Research Objective 6.1: Continue monitoring and assessment of OA in coral reef ecosystems

Nearshore OA monitoring is essential for tracking temporal and spatial variability in carbonate chemistry and the progression of OA in highly sensitive coral reefs. When co-located with biological assessments and ecological surveys, long-term monitoring can offer an integrated ecosystem perspective of OA impacts on reef ecosystems and provide important baseline data for science-based management strategy.

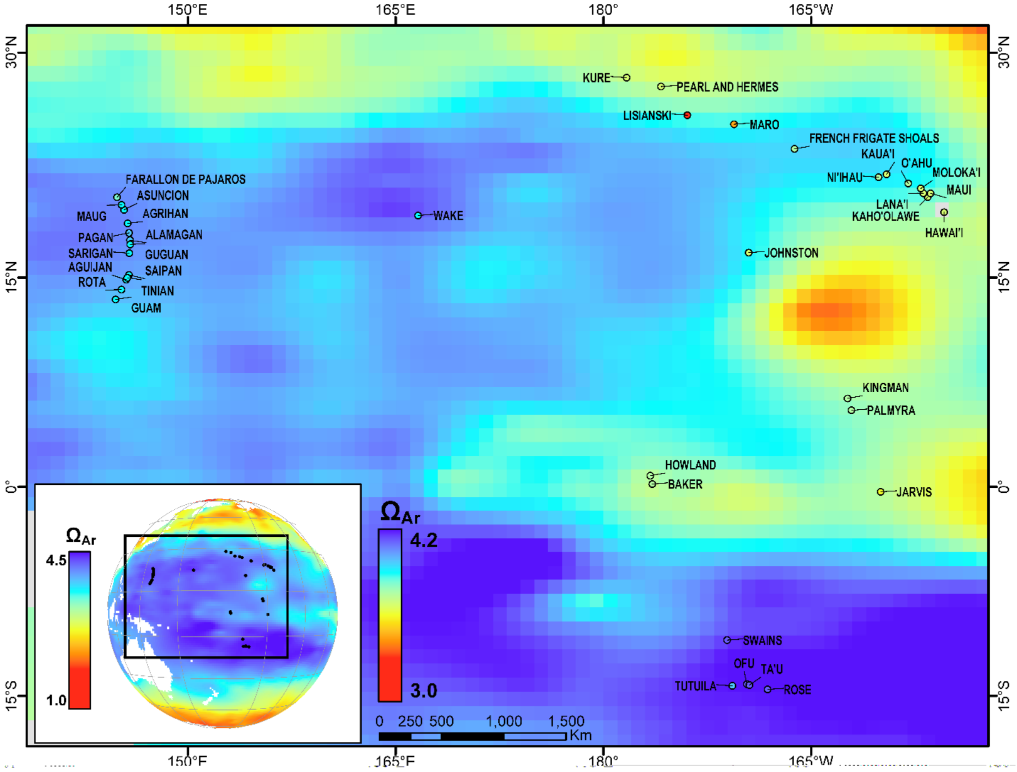


Figure 6.3. Climatological aragonite saturation state (ΩAr) for the Pacific Islands region from the GLobal Ocean Data Analysis Project (GLODAP) v2 (Lauvset et al., 2016). Islands that NOAA surveys as part of the Pacific Reef Assessment and Monitoring Program are shown as points, with shading corresponding to the average 2010-2017 in situ ΩAr (calculated from DIC and TA).

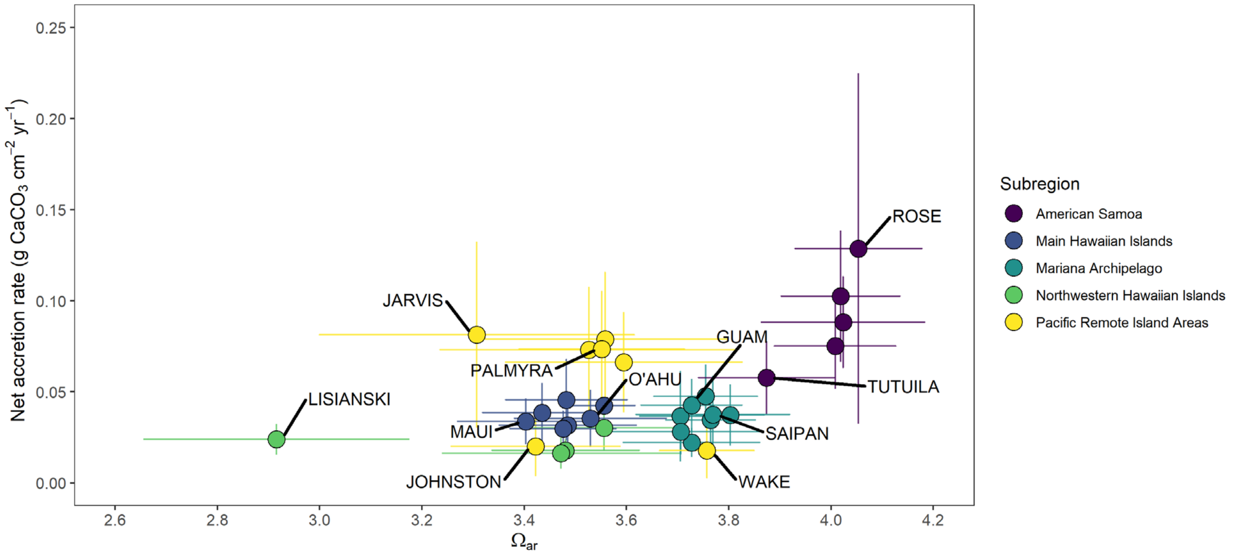


Figure 6.4. Mean (± one standard deviation) in situ ΩAr plotted against mean (± one standard deviation) net calcium carbonate accretion rates (measured from Calcification Accretion Units, CAUs) for 31 Pacific Islands from 2010 to 2017. Islands are colored by subregion, and islands of interest are labelled. See Vargas-Ángel et al. (2015) for additional information on CAUs.

***Action 6.1.1*:** Maintain carbonate chemistry water sampling in shallow coral reef environments and expand nearshore OA monitoring in collaboration with local partners to describe spatial patterns and longer-term temporal trends in OA across Pacific insular areas.

***Action 6.1.2*:** Conduct short-term, high-resolution instrument deployments to measure carbonate chemistry and other physical and biogeochemical parameters (e.g., temperature, salinity, water flow, light, and dissolved oxygen) and contextualize lower frequency observations (*Action 6.1.1*).

***Action 6.1.3*:** Maintain and expand moored autonomous buoy deployments at representative coral reef sites and offshore reference stations and increase coordination and collaboration with other international moored observing networks in the region to document high-resolution temporal variability in carbonate chemistry and capture multi-decadal OA trends.

Research Objective 6.2: Expand regional OA observing system to include pelagic and deep-sea environments

Establishing comprehensive OA monitoring programs in insular mesophotic, subphotic, and deep sea environments and expanding GOA-ON monitoring in U.S. Pacific Islands pelagic waters (in coordination with *Open Ocean Region Chapter 2, Research Objective 2.1*) will improve understanding of spatial and temporal carbonate chemistry variability and enable predictions of OA effects on pelagic and deep sea ecosystems.

***Action 6.2.1*:** Maintain and expand shipboard underway $p\mathrm{CO}_2$, dissolved inorganic carbon (DIC), total alkalinity (TA), and/or pH analyzers on NOAA ships to measure the two or more pelagic surface carbonate chemistry parameters needed to constrain full carbonate system chemistry along cruise tracks.

***Action 6.2.2*:** Deploy autonomous data collectors (e.g., Saildrones, gliders, biogeochemical-ARGO floats) equipped to measure at least two carbon parameters ($p\mathrm{CO}_2$, pH, TA, DIC) and temperature, salinity, and other physical and biogeochemical parameters at the ocean surface and along vertical depth profiles to augment or replace shipboard collections.

***Action 6.2.3*:** Collect subsurface oceanographic data and carbonate chemistry samples along vertical depth profiles to establish baseline carbonate chemistry levels and monitor OA in mesophotic, subphotic, and deep-sea ecosystems.

NOAA divers service instrumentation that monitors acidification near a coral reef at Hawai'i Island. Credit: Paul Cox/Hawai'i Marine Education and Research Center

Research Objective 6.3: Create real-time and forecast OA spatial products

Regional OA maps that leverage available physical and biogeochemical datasets and model output can provide predictive and actionable spatial products. These products can be used to assess OA risk, identify vulnerable species and communities, and advise decision making at spatial scales and time frames relevant to management planning and policy decisions (*in coordination with Open Ocean Region Chapter 2, Research Objectives 2.3 and 2.4*).

Action 6.3.1: Construct time-varying insular and pelagic maps of Pacific carbonate chemistry parameters (pCO₂, pH, Ω_{arag}) using remote-sensing data, assimilative models, and *in situ* sample data to provide regional-scale perspective on spatial patterns and temporal variability in OA.

Action 6.3.2: Couple hydrodynamic and biogeochemical models with climate models to improve understanding of carbonate chemistry dynamics and OA prediction in both pelagic and coastal environments and identify hotspots and refugia.

Biological Sensitivity in the U.S. Pacific Islands Region

Corals, crustose coralline algae, calcareous plankton, and other marine calcifiers are among the Pacific taxa most vulnerable to the direct impacts of OA. In general, OA effects on the growth, reproduction, and survival of many warm water coral reef organisms are now relatively well known (Kroeker et al., 2010). As part of Pacific RAMP and NCRMP monitoring, NOAA has collected data on calcium carbonate accretion and dissolution rates (Enochs et al., 2016a; Vargas-Ángel et al., 2015; **Figure 6.4**); coral calcification and bioerosion (DeCarlo et al., 2015); cryptobiota and microbial diversity; and benthic and fish diversity, density, size structure, and biomass within the U.S. Pacific Islands (Smith et al., 2016; Williams et al., 2015). Of the region's coral reefs, the deep-sea and mesophotic ecosystems exposed to shoaling aragonite saturation horizons may be among the first that OA impacts (Guinotte et al., 2006; Hoegh-Guldberg et al., 2017). However, the OA sensitivity of these communities remains poorly constrained.

The mechanism and severity of possible OA effects on protected and managed species are critical knowledge gaps in the Pacific Islands region. The major pelagic and coastal fisheries — including pelagic longline and purse seine fisheries for tunas and billfish and insular bottom fish, coral reef, and shellfish fisheries — may be susceptible to OA-driven reductions in species growth, fitness, and/or reproduction. Indirect OA impacts to these fisheries could include changes in habitat structure (e.g., changes to coral reef framework production), spawning grounds, food sources (e.g., through shifts in calcareous plankton community structure), or trophic interactions (Cooley & Doney, 2009; Nagelkerken & Connell, 2015). The critically endangered Hawaiian monk seal (*Neomonachus schauinslandi*), endangered hawksbill sea turtle (*Eretmochelys imbricata*), threatened green sea turtle (*Chelonia mydas*), and cetacean species may also be vulnerable to changes in essential feeding, breeding, and/or nesting habitats due to OA effects on seagrass beds and carbonate sand production (Hawkes et al., 2009; Price et al., 2011) and/or shifts in food availability and food web dynamics (Nagelkerken & Connell, 2015).

OA will likely alter the structure and function of marine ecosystems over the next several decades. Therefore, evaluations of climate drivers and ecosystem responses are needed to inform the efficacy of possible management actions (e.g., protecting resilient species and populations, setting fisheries annual catch limits, reducing other stressors that exacerbate OA impacts, direct interventions to reduce OA) at scales relevant to local communities. By driving local-scale interactions with a range of climate scenarios and management strategies, regional models can predict ecosystem dynamics and explicitly address tradeoffs across ocean use sectors. Recent Atlantis ecosystem model studies, including the Guam Atlantis model, have begun to incorporate OA drivers and species responses (Weijerman et al., 2015). However, refining these models will require additional data on downscaled OA projections and sensitivities of local taxa to OA (Marshall et al., 2017).

Big Momma, one of the largest coral heads in the world, can be found in the National Marine Sanctuary of American Samoa. Credit: NOAA

Research Objective 6.4: Assess direct OA impacts on key Pacific coral reef and pelagic species

Maintaining and expanding ecological monitoring, conducting laboratory perturbation experiments on understudied taxa, and synthesizing existing data to constrain the OA sensitivity of key species will improve our understanding of OA impacts on coral reef, mesophotic, deep-sea, and pelagic ecosystems (in coordination with *Open Ocean Region Chapter 5, Research Objective 2.5*).

Action 6.4.1**:** Assess calcium carbonate accretion and dissolution on coral reefs and deep-sea coral habitats across latitudinal and depth gradients, paired with long-term monitoring of benthic and fish communities, to document the impacts of OA and other stressors on coral reef communities, describe resilience potential, and identify priority areas for management or restoration efforts.

Action 6.4.2: Complete literature reviews and synthesis of OA impacts to growth, fecundity, and mortality of key Pacific species to inform the development of sensitivity scalars of those organisms to decreased pH.

Action 6.4.3**:** Conduct field assays, laboratory experiments, and multi-stressor studies to measure OA sensitivity for focal taxa (e.g., calcareous plankton, larval fish, shallow and deep-sea corals, mollusks, coralline algae, seagrass, and bioeroders)**,** build OA response curves, and assess effects on trophic and food web interactions.

Research Objective 6.5: Evaluate indirect effects of OA on fisheries and protected species

Pelagic and coastal fisheries and protected species (monk seals, sea turtles, and cetaceans) are regional research and management foci. However, robust OA impact evaluations do not currently exist for these species and populations. Determining the impacts of changes in carbonate chemistry on trophic interactions, essential habitats, and behavior will help project their vulnerability to OA and aid in the effective management of these resources (in coordination with *Open Ocean Region Chapter 5, Research Objective 2.6*).

Action 6.5.1**:** Integrate plankton and trawl surveys, fish diet studies, fisheries data, stock assessments, and laboratory experiments to assess OA-driven changes to the structure and energy flow of insular and pelagic food webs.

Action 6.5.2: Assess effects of OA on abundance and distribution of seagrass beds and determine associated impacts on sea turtle grazing behavior and habitat availability.

Action 6.5.3**:** Build carbonate sand budgets for beaches that serve as pupping and nesting grounds for monk seals and sea turtles to help assess the expected magnitude of changes in sand production related to reductions in coral, crustose coralline algae, and calcareous macroalgae calcification rates.

Research Objective 6.6: Determine ecosystem-scale OA impacts

An ecosystem-scale integration of physical, chemical, biological, ecological, and socioeconomic data is required to determine the effects of OA and other stressors on coral reef and pelagic ecosystems, fisheries, and protected species and evaluate management strategies.

Action 6.6.1: Improve ecosystem model parameterizations by synthesizing carbonate chemistry observations, species-specific OA sensitivity data, and response curves (*Action 6.4.2*).

Action 6.6.2: Refine trophic interaction ecosystem models to include OA drivers and taxa responses in order to provide decision-support tools for fisheries and coastal resource management.

Human dimensions in the U.S. Pacific Islands Region

Over the next few decades, OA impacts on marine ecosystems in the Pacific Islands will likely negatively affect ecosystem services, marine resources, and the local human communities who depend on them for their livelihoods, subsistence, wellbeing, and social and cultural continuity (Bennett, 2019; Brander & van Beukering, 2013; Leong et al., 2019; Storlazzi et al., 2019). Therefore, critical research priorities in the Pacific Islands region are evaluating and projecting the effects of OA on marine resource-reliant industries, local fisheries, and human communities, and developing ecosystem-based fisheries management strategies that are driven by OA-informed environmental, ecological, and socioeconomic considerations. As natural resource managers increasingly move toward ecosystem-based approaches and social-ecological-systems frameworks, metrics of human well-being and cultural ecosystem services will be necessary to determine the success of management interventions (Leong et al., 2019).

Recent Atlantis ecosystem model studies, including the Guam Atlantis model (Weijerman et al., 2015), have introduced conceptual models to understand the human dimensions of OA scenarios in the context of fisheries and marine tourism. However, the parameterization of economic impact models and social indicators to understand how OA could affect the vulnerability of natural resource-reliant industries and communities requires further advancements. NOAA has developed an initial framework for assessing community vulnerability for the Pacific Islands region (Kleiber et al., 2018). Ongoing work will focus on improving upon and applying this suite of Community Social Vulnerability Indicators to consider OA impacts on fishing community engagement and reliance.

A diver enjoys the vibrant reefs of the U.S. Pacific Islands. Credit: NOAA

A key challenge in addressing future OA will be securing financial and political investments to develop effective adaptive strategies and solutions. Foundational studies, including work NOAA has conducted as part of the socioeconomic monitoring component of NCRMP, have documented baselines for community understanding and awareness of the threat of OA across the Pacific Islands region (Gorstein et al., 2019, 2018a,b; Levine et al., 2016; Madge et al., 2016). Future studies will be critical to document trends in public awareness and perceptions to inform future planning and investment in local adaptation strategies. It is also imperative to prioritize development of effective science communication techniques and applications to describe potential OA impacts to environmental, biological, economic, and social systems. NOAA should pursue efforts to create visualization products and education and outreach resources in collaboration with NCRMP, local jurisdictions, and other partners that target diverse stakeholders to promote understanding and awareness of OA.

Research Objective 6.7: Assess direct and indirect impacts of OA on Pacific communities

Coupling environmental and ecological dynamics (*Research Objective 6.4*) with human-use sectors and non-use values in ecosystem models will support assessment of OA impacts on marine resource-reliant industries and communities, including impacts to human well-being and ecosystem services.

Action 6.7.1: Identify the relationships of key social, cultural, and economic drivers to biophysical, fishery, and ecosystem parameters to predict potential responses from future OA scenarios.

Action 6.7.2: Create regional economic impact and behavioral models for marine resource-reliant industries to inform consideration of benefits and costs of alternative management strategies to mitigate impacts from OA.

Action 6.7.3: Develop management objectives related to human-use sectors, non-use values, ecosystem services, and well-being, and derive indicators to monitor effectiveness.

Research Objective 6.8: Characterize community awareness and resilience to OA

Integrated assessments of trends in biological conditions, social perceptions, and community vulnerabilities are necessary to develop effective management strategies in Pacific Island communities.

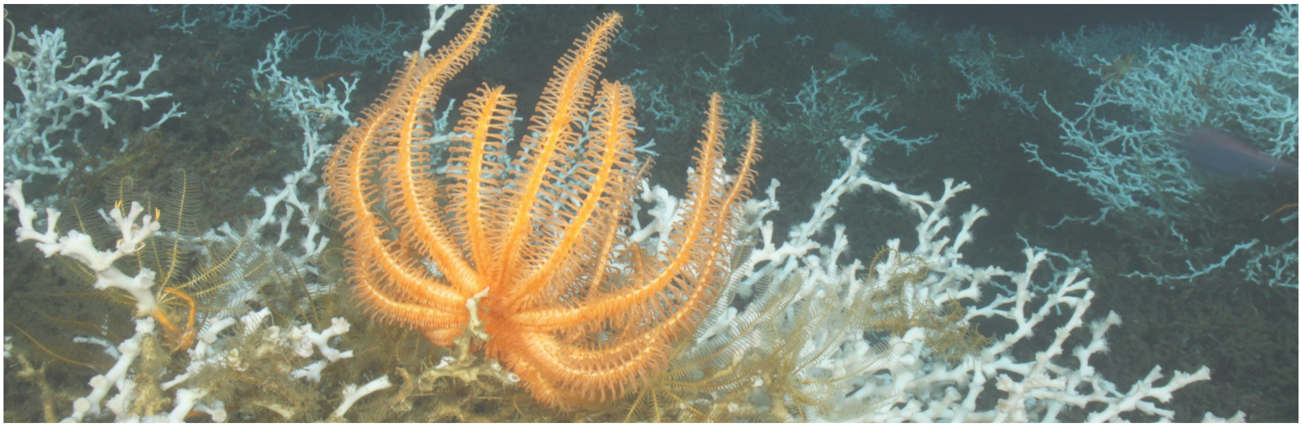
Action 6.8.1: Monitor trends in community awareness and perceptions of OA impacts and participation in stewardship activities across diverse stakeholders and make efforts to link with environmental (*Research Objective 6.2*) and biological sensitivity (*Research Objective 6.3*) trends to understand areas of coherence.

Action 6.8.2: Couple analyses of biological sensitivity (*Research Objective 6.4*) with social vulnerability and adaptive capacity frameworks to inform local community mitigation planning and management.

Research Objective 6.9: Develop innovative OA science communication products for diverse stakeholders

Investments in OA adaptation and management strategies will require effective dissemination of the potential changes, threats, and impacts from future OA scenarios on environmental, biological, economic, and social systems.

Action 6.9.1: Pursue efforts to create visualization products and education and outreach resources targeting diverse stakeholders to communicate scientific findings and promote understanding and awareness of OA processes and potential impacts.



7. Southeast Atlantic and Gulf of Mexico Region Acidification Research

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Abstract

The Southeast Atlantic and Gulf of Mexico Region encompasses continental shelf waters extending from the North Carolina to Florida coasts on the Atlantic seaboard and the marginal sea bounded by the U.S. Gulf Coast. While these two regions experience different stress factors with regards to ocean acidification (OA), they share similar needs with regards to local community engagement (or lack thereof), active research, and data availability. The regional influence of the Northward flowing Gulf Stream and southward flowing Labrador Sea currents in the Southeast Atlantic dominates the biogeochemical signatures of coastal waters in this region while the Gulf of Mexico is strongly influenced by the loop current and riverine inputs, which contribute to eutrophication and hypoxia. Impacts to coral reefs and the recreational and industrial fishing industries, and potential prevalence and frequency of harmful algal blooms are some of the issues this region faces that are potentially affected by increasing ocean acidity. NOAA's Southeast Atlantic and Gulf of Mexico research goals are to:

- Expand OA monitoring using both traditional and new autonomous technologies to observe critical regions, including the ocean sub-surface and bottom water layer, to better characterize regional processes and improve fundamental understanding;
- Characterize ecosystem impacts and adaptive potential of species, with an aim to identify indicator species that can be used for early detection of unfavorable ecosystem conditions; and
- Use new knowledge to develop socioeconomic impact assessments of OA on recreation, tourism and aquaculture industries.

Acidification in the Atlantic and Gulf of Mexico Region

The Gulf of Mexico (GoM) includes coastal areas of Florida (FL), Alabama (AL), Mississippi (MS), Louisiana (LA) and Texas (TX) and is a semi-enclosed marginal sea with coastal and open ocean waters. The eastern side of GoM includes the West Florida shelf, measuring up to 250 km while the Northern and Western GoM shelves are much narrower. The Southeast Atlantic region (SE) is composed of the coastal areas of North and South Carolina, Georgia, and the East coast of Florida and is characterized by a shelf width on the order of tens of kilometers. It is bound by the Gulf Stream, which flows northeastward along the shelf edge before detaching at Cape Hatteras, NC. The Gulf Stream is influenced by contributions from the SE and GoM region, although the influence of these regional inputs to OA variability has yet to be directly researched. Research described in this chapter excludes the Gulf of Mexico coral reefs in the keys and in the Flower Garden National Marine Sanctuary, which are instead addressed collectively with the Caribbean corals in *Chapter 8: Florida Keys and the Caribbean Region*.

Slope water composition in the Southeast Atlantic region is a varying mix of predominantly Gulf Stream and Labrador Sea water, as well as inputs from coastal marshes. There is significant interannual variability in the region, primarily driven by the influence of different water masses, which affects OA conditions (Wang et al., 2013; Wanninkhof et al., 2015). Seasonal phytoplankton blooms do not occur regularly, and biologically driven carbon dioxide (CO_2) uptake is less pronounced than in Atlantic coastal areas farther north (see *Chapter 9: Mid-Atlantic Bight Region* and *Chapter 10: New England Region*). The acidification rate in the South Atlantic Bight is higher than in the open ocean due to the combined effects of increased temperature in the middle and outer shelves, and lateral land-ocean interactions in the inner shelf (Reimer et al., 2017). Recent work using pH data collected for over a decade in two estuaries in North Carolina showed variations in pH linked to increasing river discharge and highlighted the importance of eutrophication (Van Dam & Wang, 2019). Dredging, water management, and associated activities in inlets and port areas (e.g., in Port Everglades) can cause underappreciated impacts on OA in South Florida. These activities can have coastal co-stressor effects (e.g., due to input from eutrophied, organic-rich freshwater canals and rivers) that can lead to enhanced acidification and impact local reefs and other organisms of economic interest (Enochs et al., 2019). This same area has had persistent harmful algal blooms (HABs) in the past decades (Kramer et al., 2018), but studies relating them to OA have been inconclusive.

In the GoM, ocean water enters through the Yucatan channel and exits through the Florida Straits. Main features affecting water circulation in the GoM include the meandering Loop Current, which often sheds anticyclonic eddies that drift westward and can impact the shelf, and riverine input, particularly from the Mississippi-Atchafalaya river system, which provides large volumes of fresh water, nutrients and sediments. This riverine input can lead to eutrophication, hypoxia, and enhanced acidification (Cai et al., 2011). On the West Florida shelf riverine and groundwater input with high phosphate from natural deposits can have a unique signature of biologically mediated OA. Most of the coastal acidification studies in the GoM have focused in the northern and eastern coasts (e.g., Cai et al., 2011; Huang et al., 2013, 2015; Lohrenz et al., 2010; Feely et al., 2018; Hu et al., 2018; Robbins et al., 2018). Less data are available in the Western GoM shelf, with the exception of some estuarine work (McCutcheon et al., 2019) and very little data beyond surface measurements in deep waters of the GoM. The GoM also presents considerable regional variability. The West Florida Shelf exhibits supersaturated aragonite levels that vary between 2 and 5, both at surface and subsurface levels (Robbins et al., 2018) whereas the Northern GoM presents a steeper drop in saturation levels that is enhanced due to hypoxia (Cai et al., 2011; Feely et al., 2018). OA conditions in the GoM can vary significantly on an annual scale because of interannual variability in wind, temperature, precipitation, and water mass distributions (Muller-Karger et al., 2015; Wanninkhof et al., 2015).

Overall, the various observation- and model-derived estimates for the region agree in terms of their broad patterns, but there remain discrepancies between different estimates, which indicate that continued physical, chemical, and additional biological observational data in conjunction with modelling efforts are necessary in the region (e.g., Xue et al., 2016; Laurent et al., 2017; Lohrenz et al., 2018; Chen et al., 2019).

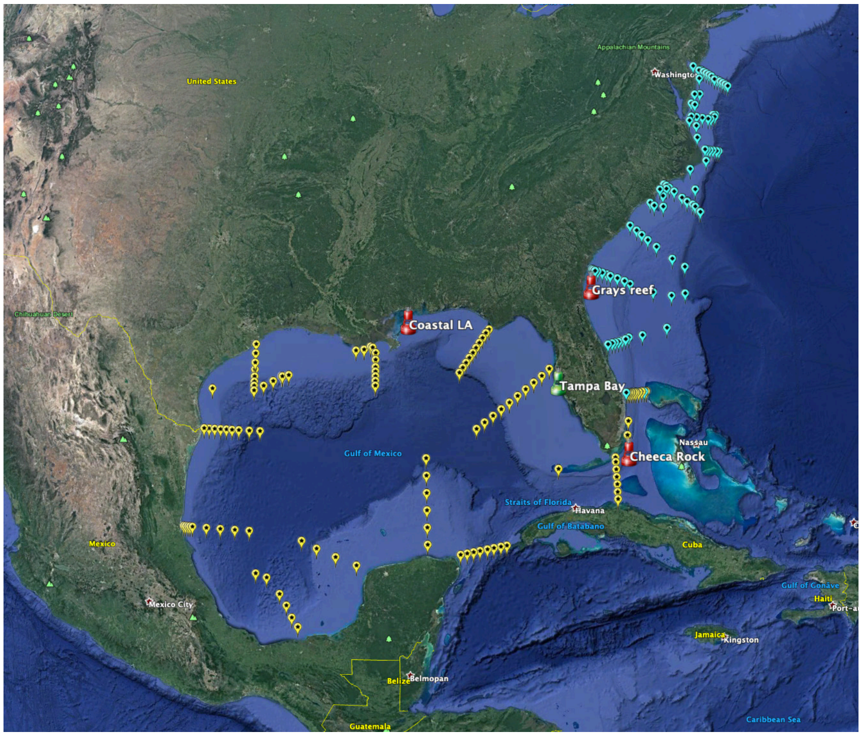


Figure 7.1. Location of NOAA-funded buoys (in red) in Gray's Reef, Cheeca Rocks and Coastal Louisiana; non-NOAA funded buoy (in green) in Tampa Bay; and transects occupied as part of East Coast Ocean Acidification (ECOA) and Gulf of Mexico Ecosystems and Carbon (GOMECC) research cruises (blue and yellow pins, respectively). Please note that the Coastal Louisiana buoy marker on the map is in its former location. It is now in waters off Coastal Louisiana (28.9°N, 90.5°W).

Environmental Change in the Southeast Atlantic and Gulf of Mexico Region

Most OA observations in the Southeast and GoM coastal regions have focused on the chemical characterization of the area, particularly through NOAA and United States Geological Survey (USGS) efforts. NOAA-supported OA monitoring in the region currently includes: a) synoptic research cruises b) underway $p\mathrm{CO}_2$ systems installed on ships of opportunity, and c) coastal buoys (**Figure 7.1**). NOAA-led OA synoptic cruises have been carried out in the summertime every four years since 2007 in the East coast (East Coast OA (ECOA) cruises) and the Gulf of Mexico (Gulf of Mexico Ecosystems and Carbon Cycle Cruise (GOMECC)) and they collect mostly physical and chemical data along a series of coastal transects (Wang et al., 2013; Wanninkhof et al., 2015). However, the GOMECC cruise (GOMECC-3), conducted in July-August of 2017, incorporated significant biological sampling in conjunction with OA water sampling, strengthening the link between OA forcing and impacts. NOAA-funded cruises in South Florida as part of the South Florida Ecosystem Restoration Program also collect OA samples along the FL keys and offshore of the Everglades several times per year. The USGS has participated in several cruises to study the effects of OA on marine organisms and habitats in the West Florida Shelf and northern Gulf of Mexico regions (Robbins et al., 2018). NOAA funds two underway $p\mathrm{CO}_2$ systems installed on NOAA fisheries ships RV *Gordon Gunter* and RV *Henry H. Bigelow* involved in regular fisheries surveys. In addition to these, NOAA supports underway $p\mathrm{CO}_2$ systems through its Ship of Opportunity Program (SOOP). These systems are installed on a variety of ships including scientific and commercial vessels that have also collected data in the Southeast and Gulf of Mexico regions. As a result, over 90% of available surface $p\mathrm{CO}_2$ data in the Gulf of Mexico has been collected through NOAA-funded efforts since 2008. Surface water samples for carbonate chemistry analysis are also collected on these ships on an opportunistic basis. Additionally, ships of opportunity provide platforms for maintenance of three NOAA OA monitoring buoys in the region (Sutton et al., 2019), and collect data for biogeochemical modeling efforts. The buoys are located off the Georgia coast in Gray's Reef ($p\mathrm{CO_2}$ record started in 2006, pH sensor added in 2011), in the Florida Keys at Cheeca Rocks ($p\mathrm{CO_2}$ and pH record started in 2011) and in coastal Louisiana ($p\mathrm{CO_2}$ and pH record available since 2011). A fourth OA buoy is located in Tampa Bay, FL, and is maintained by Dr. Kim Yates, from the USGS. **Figure 7.1** shows the location of the buoys as well as the transects occupied in the ECOA and GOMECC cruises. Although none are in use in the region, a variety of autonomous platforms equipped with a variety of OA sensors are being explored in other regions. Examples of such platforms include wave gliders for surface measurements, saildrones and BGC-Argo profiling floats, which could provide an excellent means to increase data availability in areas such as the deep GoM.

Observing capabilities over the last decade have greatly improved the spatial coverage of carbonate chemistry measurements made in the region and contributed toward the foundational understanding of the large-scale regional trends from different source waters in the region, and the impacts of riverine inputs and eutrophication on OA conditions in the region. Quantifying and understanding the high natural variability, and teasing apart anthropogenic impacts from natural variability, including from water mass composition, biological activity, and river discharge remain research foci of OA drivers and co-stressors in the region.

The ECOA and GOMECC cruises as well as several other OA cruises in the Northern GoM collect high-resolution water column data, and take place during the summer season in order to provide an interannual comparison without confounding factors from seasonal variability. As a result there are insufficient observations from other seasons to adequately characterize seasonal variability in subsurface waters and the open ocean end-member (**Figure 7.2**). Moreover, there are presently no OA buoys in the Western GoM, representing a major regional sampling gap.

Nearshore estuarine and coastal regions in the GoM and Southeastern Atlantic have also been relatively undersampled. This includes mangroves, marshes, and some estuaries that provide a wealth

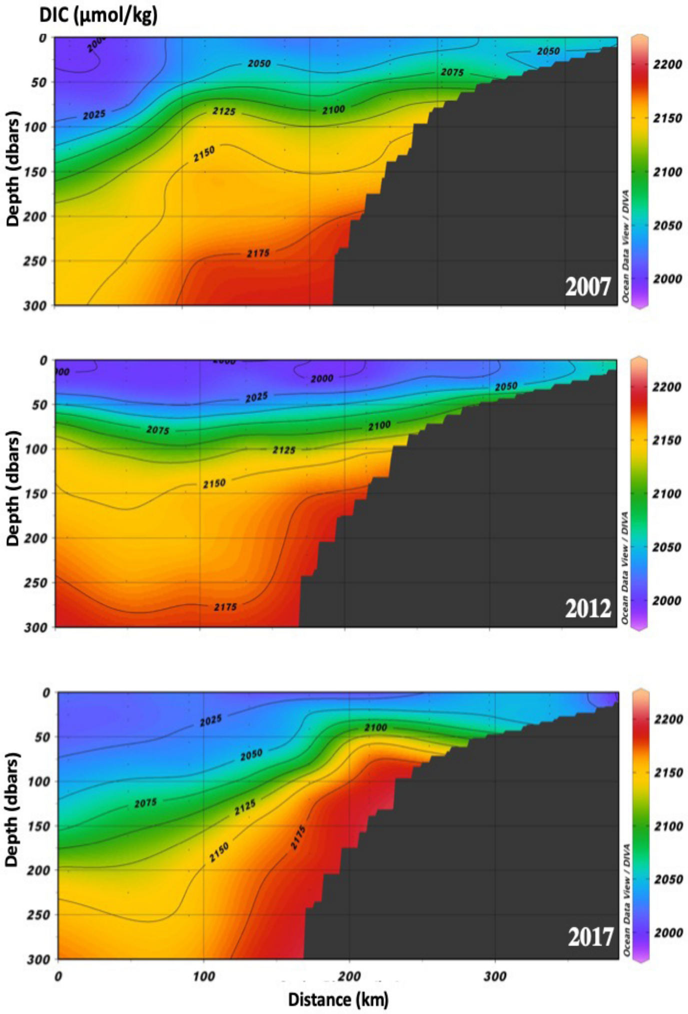
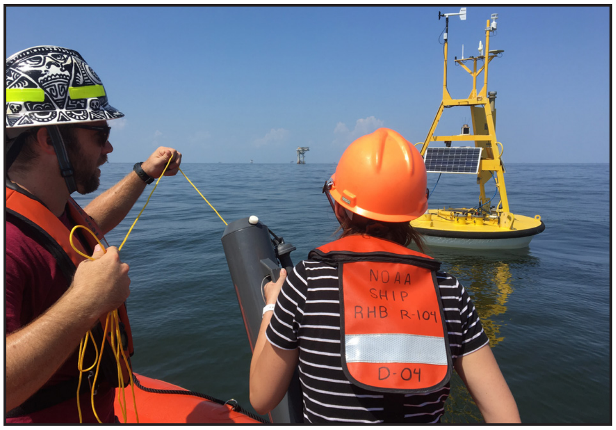


Figure 7.2. Concentration of dissolved inorganic carbon (DIC) off the West Florida shelf measured during the Gulf of Mexico Ecosystems and Carbon Cruise (GOMECC). Increased concentrations are observed in the subsurface over time. Surface measurements cannot capture changes in subsurface waters.

of ecosystem services in this region, but are also data poor environments for OA. The majority of recreational fishing and tourism occurs in these data poor nearshore waters; thus, increased sampling is commencing for nearshore waters. The GoM and Southeast Atlantic region have a combined 22 National Parks that have observational infrastructure, support, and outreach opportunities. Of these, 7 have started collecting OA samples in coordination with the synoptic GOMECC and ECOA cruises, once every 4 years. There are two National Marine Sanctuaries (NMS) in the GoM, the Florida Keys NMS and the Flower Garden Banks NMS that are coral reef areas heavily instrumented for OA research and monitoring (see Chapter 8: Florida Keys and Caribbean Region). However, there are no similar monitoring efforts in place for cold-water corals in the Gulf of Mexico, which live at depths between 300 and 600 m, and which have been identified as being particularly vulnerable communities to OA because they are already naturally exposed to lower pH levels (Lunden et al., 2013; Georgian et al., 2016). In the Southeast Atlantic region Gray's Reef NMS off the Georgia coast has a buoy with OA-monitoring systems.



NOAA researchers collect a water sample near an acidification buoy during a Gulf of Mexico/East Coast Carbon research cruise. Credit: Leticia Barbero/NOAA

The in-situ observing data in the region are used in existing modeling efforts including the OA Product Suite developed for the Greater Caribbean region and now extended to include the East Coast. The OA Product Suite utilizes satellite data and a data-assimilative hybrid model to produce monthly maps of surface water carbonate system components. Modeling results include studies in the Gulf of Mexico by Xue et al. (2016), who showed the GoM to be an annual sink for CO_2 with a flux of $1.11 \pm 0.84 \; 10^{12}$ mol C yr^{-1}, and by Laurent et al. (2017), who showed the recurring development of an extended area of acidified bottom waters in summer on the Northern GoM shelf that coincides with hypoxic waters. Global data synthesis and process-based global models have also provided estimates for coastal U.S. regions including the GoM and Southeast (see Table 1 in Fennel et al., 2019). More recently, modeling efforts are being supported to address seasonal patterns of the carbon system. Modeling results agree in general terms with observation estimates, and offer the opportunity to upscale the observations in time and space. However, the models still show significant discrepancies in some regions, specifically in the period from 2010 to 2017 depending on the model. Sustaining current modeling efforts and increasing the modeling portfolio to include nowcasts and forecasts, as well as integrating ecosystem parameters, extending to the East coast, and including robust validation is a priority to predict the expected changes in the region as a result of OA.

Research Objective 7.1: Improve characterization of OA parameters in important economic, cultural, and recreational regions

The GoM and Southeast Atlantic are particularly data poor in the nearshore region where most commercial and recreational fishing and tourist industry activities take place. These regions are also home to mangroves, marshes, estuaries, natural, and restored oyster reef sites, which are essential habitats within the region's marine ecosystems, play an important role in local carbon balances, and provide a wealth of ecosystem and commercial services.

Action 7.1.1: Develop and establish protocols that are complementary to ongoing synoptic cruises to extend regular observations of pertinent OA parameters into the nearshore environment. Focus sampling in Essential Fish Habitats for species predicted to be significantly impacted by OA, and in select National Parks and National Marine Sanctuary sites (specifically in the northern GoM where hypoxia and OA act as co-stressors).

Action 7.1.2: Explore options, including private and/or industry partnerships, to add an OA buoy or alternative observing platform in the Western GoM to extend coverage of coastal sites that are presently composed of buoys in the Florida Keys, West Florida Shelf (a non-NOAA asset), and the Mississippi-Atchafalaya area.

Action 7.1.3: Explore options to add a monitoring site in the SE region within the estuarine environment near to Grays Reef to establish a nearshore-offshore contrasting monitoring site.

Action 7.1.4: Establish OA and water quality monitoring stations at inlets and near commercially and recreationally important estuaries (e.g., oyster bed leases, public clam beds, shellfish hatcheries) to monitor coastal acidification and eutrophication co-stressors in areas where fresh water systems are highly impacted by human activities and strongly influence coastal oceans.

Research Objective 7.2: Improve the characterization of the Open Ocean

Currently, open ocean monitoring is limited to the OA synoptic cruises that take place once every four years. Exploring autonomous technologies may provide a platform to vastly increase open ocean observing in the deep and shelf waters. Better understanding of the open ocean within the region can also contribute to the understanding of coastal acidification processes, as coastal acidification can be studied by considering a conservative mixing line with a two end-member system of open-ocean and freshwater inputs.

Action 7.2.1: Evaluate capabilities of autonomous sensor(s) for surface to deep water observing (3000 m) and observing in the vicinity of cold-water coral communities.

Action 7.2.2: Establish plan to deploy BGC-Argo floats in the GoM region, following the rationale in *Chapter 2: Open Ocean Region* (*Objective 2.3*). Leverage GOMECC and other cruises to perform *in-situ* calibrations and improve quality control procedures for the data, while greatly increasing data availability for the open ocean end-member in the GoM.

Research Objective 7.3: Improve fundamental understanding of regional processes and seasonal trends

Coastal areas in the region show different seasonal surface and sub-surface patterns, but there is little data available to validate model estimates of spatial patterns and seasonal trends.

Action 7.3.1: Leverage existing cruises (e.g., Southeast Area Monitoring and Assessment Program, ecosystem monitoring and restoration, oceanographic) to increase sample collection between synoptic surveys, particularly in wintertime when observations have historically been particularly limited.

Action 7.3.2: Evaluate methods to measure how upwelling of deep GoM waters onto the shelf affect OA in shelf ecosystems that are also affected by riverine acidification impacts.

Action 7.3.3: Expand the number of observations by increasing frequency of synoptic cruises to sample during other seasons (initially winter) to improve intra-annual sampling and add subsurface sensors to existing buoys, moorings, and autonomous platforms.

Research Objective 7.4: Improve scaling and predictive capabilities

Models are a critical tool for extrapolating current observations to larger regions and to improve our mechanistic understanding of linkages between the physics, chemistry, and biology of OA. Models also provide critical information that can be translated and used to inform decisions and management practices. Continued development and use of existing regional models and the creation of new models that enhance geographic coverage within the region are needed.

Action 7.4.1: Develop, apply, and improve existing models and validate models with direct observations to assess and improve model skill to best project OA within the region.

Action 7.4.2: Incorporate OA and associated biogeochemistry into ecosystem models to help predict OA impacts on valuable components of the marine ecosystem.

Action 7.4.3: Increase utilization of satellite data, tools, and products in support of status estimates and now-casts.

Action 7.4.4: Coordinate research with university researchers to build consensus regarding regional OA projections.

Biological Sensitivity

Studies of OA impacts on organisms in the region, with the exception of some coral reef systems in the Florida Keys and Flower Garden NMS (Chapter 8), have been sparse. Changes in chemical factors directly impact the physiology of filter feeders, benthic foragers and fish (e.g., oysters, blue crab or menhaden) and also alter food web structure and the quality and quantity of food for many of the intermediate consumers and commercially important species (Hansen et al., 2019; Caron & Hutchins, 2012). Initial characterizations of food web structure - from phyto- to zooplankton - were performed during the 2017 and 2018 synoptic OA GOMECC-3 and ECOA-2 cruises across the GoM and Southeast Atlantic region. GOMECC-3 also included targeted sampling for pteropods and larval ichthyoplankton, along with rate measurements of carbon flow from primary producers to crustacean prey. Incorporation of rate-based measurements, specifically, allow for more investigation of the role of these biological communities and food webs as sinks of or links to carbon cycling in the region (Sherr & Sherr, 2002; Steinberg & Landry, 2017). Altogether, this information provides insights into how food webs and carbon transfer are altered in regions affected by eutrophication-driven acidification and hypoxia. Maps of ichthyoplankton distribution are reflective of spawning regions for fish, and can be used for studying effects of OA on marine fish populations such as stock displacement to avoid acidified waters. These data build directly on programs such as Southeast Area Monitoring and Assessment Program (SEAMAP) and would provide more power to efforts to depict changes in species ranges and patterns of distribution during the larval life stages and beyond.

Given the lack of a systematic study of OA impacts on plankton and commercially important species in this region, impacts of OA on fisheries and aquaculture industries in the region are also poorly understood. With high saturation state variability predicted for subtropical regions relative to higher latitudes, understanding the impacts of saturation state on such species will be critically important for the region. High levels of OA variability could lead to greater impacts on organisms that have a smaller tolerance to OA. Identifying such highly OA-sensitive indicator species could actually be beneficial to tracking small and/or early shifts in the marine carbonate system. The Southeast Fisheries Science Center (SEFSC) has conducted a climate vulnerability assessment for marine fishery species in the GoM and initiated one in the SE (Lovett et al., 2016), which can guide the proposed *in-situ* observing activities (*Research Objective 7.3*) and indicator species research (*Research Objective 7.6*) proposed for the region.

Oil drilling, dredging and restoration efforts both in the GoM and SE region can interact with OA and potentially have compounding impacts on organisms and ecosystems. While funding is available for research on OA, oil spills, or hypoxia, there are no coordinated calls to promote and encourage interdisciplinary research. HAB events also pose a recurring problem in the GoM and Southeast region. Florida and other Gulf Coast states experience fish kills and neurotoxic shellfish poisoning from *Karenia brevis* and other HAB species (Weisberg et al., 2019). Harmful cyanobacteria and their toxins (primarily microcystin) have also been detected in low salinity estuaries in Louisiana and Florida (Bargu et al., 2011; Riekenberg et al., 2015) and shown to accumulate in commercially-important consumer species (i.e., blue crab) that are also impacted by OA (Garcia et al., 2010). The economic impact of HABs resulting in public health issues, commercial fishery closures, and recreational tourism reduction has been reported as upwards of ~$50 million/year (Anderson et al., 2000). Laboratory studies of *Karenia brevis*, the major HAB species in the Gulf of Mexico, in connection with OA have shown conflicting results, with some concluding that at higher $p\mathrm{CO}_2$ concentrations *K. brevis* growth rates are significantly increased, although toxin production itself appeared to not be linked (Errera et al., 2014), while others did not observe a significant response in growth, or cellular composition of carbon and nitrogen (Bercel & Kranz, 2019). Although ongoing efforts to study the relationship between OA and HAB occurrence are taking place in other regions, no similar effort is currently taking place in the GoM.

Small boat operations as part of the Gulf of Mexico Ecosystems and Carbon Cruise aboard the NOAA ship Ronald H. Brown. Credit Marisa Gedney/NOAA

Research Objective 7.5: Increase understanding of the impacts of OA on ecosystem productivity and food webs

Because plankton communities are the base of marine food webs, shift in response to OA impact energy flow and ecosystem function (Roman et al., 2012). As the quantity and quality of plankton prey are altered, managed and commercially important species are affected.

Action 7.5.1: Characterize plankton communities (from phytoplankton to larval fish) along spatial gradients of eutrophication-driven acidification and hypoxia through regular sampling on GOMECC, ECOA, and other cruises to allow for attribution to OA and/ or eutrophication stressors versus seasonal or other episodic drivers (e.g., tropical storms, flood, drought).

Action 7.5.2: Quantify changes in carbon flow to higher trophic levels (e.g., crustaceans and fish) via modeling studies and shipboard observations during GOMECC and ECOA cruises. Conduct shipboard experiments to determine biological community composition during antecedent conditions (not just conditions at the time of sampling) and to understand how rates (e.g., primary productivity, zooplankton grazing) change in response to OA, eutrophication, HABs, and hypoxia, which are critical to parameterize ecosystem models.

Action 7.5.3: Synthesize existing information from previous cruises and ongoing research and monitoring in the region. Coordinate collection of biological data (e.g., plankton tows, ‘omics-approaches and rate measurements) for future GOMECC, ECOA, and other cruises. Identify regions where shifts in carbon chemistry are associated with changes in plankton community structure and function.

Research Objective 7.6: Identify indicator species for OA in the region

An indicator species that is sensitive to changes in pH specific for the GoM and for the Southeast Atlantic region can be used for early detection of OA impacts to the system and to investigate ecosystem impacts that may result from food web changes.

Action 7.6.1: Incorporate plankton and neuston net tows, and ‘omics sampling as part of the standard suite of parameters included in GOMECC/ECOA cruises.

Action 7.6.2: Incorporate carbon chemistry sampling as part of the standard suite of parameters included in already ongoing SEFSC ecosystem monitoring efforts such as SEAMAP cruises and add DIC/TA/pH water sampling to the suite of samples already being collected.

Action 7.6.3: Conduct laboratory studies to examine OA impacts in combination with other co-stressors, such as temperature and nutrients, on potential indicator species identified via field observations.

Research Objective 7.7: Characterize sensitivity and adaptive potential of critical resource species to OA and other stressors and improve the understanding of OA impacts to HAB event frequency and duration

Most species of economic interest in the region (e.g., bluefin tuna, shrimp, blue crab) lack specific studies about potential OA impacts. The SEFSC vulnerability analysis mentioned above and ‘omics tools can be used as a screening tool to identify species of economic importance that are likely sensitive to OA. In addition to this, a growing body of research is addressing whether OA may have species-specific impacts on the frequency, duration and degree of HAB blooms or their toxicity in other regions of the U.S. Despite the prevalence of HABs, research focused on GoM and Southeast Atlantic environments and species with regards to OA is scarce.

Action 7.7.1: Target species of interest to conduct experimental studies to establish responses to OA and inform species vulnerability assessments.

Action 7.7.2: Develop assessments using a multi-stressor framework to include combinations of effects such as eutrophication, river runoff, hypoxia, or increased HABs.

Action 7.7.3: Incorporate these results into ecosystem models models to drive hypotheses about how changes in indicators species and plankton dynamics will affect commercial and recreational fishery species.

Action 7.7.4: Build monitoring capacity for regionally significant HAB species to be measured during synoptic OA cruises and implement OA sampling in other opportunistic or ongoing cruises organized in relation to HABs already occurring along the Florida coast.

Action 7.7.5: Support isolation and cultivation-based laboratory experimentation of local HAB species to examine species-specific and community responses to carbonate chemistry conditions.

Action 7.7.6: Quantify socioeconomic impacts from predicted changes in HABs and their toxicity due to OA.

Human dimensions

While there are several studies that deal with socioeconomic impacts as a result of acidification in coral reef regions, there are currently no non-coral studies in the GoM and the Southeast region that quantify potential socioeconomic impacts from OA on fisheries of interest in the region. Ekstrom et al. (2015) identified the coastal communities of TX, LA, MS and Northern FL as being highly socially vulnerable to OA impacts, despite a lower marine ecosystem exposure than other U.S. coastal regions. However, no specific socioeconomic studies have been released yet. Local communities in the SE such as those of Gullah/Geechee descent consume marine species vulnerable to OA (e.g., oysters, blue crab) for sustenance and as part of cultural traditions. This type of activity could be included as part of the evaluation and research of socioeconomic impacts as an opportunity to build relationships and partnerships with vulnerable communities. Stakeholder engagement efforts should be cognizant that the region experiences threats from multiple drivers, some of which have a more direct impact than OA. Therefore efforts to engage stakeholders and identify needs should take a multi-stressor approach. By improving the understanding of stakeholder needs strategic investments can be made in capacity building and targeted research that is responsive to the needs within the region.

A commercial shrimp fishing vessel off of the U.S. southeast coast. Credit: NOAA

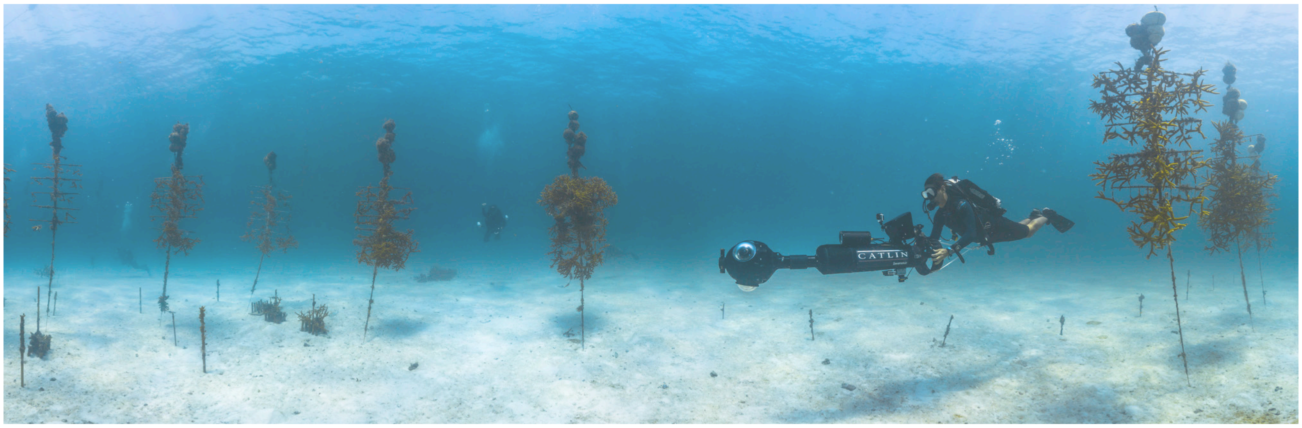
Research Objective 7.8: Improve assessment of socioeconomic impacts of OA on local tourism, recreational fishing, commercial fishing, and aquaculture (shellfish, fisheries) industries

To date, no socioeconomic studies have been conducted to quantify the impact OA might have on commercially relevant fisheries, aquaculture, tourism, or recreational fishing in the region.

Action 7.8.1: Evaluate the socioeconomic impacts from from key species being impacted by OA either directly or in through food web interactions (*Research Objective 7.7*).

Action 7.8.2: Conduct socioeconomic research to quantify the impacts of OA for specific fisheries, including direct (fishermen/aquaculture) and indirect (related service industries) impacts.

Action 7.8.3: Based on outcomes from above, involve local stakeholders and raise awareness about OA to increase community resilience and proactively develop OA mitigation plans for affected ecosystems, industries, and economies.



8. Florida Keys and Caribbean Region Acidification Research

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Abstract

This region encompasses the Florida Keys and coastal waters of south Florida, as well as Puerto Rico, the U.S. Virgin Islands, and the surrounding areas between the Gulf of Mexico and Atlantic Ocean. Processes driving acidification in this region range from global incorporation of anthropogenic carbon in surface waters to localized alteration of seawater chemistry by natural ecosystems, as well as human activities. Fluctuations in seawater carbon dioxide (CO_2) manifest on timescales ranging from decades to hours, making holistic characterization a challenging task. The region is home to especially sensitive coral reef ecosystems and commercially important fisheries, which are all inexorably linked to coastal communities and economies. NOAA's Florida Keys and Caribbean research goals are to:

- Enhance the temporal and spatial resolution of ocean acidification (OA) monitoring to capture the ecologically-relevant variability of this dynamic region;
- Monitor responses to OA on scales ranging from individuals to ecosystems, specifically targeting those that have been previously identified as susceptible to or threatened by OA;
- Experimentally investigate the sensitivity and resilience of ecologically and economically important species, as well as the underlying molecular mechanisms that drive their differential responses to OA; and
- Develop interdisciplinary tools that integrate socioeconomic data with ecological outcomes.

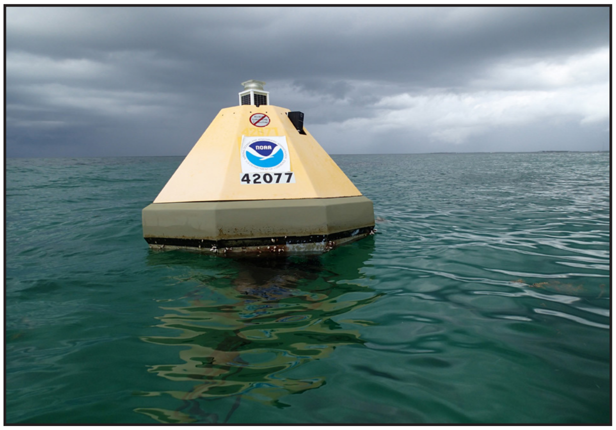
Acidification in the Florida Keys and Caribbean Region

The Florida Keys and wider Caribbean region contain numerous shallow-water ecosystems, including coral reefs, seagrasses, mangrove habitats, as well as sand and hard bottom communities. These systems support economically important fisheries, active tourism industries, and fulfill important roles for coastal protection. Numerous taxa that occupy and form these habitats are sensitive to elevated CO_2 and associated OA, further threatening systems that are already degraded due to warming, disease, overfishing, and eutrophication (e.g., Gardner et al., 2003). These ecosystems' heightened sensitivity to stress and their close relationship with carbonate chemistry serve to underscore the importance of OA in the region. The Caribbean exhibits some of the highest carbonate mineral saturations states in the world, but has experienced among the most rapid rates of decline since pre-industrial times (Gledhill et al., 2009). The carbonate chemistry of the Florida Keys and Caribbean is spatially variable and driven by interconnected ecosystems and waterways. For example, seagrass communities sequester CO_2 via photosynthesis and influence the chemistry of surrounding waters in the Florida Keys (Manzello et al., 2012) and navigational inlets and urbanized waterways lead to localized hotspots of acidification in southeast Florida (Enochs et al., 2019). These spatial patterns are temporally dynamic. For example, seagrasses have a pronounced growing season with elevated rates of productivity during the spring and early summer that can significantly increase seawater pH, possible alleviating OA stress (Manzello et al., 2012). On a more episodic basis, tropical cyclones contribute to periods of undersaturation as a result of reduced photosynthesis and stress-driven increases in respiration (Manzello et al., 2013). The relative importance of these dynamic processes varies greatly across the region, which represents a large geographic area that encompasses both islands and continentally influenced coasts.

Over the last decade NOAA-supported OA research has made great strides in establishing a monitoring program to characterize carbonate chemistry across space and time, as well as the status of closely-related biological processes such as calcification and bioerosion on coral reefs. This has been done in a highly leveraged manner, through close collaboration with existing monitoring programs, chief among them the National Coral Reef Monitoring Program (NCRMP, coris.noaa.gov/monitoring). NOAA has also supported several experiments on the OA sensitivity of key coral taxa, three associated with coral reefs and two that are important in local fisheries. Despite these advances, significant gaps remain that are crucial to the management and persistence of economically important marine resources within the region.

Environmental Change in the Florida Keys and Caribbean Region

Climate-quality geochemical surveys have historically not taken place in much of the region because it is a marginal sea, rather than an open ocean, and has therefore been of lower priority to carbon inventory studies. However, extensive underway and ship-of-opportunity efforts have occurred for more than a decade at NOAA with support from partnering programs to expand surface observations in this region. Two quadrennial OA surveys have conducted repeated transects of climate-quality full-water column measurements of OA and affiliated biogeochemical sampling within the region since 2007. The Gulf of Mexico Ecosystems and Carbon Cruise (GOMECC) has sampled waters offshore of the Florida Keys, while the East Coast OA (ECOA) cruise has sampled the east coast down to Miami. Monthly Caribbean-wide estimates of carbonate mineral saturation state, derived from satellite measurements and models are available from the Ocean Acidification Product Suite (OAPS, https://www.coral.noaa.gov/accrete/oaps.html; Gledhill et al., 2009).



An ocean acidification buoy at Cheeca Rocks, an inshore patch reef within the Florida Keys National Marine Sanctuary. Credit: NOAA

NOAA's NCRMP was established to collect biological, physical, and socioeconomic information needed to gauge changing conditions of U.S. coral reef ecosystems. NOAA conducts sustained, long-term measurements of the chemical progression of OA and associated ecological impacts in and around coral reefs. OA monitoring on reefs throughout the Keys and Caribbean has been a highly leveraged collaboration with numerous academic, state, and federal partners.

NOAA utilizes a tiered approach of monitoring classes whereby seawater CO_2 measurements are made with very high frequency at a few locations, and at lower frequency across many locations (150 per year). There are presently two fully operational Class III, or sentinel OA monitoring sites on coral reefs at La Parguera, Puerto Rico (since January 2009) and Cheeca Rocks, Florida Keys (since December 2011). These sites each have a Moored Autonomous pCO_2 (MApCO_2) buoy providing high-resolution time-series data of xCO_2 and pH, accompanied by bi-weekly discrete measurements of total alkalinity (TA) and TCO_2. Flower Garden Banks is a third Class III location installed in 2015, but is not fully operational because it lacks a MApCO_2 buoy or comparable instrumentation that provide climate-quality, long-term CO_2 measurements. Class II sites (Dry Tortugas, St. Croix, and St. Thomas) include the same metrics as the class III sites, but lack the MApCO_2 buoy. Diurnal CO_2 measurements are obtained from the Class II sites using subsurface automatic samplers (SAS) every three years. Class I sites provide fixed *in situ* temperature data, whereas Class 0 sites represent discrete seawater collections for carbonate chemistry, obtained by the NCRMP biological teams, from stratified random reef locations in each jurisdiction once every two years. In association with NCRMP carbonate chemistry monitoring, a suite of eco-response measurements are made once every three years at Class III sites. These includes *ReefBudget* census-based carbonate budget monitoring (Perry et al., 2012), Calcification Accretion Units (CAUs, Vargas-Ángel et al., 2015), Bioerosion Monitoring Units (BMUs, Enochs et al., 2016a), and cores to elucidate coral calcification rates. CAUs and BMUs were recently added to all 15 m class I sites to increase spatial resolution. Higher frequency seawater sampling in southeast Florida (quarterly, 2014-2015, Enochs et al., 2019) and the Florida Keys (bimonthly, 2010-2012, 2014-present), accomplished via program leveraging, has led to a more thorough understanding of carbonate chemistry variability.

Research Objective 8.1: Characterize spatial carbonate chemistry patterns

Considerable seawater CO_2 variability has been measured throughout the region and current monitoring efforts are likely limited in their ability to detect ecologically important patterns across spatial and temporal scales.

Action 8.1.1: Improve the spatial resolution of existing carbonate chemistry monitoring in order to better detect regional and local patterns.

Action 8.1.2: Improve upon the deficiency in measurements taken at depth on coral reefs.

Action 8.1.3: Initiate routine sampling in understudied ecosystems (e.g., seagrass beds, mesophotic coral reefs, mangroves, and soft-bottom communities).

Action 8.1.4: Expand Ship of Opportunity Program (SOOP) coverage into the Caribbean.

Action 8.1.5: Explore the use of advanced autonomous systems (e.g., carbon Waveglider, Saildrone, glider) to achieve improved constraint of OA conditions.

Research Objective 8.2: Characterize temporal carbonate chemistry patterns

Spatial gradients in carbonate chemistry can be dramatic, but are often linked to temporal variability driven by processes such as seasonally-enhanced seagrass productivity. Infrequent sampling may not detect these patterns.

Action 8.2.1: Improve the frequency of carbonate chemistry measurements to better understand diel and seasonal oscillations, and capture episodic events.

Research Objective 8.3: Better understand ecosystem response to OA through paired monitoring of carbonate (and ancillary) chemistry and biological/community-scale metrics

Establishing causation between stressors and responses can be difficult and is complicated by the high variability of coastal CO_2, diverse ecological interactions, and the subtle but steady progression of global OA. Regardless, real-world biological responses to OA are central to understanding how ecosystem services are presently and will be impacted.

Action 8.3.1: Monitor individual responses of species with documented sensitivities, especially those that have ramifications for ecosystem health (e.g., calcifying and bioeroding species).

Action 8.3.2: Evaluate the importance of biogeochemistry within sediment pore waters (e.g., dissolution, Cyronak et al., 2013; Eyre et al., 2014, 2018) and improve understanding of how this relates to ecosystem function and services, particularly for coral reefs.

Action 8.3.3: Cross-validate, standardize, and establish best-practices for techniques to quantify net community calcification (NCC) and net community productivity (NCP) and integrate them into monitoring programs (Cyronak et al., 2018).

Research Objective 8.4: Ecosystem modeling that integrates multiple functional groups

There is an urgent need to develop modeling tools to gauge present day reef state and forecast their persistence in future OA conditions.

Action 8.4.1: Develop a habitat persistence (e.g., carbonate budget) model that incorporates the species-specific sensitivities of key calcifying and bioeroding taxa to forecast reef habitat permanence under OA scenarios (Perry et al., 2012; Kennedy et al., 2013).

Action 8.4.2: Apply spatiotemporal patterns in carbonate chemistry to OA-sensitive carbonate budget models to identify hotspots and refugia.

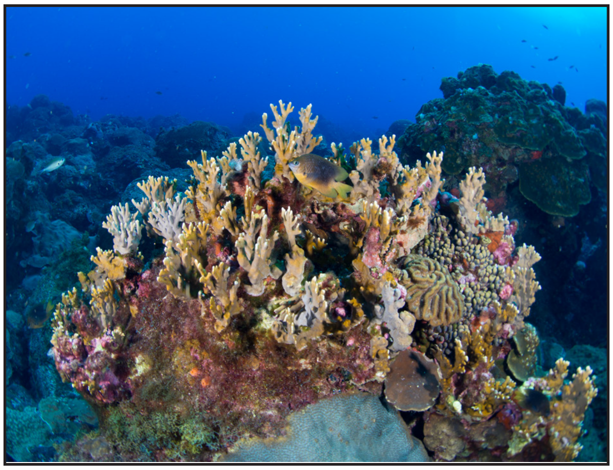
Biological Sensitivity in the Florida Keys and Caribbean Region

Over the last decade, NOAA has supported experimental investigation of Caribbean taxa and their responses to OA. To date, OA sensitivity research has been conducted by NOAA on three species of reef-dwelling animals from different functional groups: a stony coral (*Acropora cervicornis*, listed as threatened under the Endangered Species Act; Hogarth, 2006), a soft coral (*Eunicea flexuosa*), and a bioeroding sponge (*Pione lampa*). *A. cervicornis* responds to OA stress with reduced calcification and skeletal density (Enochs et al., 2014), but exhibits accelerated growth rates in more-variable contemporary CO_2 environments (Enochs et al., 2018). By contrast, soft corals such as *E. flexuosa* are apparently resilient to OA and may be competitively favored in the future (Enochs et al., 2016b). Caribbean bioeroding sponges such as *P. lampa* have accelerated rates of biological dissolution under moderate OA scenarios (Enochs et al., 2015b). In addition to reef species, NOAA has supported experimentation with commercially important Caribbean taxa. For instance, elevated CO_2 resulted in morphological alteration of the ear stones of larval cobia (*Rachycentron canadum*), which could alter their hearing ability and detrimentally influence dispersal and recruitment (Bignami et al., 2013). OA and warming conditions reduced the survivorship of larval stone crabs (*Menippe mercenaria*), with implications for stock size maintenance and the sustainability of the fishery (Gravinese et al., 2018).

Periodic exposures to extremes (high vs. low CO_2) are relevant to the calcification of *A. cervicornis*, resulting in higher growth rates in more-variable contemporary conditions (Enochs et al., 2018). Carbonate chemistry fluctuations are expected to increase due to global OA (Shaw et al., 2013) and land use changes may result in regional alteration of CO_2 dynamics, including the magnitude of seasonal changes (Wallace et al., 2014; Duarte et al., 2013). While data are scarce (Rivest et al., 2017), this variability likely has strong ramifications for other ecologically important taxa and should be investigated further.

The potential for intraspecific variability in OA responses also requires attention. Different genotypes within a single species can have significantly different rates of calcification and thermal tolerance (Dixon et al., 2015; Parkinson et al., 2015). It is of vital importance to determine if there are genes or molecular mechanisms that confer OA resilience. It may be possible to selectively breed for these traits in coral nurseries as is being done for resistance to heat stress (e.g., Dixon et al., 2015; van Oppen et al., 2015).

Relative to calcifying species, the influence of OA on the more biodiverse community of bioeroding flora and fauna is poorly understood (Schönberg et al., 2017). These organisms act in opposition to calcifiers and the balance of the two processes (bioerosion vs. calcification) is ultimately what determines the fate of reef habitat. Experimental studies, primarily from the Pacific, suggest that OA will accelerate chemical dissolution of reef carbonate by clionaid sponges (Wisshak et al., 2012) as well as endolithic algae (Tribollet et al., 2009; Reyes-Nivia et al., 2013). Preliminary evidence from the Caribbean supports these findings (Enochs et al., 2015b; Stubler et al., 2015). As coral cover continues to decline throughout the Caribbean (Gardner et al., 2003), the relative impact of bioeroders is increasing, shifting many reefs into erosional states and making bioerosion the primary driver of reef carbonate budgets (Alvarez-Filip et al., 2009; Kennedy et al., 2013; Perry et al., 2013; Enochs et al., 2015b).



Flower Garden Banks National Marine Sanctuary is home to some of the most healthy and vibrant coral reefs, like the ones shown here, in the northern Gulf of Mexico. Credit: GP Schmahl/NOAA

Several key taxa are of particular importance to the ecology, economies, and cultures of the region yet their OA sensitivities remain largely unexplored. Lobster (*Panuliris argus*) supports the single most valuable fishery in Florida and the greater Caribbean (Phillips & Kittaka, 2000). In addition to the numerous impacts of OA documented for related crustacean species (e.g., Whiteley, 2011), a single study found that warmer, more saline, and lower pH environments impacted the chemosensory habitat selectivity of *P. argus* (Ross & Behringer, 2019). Stone crabs (*M. mercenaria*) are also an important commercial and recreational fishery in Florida. Studies have demonstrated the sensitivity of early life stages, which could have damaging effects on the fishery by limiting population growth and dispersal (Gravinese, 2018; Gravinese et al., 2018). The queen conch (*Lobatus gigas*) fishery is the second largest benthic fishery in the Caribbean, yet decades of overfishing and habitat degradation have led to Caribbean-wide declines and fishery closures (CITES, 2003). Preliminary data from Mexico indicate warming and OA decrease larval survival and calcification, as well as increase the development rate of veligers, resulting in a faster settlement and shorter dispersal (Aranda, presented at 69th GCFI meeting, Nov. 2016). Finally, while larval cobia have been shown to be sensitive to future OA (Bignami et al., 2013), it is unknown if other commercially important fishes will be similarly impacted (e.g., snappers, groupers). Further work is needed to isolate the direct OA impacts on the physiology of multiple life stages of these species.

Other marine species in the region are not directly fished, but should be prioritized due to their ecological influence. For instance, unprecedented blooms and mass strandings of floating *Sargassum* have been reported along Caribbean and Florida coasts since 2011. These strandings have major implications for nearshore areas as they can increase nutrients, fuel hypoxic events, and trigger fish and invertebrate kills (e.g., van Tussenbroek et al., 2017). *Sargassum* from a temperate habitat has been shown to thrive in naturally acidified environments (Kumar et al., 2017) and similar studies are needed for tropical species. Finally, the urchin *Diadema* was once extremely abundant throughout the Caribbean and was instrumental in algae control on reefs, as well as framework erosion. Since the 1980s it has experienced a stark decline in abundance due to a Caribbean-wide die-off (Lessios, 2016). *Diadema* has potentially soluble, high magnesium calcite structures and OA could be a contributing factor in the limited recovery of this species (Dery et al., 2017; Uthicke et al., 2013).

As research progresses, it is imperative to incorporate ecological complexity into the evaluation of the impacts of OA. This involves the collection of multi-species community response data, rather than changes in the physiology (e.g., growth rates) of a single or small number of species. Natural ecosystems reflect ecological complexity orders of magnitude higher than that replicated in even the most biodiverse artificial mesocosm studies and interacting species that are differentially influenced by OA stress can give rise to unexpected outcomes

(Enochs et al., 2016a). Similarly, environmental complexity and multiple stressors can exacerbate (e.g., nutrients, warming) or ameliorate (feeding) the influences of OA. Communities presently existing in naturally high CO_2 environments provide insights into real-world community response to OA. While naturally acidified ecosystems are known from the Caribbean (e.g., vents, McCarthy et al., 2005; inlets, Enochs et al., 2019; ojos, Crook et al., 2013), they remain understudied relative to the Pacific (e.g., Manzello, 2010; Fabricius et al., 2011; Shamberger et al., 2014; Enochs et al., 2015a, 2016a). As such, the identification of new high-CO_2 analogs within the region is of paramount importance, along with detailed investigation of how OA-like conditions alter the ecology of surrounding biota.

Research Objective 8.5: Improve understanding of the responses of bioeroding communities

Understanding the responses of bioeroders to OA and co-occurring stressors is critically important for determining reef persistence, yet this relationship is poorly understood in the Caribbean.

Action 8.5.1: Conduct experiments to assess the responses of Caribbean bioeroding organisms to OA and co-occurring stressors (e.g., temperature and land-based sources of pollution).

Research Objective 8.6: Evaluate the influence of carbonate chemistry variability on ecosystem engineering taxa such as bioeroding and calcifying species

Further work is necessary to understand how real-world diel and seasonal fluctuations in carbonate chemistry influence ecologically, and economically important species.

Action 8.6.1: Conduct laboratory experiments to assess the responses of key Caribbean taxa to fluctuating carbonate chemistry.

Action 8.6.2: Compare the biological responses of species living in environments with different carbonate chemistry dynamics.

Research Objective 8.7: Evaluate differences in OA-sensitivity within coral species and molecular mechanisms associated with OA resilience

An understanding of different genotypic responses to OA will lead to science-based restoration practices that incorporate the threat of OA.

Action 8.7.1: Incorporate genotypes as a factor when designing OA response experiments.

Action 8.7.2: Conduct experiments to assess how the transcriptomes and proteomes of key taxa are influenced by OA, prioritizing comparisons between sensitive and resilient individuals.

Action 8.7.3: Examine the genome and gene expression of key taxa living in OA hotspots.

Research Objective 8.8: Investigate the direct response of understudied ecosystems, as well as iconic, invasive, endangered, and commercially important species to OA

Ecosystems are chemically and biologically interconnected, and their persistence is therefore interdependent. The OA sensitivities of many ecologically, economically, and culturally important species remain relatively unknown.

Action 8.8.1: Assess the sensitivity of seagrass and mangrove ecosystems to OA using field studies and laboratory experiments.

Action 8.8.2: Assess the sensitivity of key understudied taxa (e.g., Lobster, Conch, Stone crabs, fishes, *Sargassum* and *Diadema*) to OA.

Research Objective 8.9: Identification and investigation of natural high-CO_2 analogs

Naturally high CO_2 systems provide a means of investigating complex ecosystem-level responses to OA, where long-term exposure (decades to centuries) can reveal the implications of subtle responses, as well as acclimatization.

Action 8.9.1: Identify and characterize new high-CO_2 analogs within the region.

Action 8.9.2: Leverage naturally high-CO_2 ecosystems to better understand and predict real-world responses to OA.

Human dimensions in the Florida Keys and Caribbean Region

Focusing solely on biological and chemical research and monitoring can lead to ineffective management of coastal resources. Many key drivers of ecosystem decline are linked to human behavior and activities. Therefore, management can benefit from an approach that recognizes people and society as part of the ecosystem, addressing their interrelationship, important ecosystem services, and perceived ecosystem values. Ultimately, this deeper understanding of the human connections helps managers assess the social and economic consequences of management policies, interventions, and activities. The socioeconomic component of NCRMP presently includes survey questions on knowledge, perception, and awareness of a few key climate and OA related topics, but NOAA-supported work within the region is limited.

Fishermen out for a trip in Florida Keys National Marine Sanctuary. Photo: Nick Zachar/NOAA

A new report led by the U.S. Department of the Interior U.S. Geological Survey has evaluated the role of U.S. coral reefs in coastal hazard risk reduction. Coral reefs can substantially reduce coastal flooding and erosion by dissipating shoreline wave energy. The annual value of flood risk reduction by U.S. coral reefs is more than 18,000 lives and $1.805 billion (2010 USD, Storlazzi et al., 2019). In Florida alone, over $319 million (2010 USD) of economic activity is of economic activity is preserved due to flood protection from coral reefs, while in Puerto Rico and the U.S. Virgin Islands reef protection has been valued at $117 million and greater than $25 million, respectively (Storlazzi et al., 2019). Coupling these valuations with OA-specific forecasts for loss of coral reef structural integrity and rugosity may provide increased clarity for decision makers on the economic cost of OA-related reef degradation.

On a limited basis, other projects are beginning to address ecosystem services through economic valuation. Again, coupling this approach with OA-relevant ecosystem forecasts can lead to the tangible measurement of the economic impact of OA within the region. Providing these data to agencies, decision makers, and lawmakers (local, state and national) aids with budget allocations, environmental mitigation, and research support prioritization. This should be done for important fisheries, which in Florida alone have been estimated to generate $28.7 billion, and support 177,000 jobs (NOAA's Fisheries Economics of the United States 2015 Report). With respect to ecotourism, NOAA's Florida Keys National Marine Sanctuaries and CRCP suggest that coral reefs in southeast Florida have an asset value of $8.5 billion, generating $4.4 billion in local sales, $2 billion in local income, and 70,400 full and part-time jobs, much of which will be threatened due to OA's effects on reef-building corals. Additional assessments are needed to quantify the economic impact of accelerated reef structure erosion leading to less protected coastal infrastructure and property. This is particularly relevant for the Florida Keys and Caribbean that rely heavily on Blue Economy drivers such as coastal tourism and shipping.

Combining natural and social science data by mapping indicators is an approach that could be utilized to prioritize management and inform policy (Pendleton et al., 2016). For example, an interdisciplinary approach might involve comparing chemical and ecological monitoring with public perception of reef health or OA awareness. Some of these data may be gleaned from NCRMP and other related social science efforts (Gorstein et al., 2016, 2017). At the global scale, there are pre-existing tools that have been developed to assess human vulnerability and resilience to climate impacts (Wongbusarakum and Loper, 2011). These tools can be adapted for this region, and for development of a set of socioeconomic indicators related to ocean and climate change. These could then be included into a socioeconomic assessment of any site for which ocean and climate change impacts are an important issue. The resulting information can then inform coastal management needs and adaptive management practices.

Research Objective 8.10: Economic assessment of the impact of OA in region

By coupling ecosystem forecasts with economic valuations, OA impacts can be assessed, providing important information and projections to decision makes and lawmakers.

Action 8.10.1: Quantify the economic impact of OA-accelerated reef structure erosion leading to less protected coastal infrastructure and property.

Action 8.10.2: Quantify the economic impact of OA on recreational and commercial fisheries through direct physiological and behavioral alteration of fished species, as well as degradation of essential habitat.

Research Objective 8.11: Interdisciplinary and integrated socio-ecological approaches

Spatially-explicit economic indicators and visual mapping tools are an effective means to clearly communicate risk.

Action 8.11.1: Develop mapping tools and socioeconomic indicators related to OA.

Action 8.11.2: Use indicators to communicate risk, and inform management and adaptation.

9. Mid-Atlantic Bight Region Acidification Research

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Abstract

The Mid-Atlantic Bight Region includes the eastern United States continental shelf area extending from Cape Hatteras, NC to Cape Cod, MA. Ocean acidification (OA) in the region is modified by ocean circulation patterns, particularly influenced by the Labrador Sea water that forms the cold pool, natural seasonal and decadal variability, and eutrophication. The Mid-Atlantic Bight is home to important commercial shellfisheries and finfish, which have shown some sensitivity to OA. NOAA's Mid-Atlantic Bight Region research goals are to:

- Improve OA forecasts across daily to decadal timescales informed through a modified regional observing system that better quantifies the primary drivers of vertically resolved carbonate dynamics with an increased emphasis at reactive interfaces (e.g., sediment boundary, land-ocean, etc.) in context with other environmental change;
- Determine how OA in concert with other stressors impact ecologically and/or economically important marine species, with a focus on understanding impacts to aquaculture stocks;
- Evaluate costs and benefits of mitigation and adaptation strategies for communities, ecosystems and economies; and
- Promote integration of OA understanding into regional planning and management.

Acidification in the Mid-Atlantic Bight Region

Presented in this chapter are the mid-term priorities and objectives of NOAA's OA research, modeling, and monitoring interests specific to the waters of the Middle Atlantic Bight (MAB; **Figure 9.1**). The MAB extends from Cape Hatteras, NC, to the southern coast of Cape Cod, MA, and is part of the Northeast U.S. Continental Shelf Large Marine Ecosystem (LME). For information on the northern region of the Northeast LME, please refer to *Chapter 10, New England Region Acidification Research Plan*.

The MAB is characterized by a large continental shelf, multiple shelf break canyons, five geographically distint estuarine ecosystems (Chesapeake Bay,

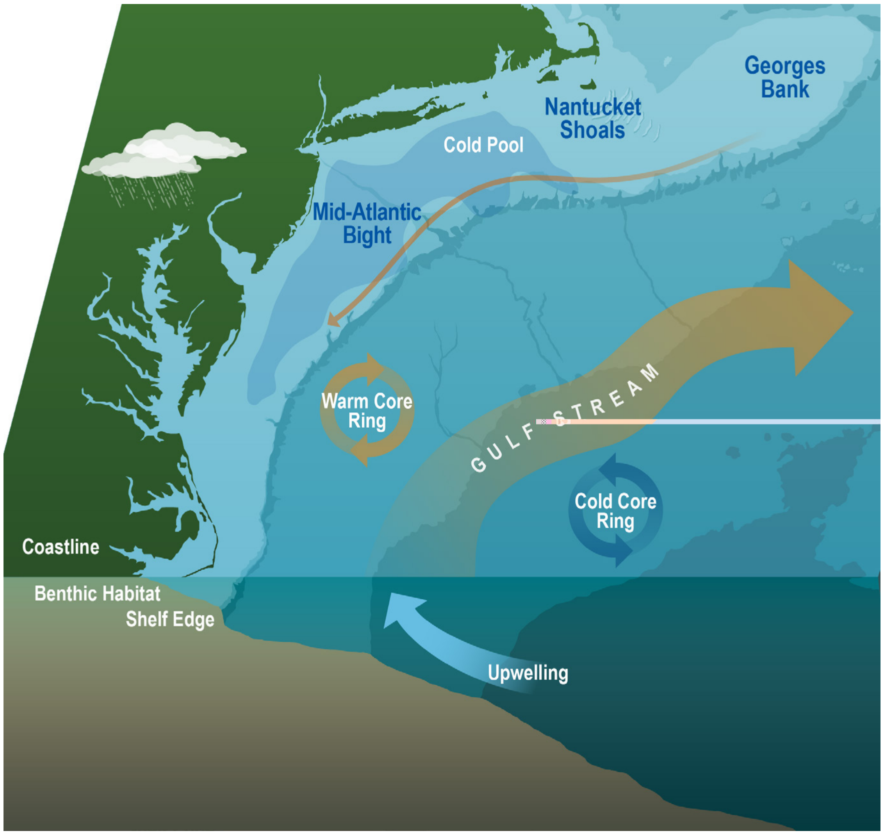

Figure 9.1. The Mid-Atlantic Bight region with depth, from Southern Massachusetts to Cape Hatteras, NC. Water from the Gulf Stream comes in from the south, while the Shelf Break Jet brings water from the North. Warm and cold core rings can be found along the Gulf Stream. Credit: NOAA

Delaware Bay, Long Island Sound, the coastal bays in Maryland and Virginia, and the Albemarle-Pamlico Estuarine System), and barrier islands that enclose shallow coastal bays (e.g., Great South Bay (NY), Barnegat Bay-Little Egg Harbor Estuary (NJ), Assawoman Bay (DE), and Chincoteague Bay (MD). Polar water from the Labrador Current and warmer water from the Gulf Stream meet in this region, resulting in dynamic distributions of temperature, salinity, and density over vertical and lateral scales. During the fall, storms (i.e., hurricanes, Nor'easters) bring strong winds, which lead to a well-mixed water column (Lentz, 2003; Rasmussen et al., 2005). However, during the late spring/early summer strong surface heating and weakening winds lead to the development of a thermocline about 20 meters deep, spread across the entire shelf, creating a continuous mid-shelf "cold pool" (**Figure 9.2**; Goldsmith et al., 2019; Wang, 2016). The "cold pool" has been linked to the distribution and recruitment of commercial and recreational fin and shellfish species in this region (Powell et al., 2020; Weinberg, 2005). The MAB is also characterized by regions of upwelling along the shelf break (Benthuysen et al., 2015; Brooke et al., 2017). Along the coast, southwest winds associated with the Bermuda High and Ekman forcing can also result in upwelling regions (Glenn et al., 2004). Upwelling areas in the MAB are characterized with enhanced primary productivity, intense fishing activity, and low dissolved oxygen concentrations.

Key physical and biogeochemical drivers, such as seasonal changes in net-community production, temperature, salinity, physical mixing, and nutrient loading, in addition to air-sea gas exchange influence acidification in the MAB region. For example, Gulf Stream waters along the southern portion of the MAB have elevated aragonite saturation (Ω_{arag}). In contrast the less buffered northern region of the MAB is influenced by colder southward coastal currents fed by Labrador Sea (Wanninkhof et al., 2015) and Gulf of Maine (Wang et al., 2013) water result-

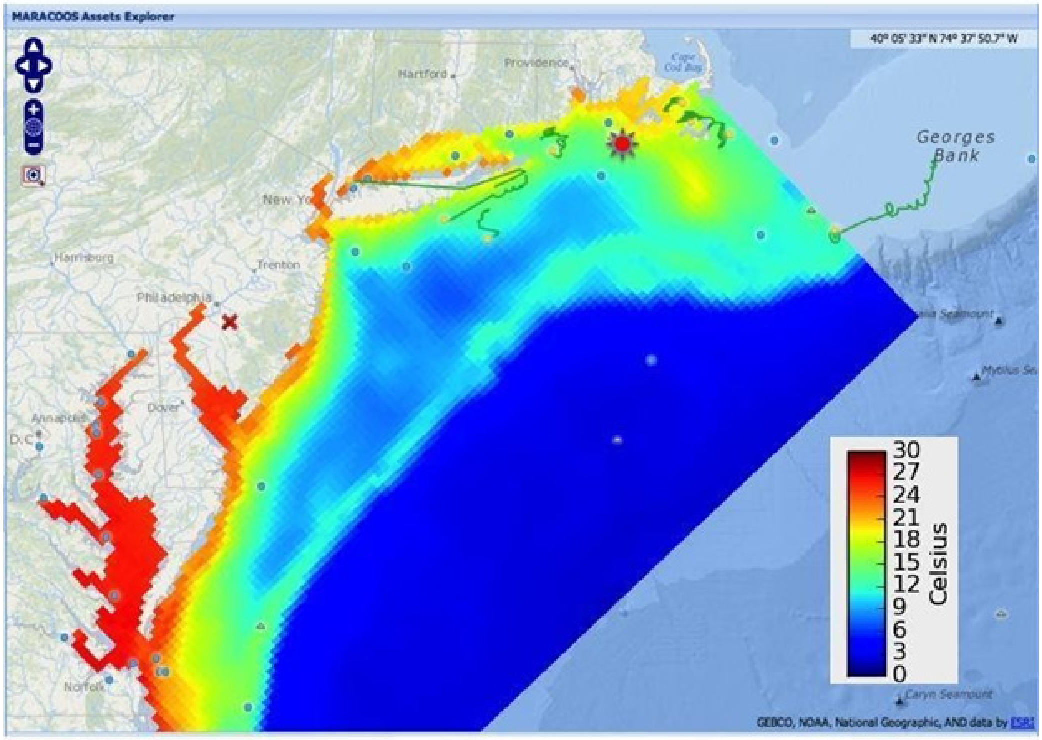

Figure 9.2. Bottom temperatures for part of the Mid-Atlantic region, showing the Cold Pool. Courtesy of: MARACOOS/Rutgers University

ing in comparatively lower Ω_{arag}. Closer to the coast, biological activity and eutrophication can affect temporal and spatial variability in carbonate parameters (Cai et al., 2011; Wanninkhof et al., 2015; Xu et al., 2017). Because the MAB supports a diverse assemblage of commercially and recreationally important finfish (bony and cartilaginous) species (Gates, 2009; Sherman et al., 1996), and critical shellfish fishing grounds, hatcheries, aquaculture beds, and oyster restoration areas, it may prove to be an area uniquely vulnerable economically to both ocean and coastal acidification.

The MAB has a diverse assemblage of flora and fauna including commercially and recreationally important shellfish and finfish, deep water hard corals, soft corals and sea fans, as well as shellfish hatcheries, aquaculture leases, and oyster restoration areas (Dubik et al., 2019; McManus et al., 2018; Munroe et al., 2016; Narváez et al., 2015; Powell et al., 2020; Schweitzer & Stevens, 2019; Waldbusser et al., 2013). Fisheries in the MAB region totaled $800 million in 2016 with sea scallops, blue crab, and the eastern oyster accounting for 56% of the total revenues (NEFSC, 2018; NOAA Fisheries, 2019b). As in the Northeast (NE) region, marine aquaculture is expanding in every state with the potential of offshore aquaculture throughout the coastal zone, highlighting the importance of characterizing the drivers of OA in the MAB. With 5 major estuaries and many coastal barrier island bays, eutrophication may contribute substantially to OA in this region (Goldsmith et al., 2019; Kennish et al., 2007, 2016; Saba et al., 2019) affecting growth, survival, and calcification of several larval shellfish species (Clements & Chopin, 2017; Clements & Hunt, 2014; Gobler & Talmage, 2014; Hattenrath-Lehmann et al., 2015), finfish species (Chambers et al., 2014; Perry et al., 2015), and crustaceans (Giltz & Taylor, 2017; Glandon et al., 2018; Glandon & Miller, 2016). Consequently, many coastal communities in the MAB have a medium-high to high vulnerability risk to OA, with anticipated effects by 2071 (Ekstrom et al., 2015). Understanding the physical and biogeochemical drivers of OA, organism responses to these drivers, and the socioeconomic effects on the fishing and aquaculture industries, recreational fisheries, and tourism will help determine if mitigation strategies need to be implemented in some communities to reduce the effects of OA.

Environmental Change in the Mid-Atlantic Bight Region

Surveys of surface carbonate chemistry in the MAB conducted by NOAA and other research institutions have shown large natural variability on decadal timescales (Boehme et al., 1998; Wang et al., 2017, 2013). Regional satellite-derived surface $p\mathrm{CO}_2$ algorithms depict strong seasonal variability with lower $p\mathrm{CO}_2$ values in winter and spring and higher $p\mathrm{CO}_2$ values during the summer and fall primarily driven by seasonal temperature dynamics. Repeated shipboard campaigns have shown relatively low pH, Ω_{arag}, and buffering capacity of waters of the northeastern U.S. shelves, which indicates elevated risk to continued acidification compared to southern counterparts (**Figure 9.3**; Wang et al., 2013). Limited MAB bottom water CO2SYS surveys have shown enhanced seasonal stratification relative to surface conditions, as respiratory DIC production, and lower temperature and salinity conditions brought in from the north as Labrador Sea slope water. The complexity of the surface and bottom MAB waters demands simultaneous observations of physical, biological, and chemical parameters within the region to better inform OA forecasts and projections.

Improved biogeochemical models that describe OA conditions and interactions with environmental conditions are necessary to develop decision support tools. These models should focus on creating accurate short- and long-term projections that aid efforts to better evaluate species sensitivity and potential Blue Economy vulnerability. Specifically, using down-scaled Global Circulation Models (GCMs) to hindcast historical changes in carbonate chemistry would help assess the evolution of acidification through time beyond the limited domain of the observing system. Further refinement of down-scaled GCMs may then be used to project future long-term changes with respect to OA. Because temperature, oxygen levels, and eutrophication change on weekly timescales, improved models can also be used to generate shorter-term forecast conditions (1-3years) in the the MAB to provide valuable environmental intelligence for use by local stakeholders

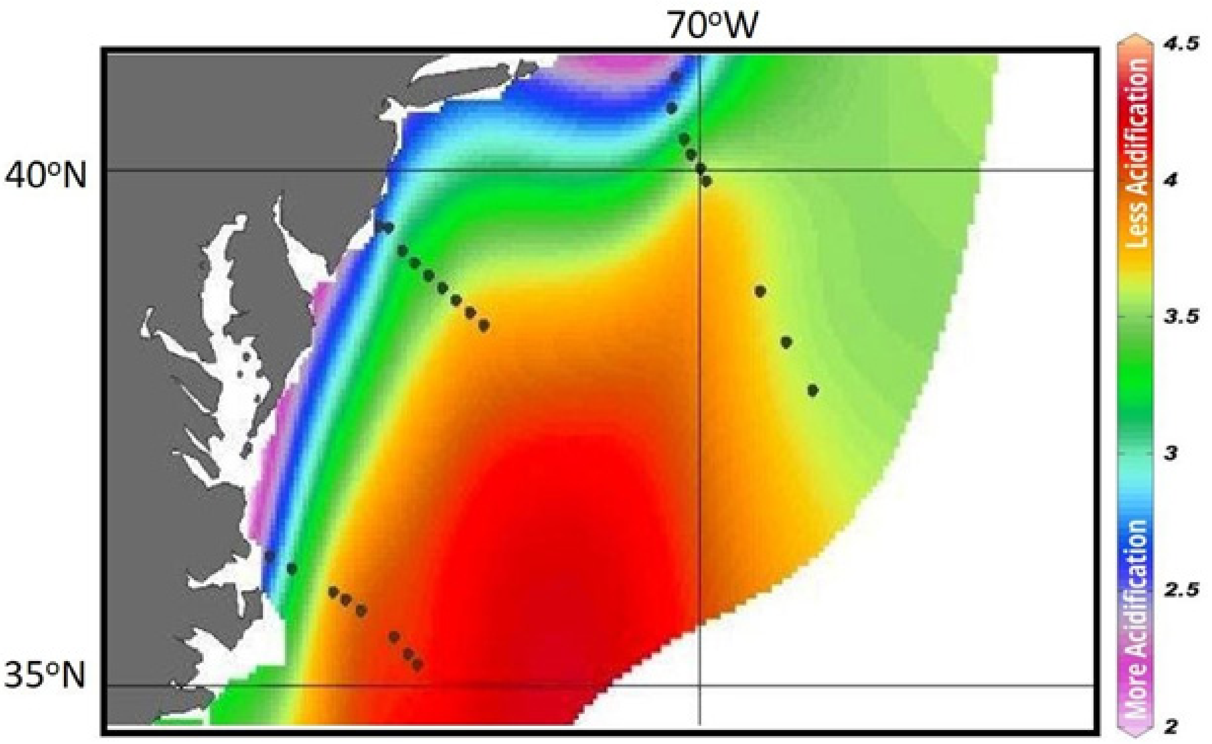

Figure 9.3. Aragonite saturation state of surface water in the MAB. Dots represent transects where data are collected. Source: http://www.aoml.noaa.gov/ocd/ocdweb/occ_oa.html

and managers. Such models must be informed and validated by high quality monitoring data that encompass direct field measurements of carbonate chemistry and related biogeochemical and physical processes.

A buoy used to monitor the changing chemistry in the Chesapeake Bay. Credit: NOAA

Research Objective 9.1: Improve OA forecasts on daily to decadal timescales in context with other environmental change

The existing portfolio of OA-capable observing assets in the region are sparse and/or are taking measurements too infrequently to reliably describe all the dominant modes of variability needed to constrain and validate regional BGC models. Processes within the MAB Region (i.e., eutrophication, cold pools, upwelling, and estuarine biogeochemistry) have implications for OA that are not well understood. By using modified a regional observing system that is able to better quantify the primary drivers of vertically-resolved carbonate dynamics with an increased emphasis at reactive interfaces (e.g., sediment boundary, land-ocean, etc.), OA forecasts for this region can be improved. Collaborations with hatcheries, state, and other federal agencies to monitor coastal conditions should be promoted wherever feasible to leverage observing capabilities and coverage.

Action 9.1.1: Carbonate chemistry measurements should be coupled with other environmental parameters (i.e., salinity, temperature, physical mixing, nutrient loading) and should range from surface to the benthos, across the shelf and into estuaries.

Action 9.1.2: Synthesize data to understand carbonate chemistry dynamics of different water masses and temporal changes within the MAB including biochemical feedbacks within the water column and the benthos.

Action 9.1.3: Synthesize, promote, coordinate, and augment sampling at riverine inputs to the estuaries to determine how river discharge effects alkalinity and OA within the MAB estuaries, coastal embayment, and coastal zone.

Action 9.1.4: Promote the use of autonomous technologies to better assess the relative contribution of upwelling, hypoxia, nutrient, and sediment loading on OA in the region.

Research Objective 9.2: Simulate full-water column carbonate chemistry dynamics of shelf and primary estuarine systems

The limited spatial and temporal frequency of existing water column and near-bottom biogeochemical measurements in the MAB make it difficult to fully resolve short-term variability and long-term trends in carbonate chemistry across the region. As most potentially impacted commercial species reside at depth or even at the benthos, it's important that modeling efforts seek to fully describe the system in 4-D and that such models include all major drivers of carbonate dynamics (e.g., OA, changes in currents, exchange with off-shelf waters, etc.).

Action 9.2.1: Collate and synthesize existing carbonate chemistry data in the region that can be used for model validation and other studies.

Action 9.2.2: Continue development of biogeochemical models to characterize OA conditions and evaluate our understanding of the mechanisms driving environmental conditions.

Action 9.2.3: Develop and/or support biogeochemical Regional Ocean Models (ROMs) efforts informed by GCM down-scaling to hindcast (past decadal changes), nowcast (hourly), forecast (days to weeks), and project OA conditions (years to decades) with concomitant changes in temperature, oxygen levels, and eutrophication.

Action 9.2.4: Conduct studies to inform biogeochemical models to evaluate dynamics at the sediment-water interface with increased OA, eutrophication, and hypoxia.

Biological Sensitivity in the Mid-Atlantic Bight Region

The MAB region is a dynamic area experiencing changes in temperature, precipitation, and eutrophication. From 1977 to 2016, sea surface temperature increased an average of 0.057°C during the winter/spring and 0.047°C during fall/winter (Saba et al., 2016; Wallace et al., 2018). The MAB region also has coastal areas that are affected by eutrophication (Bricker et al., 2008; Ekstrom et al., 2015; Greene et al., 2015). The increase in temperature and high level of eutrophication have considerable implications on the regional marine ecosystem. A recent vulnerability analysis of 82 species from the Northeast Continental Shelf Region, which includes MAB, found 27% of taxa to be highly vulnerable to climate-related changes (Hare et al., 2016). Potentially vulnerable species include: Atlantic surfclams (*Spisula solidissima*), Atlantic sea scallops (*Placopecten magellanicus*), blue crab (*Callinectes sapidus*), shortnose and Atlantic sturgeons (*Acipenser brevirostrum, A. oxyrhynchus*), and winter flounder (*Pseudopleuronectes americanus*). Importantly, the majority (69%) of the shellfish and finfish managed by the Mid-Atlantic Fisheries Management Council have not been investigated for OA impacts.

OA laboratory experiments on bivalves, crustaceans, and finfish have demonstrated species-specific response to OA. For bivalves, (i.e., eastern oyster and hard clam) reduced larval growth, calcification, and survivorship (Boulais et al., 2017; Gobler & Talmage, 2014; Miller et al., 2009; Talmage & Gobler, 2009), and changes in physiology (i.e., respiration, feeding rates, Ivanina et al., 2013; Vargas et al., 2013) have been observed. A few multi-stressor OA studies (i.e., combined effects of carbon dioxide (CO_2) and hypoxia) on bivalve larvae reported decreased growth and survival (Clark & Gobler, 2016; Ekstrom et al., 2015; Gobler & Talmage, 2014), while decreases in salinity and increases in temperature have also been linked to decrease calcification in bivalves (Ries et al., 2016; Speights et al., 2017). Research on juvenile blue crabs have found that OA affects survival, respiration, growth, development, and food consumption, and that higher temperatures amplify this effect (Glandon et al., 2018; Glandon & Miller, 2016; Glaspie et al., 2017).

A whooping crane captures a blue crab, a shellfish of economic and ecological importance in the Mid-Atlantic Bight Region. Credit: NOAA

Experimental studies of CO_2 effects on regionally important finfish have examined a select group of shelf, nearshore, and inshore/estuarine inhabitants. Among these, summer flounder (*Paralichthys dentatus*) embryos had diminished survival to hatching and the developmental rate of larvae was accelerated by elevated CO_2 (Chambers et al., 2014). Various forage fishes including Atlantic silverside (*Menidia menidia*), inland silverside (*M. beryllina*), and sheepshead minnow (*Cyprinodon variegatus*) have been examined for CO_2 effects and these taxa exhibited a range of impacts. From these forage fish to economically important ones (e.g., red drum, *Sciaenops ocellatus*), evidence is building that estuarine taxa are likely to be more resilient than species living in offshore habitats to elevated CO_2 (Lonthair et al., 2017). A handful of studies have examined fish of more advanced ages and results show older fish to be more tolerant that younger ones to elevated CO_2 (e.g., juvenile scup, *Stenotomus chrysops*, Perry et al., 2015). These experimental studies highlight the complex responses exhibited by marine organisms to CO_2 under multi-stressor conditions. A summary of research on species found in the MAB appears in Saba et al. (2019). Further research on the MAB species should include laboratory studies of advanced experimental approaches that can examine the scope of response and adaptation potential, environmental variation, population-level differences, and transgenerational responses that provide data that can be combined with habitat suitability modeling.

Research Objective 9.3: Determine how OA and other multi-stressors impact ecologically and/or economically important marine species

OA in combination with eutrophication, increased temperature, and declining oxygen concentrations may be altering the habitat suitability for ecologically and/or economically important marine species at different times in their life histories. These experiments should include direct and indirect (i.e., predator-prey interactions, pathogen, disease) effects as needed. Experiments on estuarine-dependent species should also include temporally varying stressors that mimic environmentally relevant patterns.

Action 9.3.1: Develop experiments to address population and life-stage responses with respect to OA and environmental stressors for important shellfish, crustaceans, and finfish in the region.

Action 9.3.2: Characterize phenotypic plasticity and the genetic potential to understand selective mortality emanating from OA and related stressors.

Action 9.3.3: Determine the energetic costs of acclimation to OA using experimental mechnistic measure, including physiology.

Action 9.3.4: Encourage field experiments that use existing platforms (i.e., hatcheries, restored oyster reefs) to monitor physiological and life-stage responses.

Research Objective 9.4: Use experimental results to parameterize dynamic process models that allow evaluation of the within- and among-generation consequences of OA-impaired biological outcomes in populations

Develop more realistic, biologically informed models to capture population, community, and ecosystem responses to OA and environmental co-stressors, thereby enabling population projections and servicing ecosystem-based management strategies.

Action 9.4.1: Link experimental and population/ecosystem modeling efforts to identify and rank highest value information at appropriate scales to develop, augment, and/or evaluate dynamic process models of populations and ecosystems.

Action 9.4.2: Ground truth model predictions with experimental testing of predictions within and beyond the parameterized framework of the model.

Action 9.4.3: Compare and contrast models for sensitivity and robustness in applications within the MAB and the model utility in other regions.

Human Dimensions in the Mid-Atlantic Bight Region

Many coastal communities in the Mid-Atlantic Bight region are reliant on commercial fishing (valued near $800 million), and recreational fishing/tourism (valued $3.5 billion, NOAA Fisheries, 2017; NEFSC, 2018). The region is particularly dependent on benthic shellfish species and therefore the social vulnerability to OA is high. This high vulnerability could be potentially exacerbated by eutrophication, which can amplify OA in estuaries (Ekstrom et al., 2015). While the wild harvest of oysters is in decline, oyster aquaculture is increasing quickly throughout the Mid-Atlantic, especially in Virginia. Virginia ranks first in the U.S. for hard clam production and first on the East Coast of the U.S. for eastern oyster production, with a combined value of $53.4 million in 2017 (Hudson, 2018). Additionally, shellfish hatcheries throughout the MAB are increasing in both numbers and production capacity with concomitant increases in part-time and full-time jobs (Calvo, 2018; Hudson, 2018). Despite the importance of OA-susceptible species to coastal communities and economies, human dimension research has lagged behind research on biogeochemistry, physiology, and ecology.

Several areas of research are needed, including modeling how changes in carbonate chemistry impact profitability of shellfish harvests and predicting economic impacts on fishery stocks and aquaculture operations. Examination of synergistic/antagonistic effects of multiple stresses (*Objective 9.4.1* above) should link to economic and human impacts. As it is likely that OA will differentially impact the various sectors of fisheries (i.e., hatcheries, aquaculture, and wild fisheries), these investigations should be conducted by sector. Additional research is needed to better understand the social and economic vulnerability of fishing and aquaculture communities and the capacity of industries to develop mitigation and adaptation strategies. Tribal governments and indigenous communities should be engaged in science and monitoring, and their vulnerability assessed.

A paddler enjoys a sunset over the Chesapeake Bay which benefits fish, crabs, oysters, and people. Credit: NOAA

Applications of any OA research findings must fit into existing management structures at the federal, state, and tribal levels. The Mid-Atlantic Fishery Management Council (MAFMC) and the NOAA National Marine Fisheries Service manage the federal fisheries in this region; however, some commercially important species (e.g., oysters, blue crab, and sea bass) are managed at the state level. Two species (spiny dogfish and monkfish) are jointly managed by both the New England Fishery Management Council (NEFMC) and the MAFMC. The region has collaborated on a regional ocean planning document (https://www.boem.gov/Mid-Atlantic-Regional-Ocean-Action-Plan/) that included stakeholders from a variety of sectors (fishing, tourism, offshore wind, marine transportation, etc.). The ocean planning activities allow for better spatial management across sectors. Effective communication of how OA will affect these efforts should be incorporated.

Research Objective 9.5: Understand how OA will impact fish harvest, aquaculture, and communities

Enhanced modeling and predictive capability of OA impacts to shellfish and fish populations can be linked to economic models that project outcomes for fishery sectors and communities. This information will be central to improving planning and management measures in the face of OA.

Action 9.5.1: Expand observation capability at aquaculture sites by including hatcheries and shellfish farms as OA monitoring sites to better understand drivers at the local scale.

Action 9.5.2: Expand model capability to use species-specific data to predict economic impacts.

Action 9.5.3: Expand model capacity to include how changing OA conditions combined with eutrophication/ hypoxia economically affect fishery and aquaculture stocks and the communities that depend on them.

Action 9.5.4: Estimate the threshold when changes in the carbonate chemistry will make harvesting or growing shellfish unprofitable by creating habitat suitability maps and documenting historical changes by mapping pre-industrial distributions and future projections (2060 and 2120).

Research Objective 9.6: Evaluate benefits and costs of mitigation and adaptation strategies

Understanding the costs and benefits of adaptation and mitigation strategies under different projected OA conditions will be vital to ensuring coastal community sustainability. Adaptation and mitigation practices should be tailored to the stakeholder (e.g., fishers, shellfishers, aquaculturists, recreationalists).

Action 9.6.1: Determine costs of mitigation strategies and fishers relocating to follow species displaced by OA.

Action 9.6.2: Identify specific strains/breeds of species (shellfish, in particular) that are able to respond better to OA conditions (e.g., genetic hardening).

Action 9.6.3: Investigate alternative management options to ensure maximum sustainable fisheries yield and aquaculture production under future conditions.

Research Objective 9.7: Integrate OA understanding into regional planning and management

Rapid changes in OA conditions will require management to react quickly to changes in harvestable species and consider OA in future planning.

Action 9.7.1: Conduct comprehensive management strategy evaluations and scenario development to assess the ability of fisheries management to react to changes in harvested populations.

Action 9.7.2: Support economic modeling and sociological studies to determine the ability of fishers and aquaculturists to alter practices as harvested and/or cultured populations change.

Action 9.7.3: Develop Climate-Induced Social Vulnerability Indices (CSVIs) with respect to OA to improve the understanding of how communities might respond to OA in a resilient way.

Action 9.7.4: Incorporate OA research findings into existing NOAA products that support management, such as NMFS ecosystem status reports.

10. New England Region Acidification Research

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Abstract

The New England Region geographically includes the Gulf of Maine, Georges Bank, and Scotian Shelf. Ocean acidification (OA) in this region is driven mainly by temperature changes and regional ocean circulation patterns of various water masses. This region is experiencing temperature changes three times greater than the global average. This area is also characterized by increases in precipitation during winter and spring, enhancing freshwater influx from riverine sources and contributing to eutrophication. Economically important species such as the Atlantic scallop and American lobster are impacted by regional changes in ocean chemistry and pose a threat to the fishing and aquaculture industries and the economy of the region. NOAA's New England research goals are to:

- Improve regional biogeochemical characterization and understanding of trends and dynamics of ocean pH, particularly in response to temperature and riverine influence, to develop dynamic regional forecasts of OA;
- Understand the response of critical marine species under multi-stressor (low pH, high temperature, low oxygen) conditions and assess adaptive capacity to OA to inform ecosystem management; and
- Use new knowledge to assess OA impacts to communities and economies to include OA into regional management plans and evaluate the costs and benefits of various mitigation and adaptation strategies.

Acidification in the New England Region

Presented in this chapter are the mid-term priorities and objectives of NOAA's OA research, modeling, and monitoring interests specific to waters in the Northeast United States that include the Gulf of Maine, Georges Bank, and western Scotian Shelf regions within the Northeast U.S. Continental Shelf Large Marine Ecosystem (LME; **Figure 10.1**). For information on the southern region of the Northeast LME, please refer to *Chapter 9 Mid-Atlantic Bight Region Acidification Research Plan*.

The highly productive New England Region waters have a long history of extensive commercial fishing

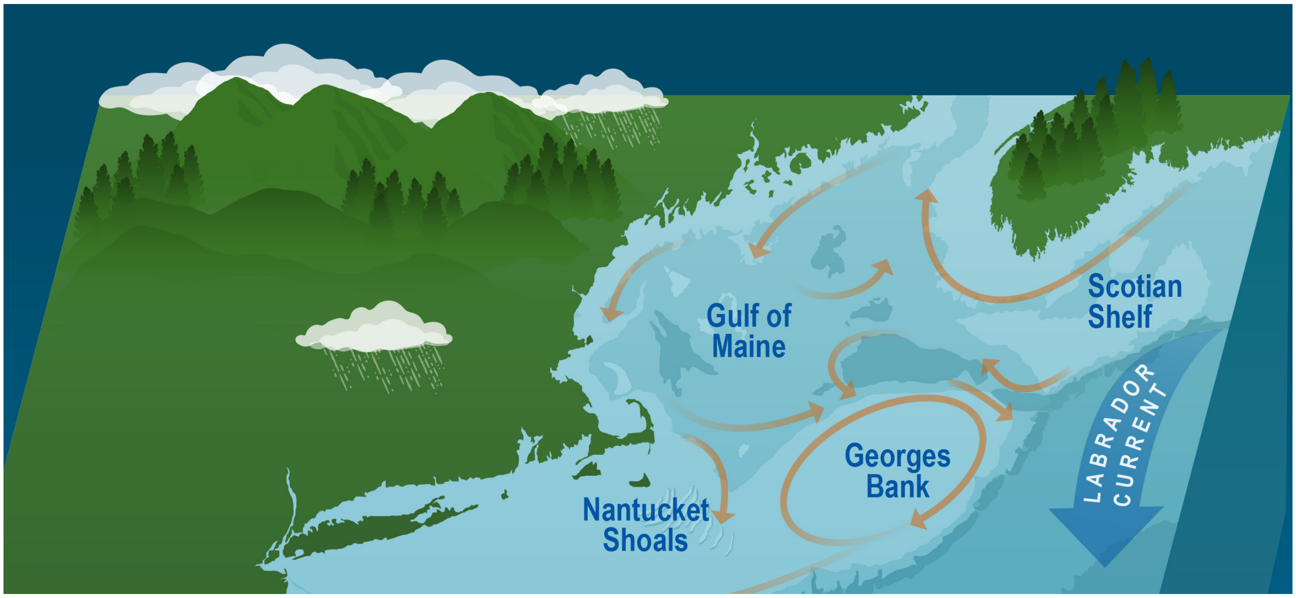

Figure 10.1. The watershed for the New England Region, which includes the Gulf of Maine, Georges Bank, and Scotian Shelf. Credit: NOAA

(Colburn et al., 2016; Jepson & Colburn, 2013; Townsend et al., 2006) and are characterized by the many physical processes that influence biogeochemistry in the region. The region includes a wide (>200 km) continental shelf, shallow tidally-mixed banks, deep basins, submarine canyons, and multiple riverine systems that feed into the Gulf of Maine. Oceanic current systems strongly influence the temperature and salinity characteristics, while oceanographic features such as circulation patterns, tidal mixing, and frontal zones affect every aspect of the ecology of the system. The hydrological characteristics of the New England Region strongly influence the OA signal, however thermodynamic heating, salinity anomalies, increased acidic river discharge, and coastal eutrophication can have both synergistic and antagonistic effects on OA in the region (Salisbury et al., 2008; Salisbury & Jönsson, 2018; Wang et al., 2017; Wanninkhof et al., 2015).

Understanding how physical drivers influence OA in the surface and bottom waters is critical due to the commercial and recreational use of the water column and benthos. The New England Region has low *in situ* pH, aragonite saturation state (Ω_{arag}), and buffering capacity attributed to inputs of fresh and lower alkaline waters and the accumulation of respiratory products from high primary productivity (**Figure 10.2**; Wang et al., 2017). However, in some portions of the region, processes such as net warming, variable salinity, and introduction of less buffered freshwater (i.e., river discharge) can make it difficult to detect long-term rates of change for OA (Fay et al., 2017; Salisbury et al., 2008; Salisbury & Jönsson, 2018; Tjiputra et al., 2014). On decadal timescales, the change in pH is dominated by carbon dioxide (CO_2) from the atmosphere, however, the Ω_{arag} signal is a combination of changes in total alkalinity (TA), sea surface temperature (SST), and salinity (Salisbury & Jönsson, 2018). With higher precipitation predicted in the future (Guilbert et al., 2015; Rawlins et al., 2012; Sinha et al., 2017), increased inputs of fresh water to the coastal zone may increase eutrophication, decrease TA, and consequently influence pH and $\Omega_{arag.}$ Changes in the climate, hydrology, and biogeochemistry all impact the OA signal, thus it is critical to characterize the respective drivers of OA and the ranges of chemical conditions within the system to determine species and ecosystem risk.

Fisheries landings in the New England Region totaled $1.2 billion in 2015 with Atlantic sea scallops and American lobsters accounting for 73% of the total landings making the fishing and marine aquaculture industry particularly vulnerable to changes in OA and Ω_{arag} (Lapointe, 2013). Shellfish habitats are predominantly in the coastal zones, which intersect with some of the 2019 fishing grounds for Atlantic

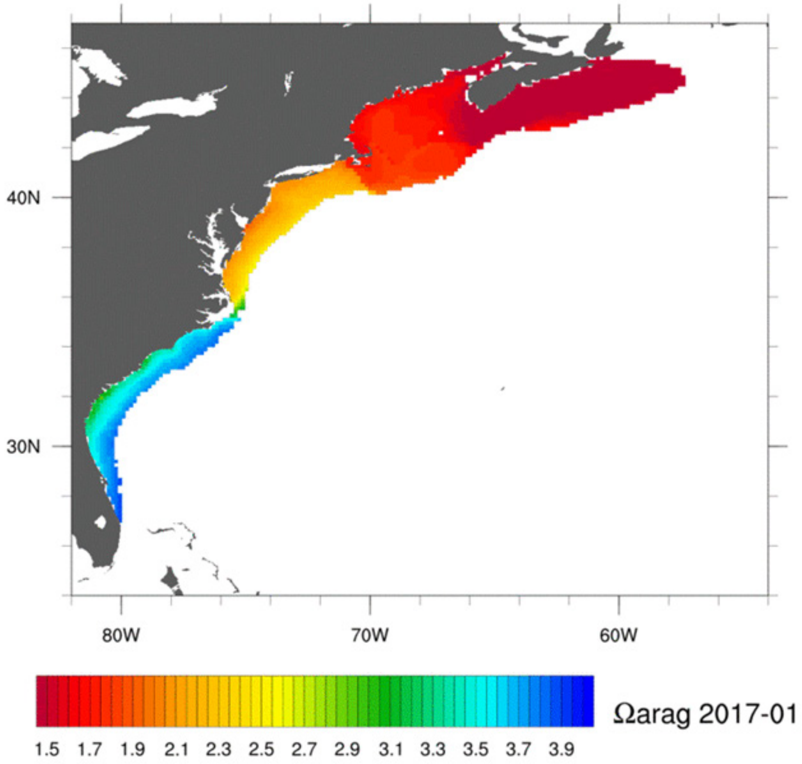

Figure 10.2. Aragonite saturation levels in 2017 for the northeast United States in January. The NE region has the lowest Ωarag on the East Coast with levels below 2.0. Image courtesy of Ruben van Hooidonk NOAA/AOML/CIMAS. The levels for the month of January is shown, with other months being represented on this web page: https://www.coral.noaa.gov/accrete/east-coast-oaps.html.

sea scallops (**Figure 10.3**). Marine aquaculture is expanding in every state of the region and the development of offshore shellfish aquaculture throughout the coastal zone, highlights the importance of characterizing OA drivers in nearshore and benthic environments, where acidification can be dominated by changes in local biogeochemical processes, and/or freshwater supply. Similarly, eutrophication and increases in heavy precipitation events due to climate change may contribute to increases in OA in coastal waters (Ge et al., 2017; Gobler & Baumann, 2016; Sinha et al., 2017) and affect the growth, survival, and calcification of several larval shellfish species (Clements & Hunt, 2014; Gobler & Talmage, 2014; Green et al., 2013; Salisbury et al., 2008). Consequently, many coastal communities have a medium-high to high vulnerability risk to OA with anticipated effects by 2031 (Ekstrom et al., 2015). Mitigation strategies, such as amending the seawater intake at mariculture facilities to compensate for low Ω_{arag} conditions and nutrient reduction, may need to be implemented in some communities. Dynamic biogeochemical environments in the region highlights critical gaps in understanding of how OA will progress and affect marine organisms and the fishing and aquaculture industries in the region.

Environmental Change in the New England Region

Understanding how OA is changing within the northernmost subareas (Gulf of Maine, Georges Bank) of the Northeast Large Marine Ecosystem (Sherman et al., 1996) demands a clear understanding of the physical and biogeochemical processes governing the disparate environments from Georges Bank, to deep Gulf of Maine basins, to coastal and estuarine systems. Scientists, the fishing industry, aquaculture industry, and policymakers need improved understanding of how OA conditions are changing contemporaneously with other factors including rapid warming, circulation changes, changes in seasonal precipitation, and shifts in the timing of the springtime freshet. These complexities necessitate that studies of OA impacts on marine species include synergistic or antagonistic effects with changes in non-OA parameters such as temperature. From an observing and modeling perspective this demands simultaneously targeting a comprehensive suite of physical, biological, and chemical parameters.

An ocean mooring in the Gulf of Maine used to monitor ocean conditions. Credit: Personnel of NOAA Ship DELAWARE II

Some of the most sensitive species in this region experience a range of different environments across their life-cycles including pelagic, benthic, estuarine, and oceanic. Only a subset of these environments have been suitably characterized with respect to OA. The current observing system in the region is comprised largely of surface observing measurements with some notable exceptions including the East Coast OA (ECOA, high spatial fidelity at quadrennial frequency) and quarterly NEFSC Ecosystem Monitoring (EcoMon, lower spatial fidelity at quarterly frequency). Improved subsurface monitoring in both time and space will require modifying the existing regional monitoring strategy including deployment of proven autonomous profiling technologies suited to measuring the entire water column inclusive of benthic environments.

Research Objective 10.1: Improve biogeochemical characterization of marine habitats most relevant to economically and/or ecologically important species

Target species will be inclusive of both pelagic and benthic species and will include observations of full life cycles. Leveraging existing datasets and supplementing the current Northeast observing system with additional subsurface capabilities through various activities will be critical to characterizing the less understood benthic and near-bottom environments.

Action 10.1.1: Support the development of new autonomous technologies suited for full carbonate chemistry water column profiling and benthic environment observing.

Action 10.1.2: Conduct data mining of existing benthic carbonate chemistry data, implementing long-term benthic monitoring at targeted locations, synthesizing exercises, and improving geochemical models to better capture the processes governing benthic environment.

Action 10.1.3: Conduct analyses to identify data gaps in parameters needed to characterize acidification dynamics within the region (past and present conditions).

Action 10.1.4: Establish long-term carbonate chemistry benthic monitoring at targeted locations to characterize interactions at the sediment water interface and relationships to surface productivity.

Action 10.1.5: Augment existing observing system to achieve improved spatiotemporal coverage of key processes and better characterize the full water column inclusive of the benthos.

Action 10.1.6: Improve and operationalize regional and subregional 4D biogeochemical modeling capabilities with enhanced data assimilation that captures land-sea, benthic, and physical processes.

Research Objective 10.2: Better understand the trends, dynamics, and changes in Scotian Shelf, Gulf Stream, and major riverine source waters and their influence on OA

Processes including advection, nutrient loading, and riverine discharge have implications for OA in the New England Region carbonate chemistry conditions that are currently not well characterized. Recent changes in the relative supply of Gulf Stream waters have resulted in dramatic increases in the Gulf of Maine water temperature elevating saturation states and altering the DIC supply to the system thereby altering its buffer capacity. Climate induced changes to the precipitation dynamics in the northeast have increased the frequency of high-intensity precipitation events and, together with warming,

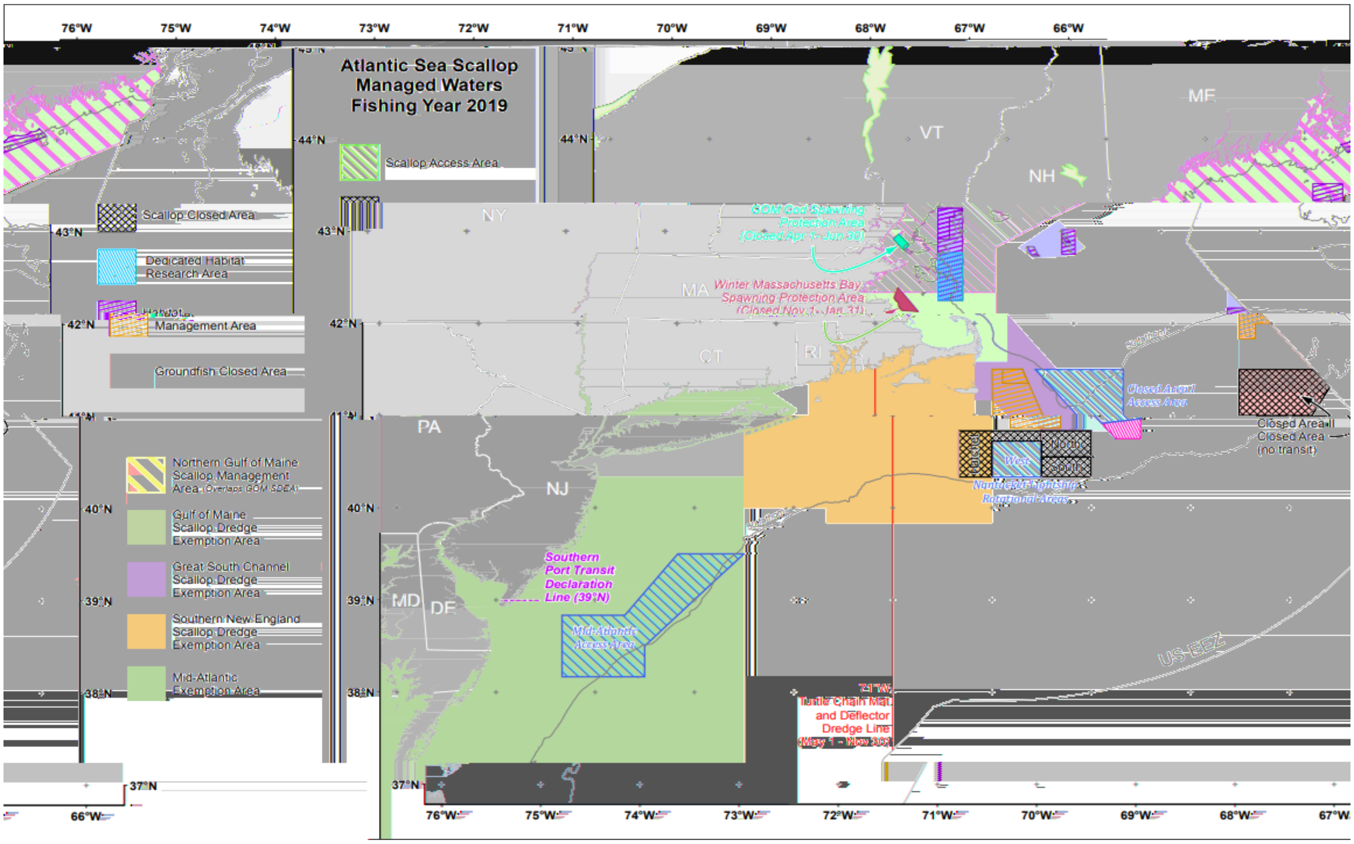

Figure 10.3. Atlantic sea scallop managed waters for fishing year 2019 (April 1–March 30). Source: https://www.fisheries.noaa.gov/resource/map/atlantic-sea-scallop-managed-waters-fishing-year-2019

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have altered the timing of the spring freshet, each of which alters the timing and extent of corrosive river plumes extending out from river mouths into the Gulf.

Action 10.2.1: Integrate OA observations in the Gulf of Maine with observations of riverine and offshore source waters and conduct a data synthesis of measurements collected by other federal and state agencies, as well as academic and NGO research facilities, including building on the data synthesis underway and housed by Northeast Regional Asociation of Coastal Ocean Observing Systems (NERACOOS).

Action 10.2.2: Better understand how carbonate chemistry in the region is affected by changes in both riverine and offshore source water fluxes and the chemistry of those source waters.

Action 10.2.3: Based on these exercises and analyses, identify new areas that are important for increased monitoring.

Research Objective 10.3: Produce forecasts of changes in OA conditions in dynamic environments on daily, monthly, seasonal, and yearly time periods

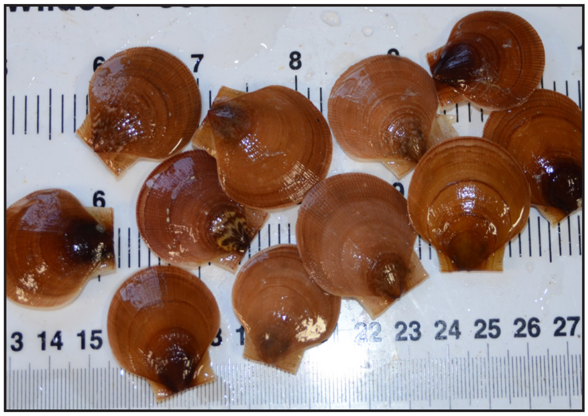
As identified through numerous regional stakeholder and industry engagement forums including those initiated via the Northeast Coastal Acidification Network, there remains a need for predictive capability at timescales not currently well addressed with existing models. These include forecasts of OA conditions for the region that align with the time frames of industry, management and business planning and decision making.

Action 10.3.1: Improve and operationalize regional biogeochemical models informed and validated by environmental monitoring data that reliably account for co-occurring changes including projected temperature changes, precipitation and nutrient dynamics to more accurately predict variability in the coastal waters.

Action 10.3.2: Configure model results to be fit-for-purpose and interpretable by decision makers to better provide needed guidance for regional planning.

Biological Sensitivity in the New England Region

The New England Region is a dynamic area that is experiencing changes in temperature, phenology, precipitation, and eutrophication with an average increase in sea surface temperature of 0.033° C per year from 1982-2016, which is three times greater than the global average (Hare et al., 2016; Pershing et al., 2015). This rapid rate of increase has considerable implications on regional marine ecosystems. A recent sensitivity analysis predicts that 27% of 82 species within the region will be susceptible to changes in the biogeochemical environment (Hare et al., 2016). For a majority of bivalve larval experiments decreased growth, survival, and rate of calcification, and/or dissolution of shells was observed (Clements & Hunt, 2014; Fabry et al., 2008; Gobler & Talmage, 2014; Green et al., 2013), with a potential minimum Ω_{arag} threshold (> 1.6) needed for survivability and settlement (Salisbury et al., 2008; Salisbury & Jönsson, 2018). Low levels of Ω_{arag} near this threshold can already be found seasonally in the region (**Figure 10.2**). A few field studies found that fewer bivalves settled under OA conditions assoicated with low pH in sediments (Clements & Hunt, 2018; Meseck et al., 2018). To date, models have been used to determine OA effects on Atlantic sea scallops (*Placopecten magellanicus*) and no data exist on Atlantic surf clams (*Spisula solidissima*). Integrated assessment models for the Atlantic sea scallops, found that under high OA the there is a potential to reduce the sea scallop biomass by approximately 13% by the end of the century (Cooley et al., 2015; Rheuban et al., 2018). Results from experiments on the commercially important crustacean American lobster (*Homarus americanus*) has produced conflicting results to elevated CO_2 (Keppel et al., 2012; Ries et al., 2009). Regarding finfish, several studies have focused on commercially and ecologically important fish of the region. In summer flounder (*Paralichthys dentatus*), survival of embryos to hatching was diminished under experimentally elevated CO_2 conditions (Chambers et al., 2014). A series of experimental studies on the forage fish Atlantic silverside (*Menidia menidia*) and inland silverside (*M. beryllina*) have highlighted the complexity of effects when CO_2 is acting alone versus in combination with other stressors (Baumann, 2019; Baumann et al., 2012). A summary of research of other organisms' responses can be found in Gledhill et al. (2015), but to date most of the research focuses on larval stages; understanding OA effects at multiple life stages is missing. Further research on New England species should include other life stages (or the entire life cycle where feasible), multigenerational effects, multiple populations, and changes in other physical parameters that are anticipated in future oceans (i.e., dissolved oxygen, salinity, and temperature). This broader perspective will provide a mechanistic understanding of the type and intricacies of the biological responses to OA. This research should also be tied to model development so the results can be used in single-species and ecosystem models to hindcast, nowcast, and forecast the effects of OA on biological systems. Research should incorporate a range of OA levels that consider both near-term and long-term time horizons, and include relevant environmental co-stressors.



Worth more than $500 million per year, sea scallops are the second most valuable fishery in the Northeast US. Credit: Mark Dixon/NOAA

Fundamental to our understanding of the consequences of the biological effects of OA is an estimation of an organism's resilience and adaptive potential. The resiliency of an organism is reflected in its acclimation plasticity, whereas the adaptive potential requires an understanding of the genetic and heritable bases to transgenerational change.

Future studies that consider the focal organism in an ecological context, where both prey and predators impacts are identified, will be fundamental to this broader understanding of OA impacts in nature. Providing such data will be useful in management efforts as scientists consider species-to-ecosystem sensitivity to OA in the region.

A major consideration is the combined effects of OA and warming trends on food webs in the region, including changes in predator-prey relationships, and the broad changes in species' ranges in the region. The NEFSC Atlantis model looked at direct and indirect effects of species response to OA and found that food web consequences of OA may extend beyond groups that are most vulnerable and to fishery yield and ecosystem structure (Fay et al., 2017). In particular, it is critical to understand how rapid warming in the New England Region interacts with the carbonate system to influence Ω_{arag} and potential OA impacts. Experiments on multiple environmental stressors, and the adaptive capacity of the organism, will provide critical process data for models and broad population metrics for key species as identified in the NOAA 2010 Acidification Research Plan for the Northeast and the Northeast Climate Vulnerability Assessment (Hare et al., 2016).

Research Objective 10.4: Identify critical (sensitive, predictive, and consequential) responses of selected keystone species to OA and multi-stressor conditions

OA progression will happen in concert with other environmental changes including warming ocean temperature, declining oxygen concentration, and nutrient loading. In order to fully appreciate the impact to marine organisms, a multi-stressor framework that evaluates multiple life stages is needed.

Action 10.4.1: Develop laboratory and field capability to expand existing single and multi-stressor OA experiments for all life-stages of shellfish and finfish of aquaculture, wild fisheries, and ecosystem importance.

Action 10.4.2: Use these expanded frameworks to evaluate the response of key bivalves, finfish and forage species in the region for the coming decades.

Research Objective 10.5: Characterize the adaptive capacity of species to OA and investigate potential mitigation patterns

Field and laboratory experiments focusing on species-specific response curves to future warming and acidification are central to predicting ecosystem response in the changing environment. Such predictions are necessary for developing viable management strategies under changing ocean conditions.

Action 10.5.1: Conduct experiments on potential for organismal acclimation and transgenerational adaptation to future environments.

Action 10.5.2: Conduct experiments to determine if there are different genetic lines within and across populations that respond differently to OA.

Action 10.5.3: Identify potential mitigation practices that could offset local acidification (i.e., kelp grown around aquaculture beds).

Research Objective 10.6: Incorporate OA and other marine stressors into single species and ecosystem models to improve ecosystem management

Incorporating knowledge from multi-stressor and adaptive capacity research into existing regional ecosystem models will improve predictions of ecosystem responses for the region.

Action 10.6.1: Encourage modelers and experimentalists to work together to identify key processes, the type and level of detail needed for incorporating biological processes into single-species models, and the interpretation of model output under various OA and climate scenarios.

Action 10.6.2: Develop unified and realistic ecosystem-level models that accurately capture essential biological and biogeochemical details as a joint effort among modelers, field scientists, and experimentalists.

Action 10.6.3: Identify future locations and times where successful recruitment of our Living Marine Resources (LMRs) may no longer be feasible.

Human Dimensions in the New England Region

The New England Region supports over 6 million workers, with a total annual payroll of $339 billion, and a regional gross domestic production of $885 billion (NOAA, 2017). New Bedford, MA, is the largest commercial fisheries port in the U.S. in terms of revenue with the American sea scallop fishery generating over $379 million (NOAA Fisheries, 2019b). In addition to these jobs, aquaculture in the region is growing at a fast rate (Lapointe, 2013). A Fisheries Climate Vulnerability assessment coupled to a Social Climate vulnerability assessment found that communities dependent on shellfish fisheries were highly vulnerable to OA (Colburn et al., 2016; Hare et al., 2016). A sensitivity analysis of overall social vulnerability to OA found that the region was medium-highly to highly vulnerable to OA, especially in Massachusetts (Ekstrom et al., 2015). The analysis further found that in the New England Region, locally high levels of eutrophication may be enhancing OA. The interdependency between human communities and marine resources determines both public interest in the OA issue and how NOAA responds to its mandates. NOAA needs to understand current and future consequences of OA to economic and social well-being. Threats that are posed to regional stakeholders as a result of OA include impacts to economically important species, especially scallops, mussels, clams, oysters, and lobster. However, how these biological impacts could translate to economic and social impacts is relatively unknown. Potential strategies that may be utilized by communities to help mitigate the influence of OA may include site selection, mitigation, selective breeding, and multi-trophic aquaculture (Clements & Chopin, 2017).

Research indicates that OA has the potential to negatively impact shellfish survival and growth as well as fish physiology, behavior, and recruitment. These potential changes in the availability of marketable stocks can lead to economic tipping points. As forecasting and modeling of the region improves (*Objective 10.2.3* and *Objective 10.3.2*), the New England Region needs to better understand how OA will change the abundance, harvestability, and economics of commercial fish stocks. Several areas of investigation are needed, including modeling to estimate when changes in carbonate chemistry could make harvesting or growing shellfish less profitable, and models that use species-specific data to predict ecological impacts on fishery stocks , and subsequent economic impacts to fisheries and fishing communities. Additional research on economic tipping points is needed to better understand the vulnerability of fishing communities and how the industry can adapt. For example, small-scale fishermen may not be equipped to adapt to fishing further offshore if a species' habitat changes. Information on potential impacts of OA on fisheries and aquaculture could help communities and industry decrease their vulnerability to impacts and increase their resilience to changing ocean conditions. Special attention needs to be paid to tribal governments and indigenous communities that conduct aquaculture operations that may be particularly vulnerable to coastal changes, including OA.

An oyster aquaculture worker in Maine packing oysters to sell. Credit: Christopher Katalinas/NOAA

The New England Region has robust existing efforts in ocean planning and regional fisheries management. The understanding and projections achieved with the research objectives described in this section should be incorporated into existing efforts to enable better planning and management. The region has embarked on a comprehensive effort to develop maps and provide a foundation for ocean planning (https://neoceanplanning.org/plan/). Habitat suitability maps (produced above) must be compared and integrated with these ocean plans. Efforts such as wind farm siting are becoming important drivers of economic activity in the coastal ocean, and these plans should include our understanding of how impacted resources will respond to OA in combination with these other activities.

Research Objective 10.7: Understand how OA will impact fish harvest, aquaculture and communities

Enhanced modeling and predictive capability of OA impacts to shellfish and fish populations developed by *Action 10.3.3* can be linked to economic models that project outcomes for fishery sectors and communities. This information will be central to improving planning and management measures in the face of progressing OA.

Action 10.7.1: Estimate the time threshold by when changes in the carbonate chemistry will make harvesting or growing shellfish unprofitable.

Action 10.7.2: Expand model capability to use species-specific data to predict economic impacts on individual fishery and aquaculture stocks.

Action 10.7.3: Support research on economic tipping points needed to better understand the vulnerability of fishing and aquaculture communities and how the industry can adapt.

Research Objective 10.8: Evaluate benefits and costs of mitigation and adaptation strategies

Understanding the costs and benefits of adaptation and mitigation strategies under different projected OA conditions will be vital to ensuring coastal community sustainability.

Action 10.8.1: Conduct modeling to determine the costs of altering the timing and location of fishing activities and mitigation strategies (i.e., seagrass, kelp, chemical alkalinity addition).

Action 10.8.2: Evaluate how the removal of excess nutrients aimed at reducing nearshore eutrophication will influence estuarine carbonate chemistry and acidification.

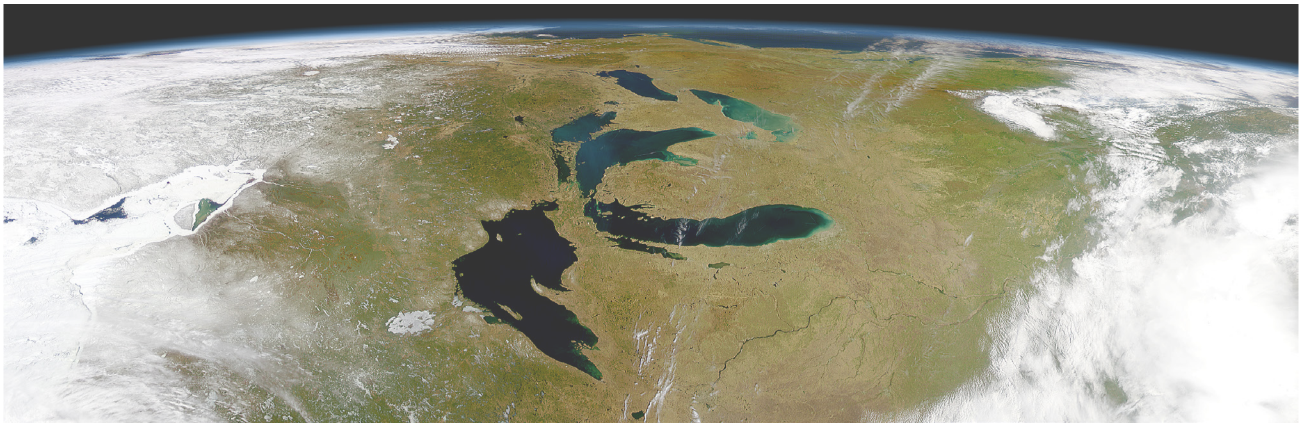
Research Objective 10.9: Integrate OA understanding into regional planning and management

Rapid changes in OA conditions will require management to react quickly to changes in harvestable species.

Action 10.9.1: Conduct comprehensive management strategy evaluations and scenario development to assess the ability of fisheries management to react to changes in harvested populations .

Action 10.9.2: Support economic modeling and sociological studies to determine the ability of fishers to alter fishery practices as harvested populations change (*Objective 10.6*).

Action 10.9.3: Develop Climate-Induced Social Vulnerability Indices (CSVIs) with respect to OA to improve the understanding of how communities might respond to OA in a resilient way.



11. Great Lakes Region Acidification Research

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Abstract

The Great Lakes Region includes Lake Superior, Michigan, Huron, Erie, and Ontario representing a combined lake surface area of 244,000 km^2. Acidification in the Great Lakes Region is predicted to occur at a rate similar to the oceans as a result of anthropogenic carbon emissions. In the Great Lakes, pH is also influenced seasonally and spatially by local primary productivity and historical impacts from acid deposition associated with poor air quality. This region supports culturally and economically significant fisheries and recreational tourism that create significant income for the regional and U.S. economy. NOAA's Great Lakes research goals include:

- Establish a monitoring network that is designed to detect trends in pH and carbonate saturation states, taking into account the considerable spatial and temporal variability;
- Conduct research to understand the sensitivity of dreissenid mussels, plankton, fish, and other biota to changes in pH and carbonate saturation states, including early life stages;
- Develop physical/biogeochemical and food-web models that can project the impacts of changing pH and carbonate saturation states on important ecological endpoints, including plankton community composition and productivity, nuisance and harmful algae, dreissenid mussels, and fish; and
- Engage stakeholders in the process of evaluating impacts in order to identify research topics, communicate research findings, and develop mitigation and adaptation strategies.

Acidification in the Great Lakes Region

The Great Lakes are the largest freshwater system on Earth, holding 95% of the U.S.' and 20% of the world's surface freshwater (**Figure 11.1**). The Great Lakes basin is home to approximately 43 million people, 8% of the U.S. population, and 32% of Canada's population. The lakes provide culturally and economically important assets, including drinking water, commercial shipping, hydroelectric power, recreation, and a world-class fishery producing $7 billion in annual economic value (American Sportfishing Association, 2013). The positive regional economic impact generated by the Great Lakes is

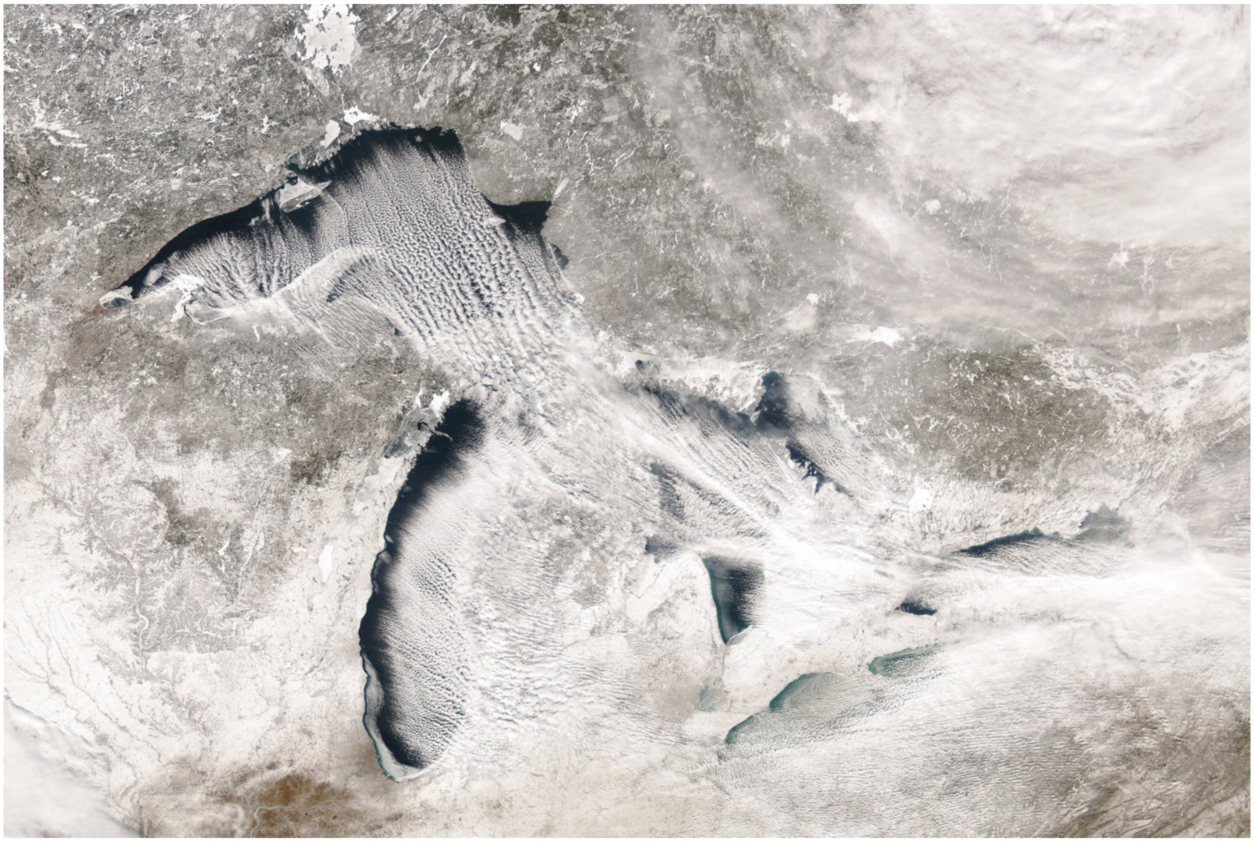


Figure 11.1. The Laurentian Great Lakes are a unique freshwater ecosystem shared between the United States and Canada. In early winter, cold air causes strong mixing in the lakes and atmospheric boundary layer, strong evaporation leading to lake-effect snow, and rapid equilibration with atmospheric gases (NOAA CoastWatch MODIS satellite image).

estimated at 1.5 million jobs directly connected to the lakes, resulting in $62 billion in wages (Michigan Sea Grant College Program, 2011). The services provided by this valuable ecosystem are vulnerable to multiple stressors, including eutrophication and oligotrophication, invasive species, contaminants, a changing climate, and acidification associated with increasing atmospheric carbon dioxide (CO_2).

Great Lakes pH is projected to decline at a rate similar to that of the oceans, in response to increasing atmospheric CO_2. Phillips et al. (2015) estimated a pH decline of 0.29-0.49 pH units by 2100, assuming current projections of anthropogenic carbon dioxide CO_2 emissions (IPCC IS92a business as usual scenario) and constant alkalinity (**Figure 11.2**). Present-day mean pH and alkalinity vary according to the geology of each lake basin, with Superior having the lowest values (pH 8.12, 838 meq m^{-3}) and Michigan the highest (pH 8.55, 2181 meq m^{-3}, Phillips et al., 2015). In addition, considerable short-term spatial and temporal variability in pH occurs, driven largely by varying rates of photosynthesis and respiration across trophic gradients. For example, episodes of high productivity can result in pH > 9.0, while net community respiration in hypolimnetic waters can lead to hypoxic conditions and pH < 7.5 (**Figure 11.3**). The predicted decline in pH would occur superimposed on this variability, making observation of long-term trends in the Great Lakes region particularly challenging (Phillips et al., 2015).

Effects of increasing atmospheric CO_2 on Great Lakes water chemistry may be confounded by regional recovery from acid deposition. The Midwestern and Northeastern United States experienced an increase in deposition of sulfuric and nitric acids from the early 20th century until air-quality regulations mitigated this trend. The pH of precipitation in the Midwest increased from ~4.2 in the 1980s to

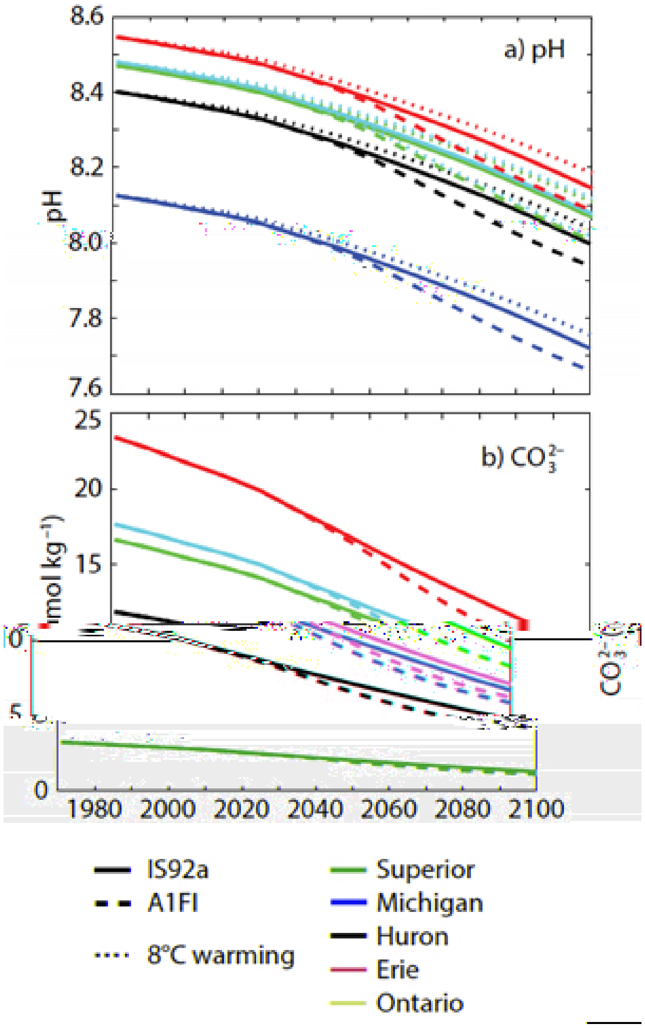


Figure 11.2. Projected mean annual (a) pH and (b) carbonate ion concentration for the five Laurentian Great Lakes under IPCC atmospheric CO_2 forcing: IPCC IS92a (the business as usual scenario) or A1FI (the fossil fuel intensive scenario). Also shown on (a) is an 8°C warming by 2100 scenario. Figure modified from Phillips et al., 2015; Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/).

~5.4 in 2018, with much of the increase occurring after 1995 (National Atmospheric Deposition Program, https://nadp.slh.wisc.edu/). The concentrations of major ions and alkalinity of the lakes were modified by the acid deposition period, and continue to change as a result of recovery from acid deposition, and the long residence time and connectivity of the lakes (Chapra et al., 2012).

In spite of the publication of the 2010 Great Lakes Acidification Research Plan little effort has been invested in monitoring or understanding potential effects of acidification in the Great Lakes on the part of NOAA or the broader Great Lakes research community. The review by Phillips et al. (2015) is a rare example of a publication devoted to the topic of Great Lakes acidification. Although not focused on acidification, there have been efforts to measure and estimate components of the lake-wide carbon budgets (Bennington et al., 2012).

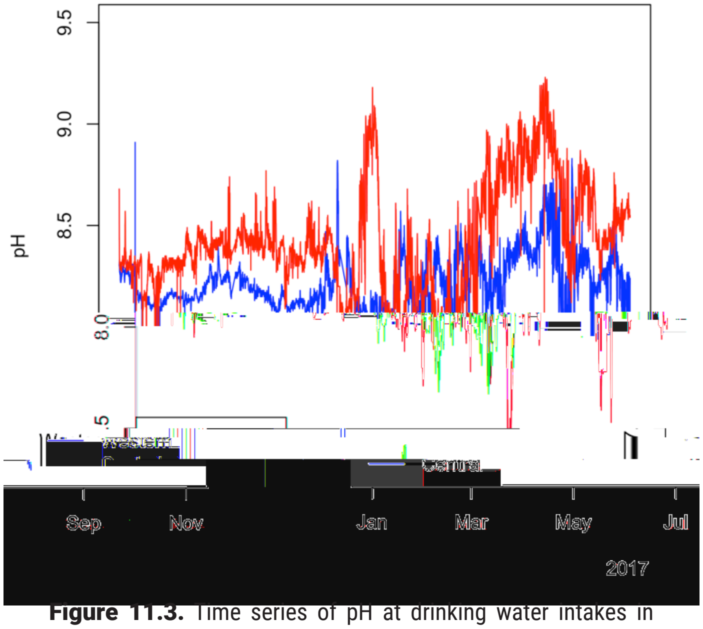
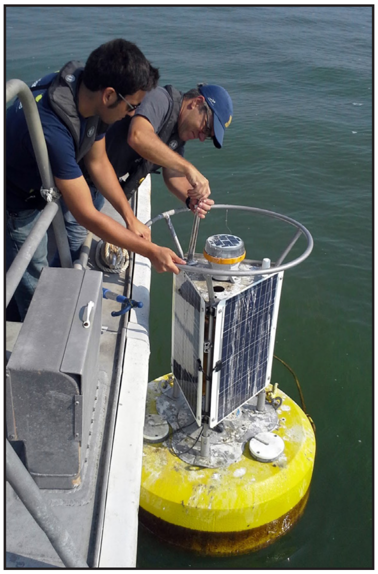


Figure 11.3. Time series of pH at drinking water intakes in the western and central basins of Lake Erie illustrating short-term variability of pH, which complicates detection of long-term trends. Episodes of high productivity cause pH > 9.0 in the eutrophic western basin, while coastal upwellings of hypoxic water in the central basin cause pH to drop below 7.5. Data source: Great Lakes Observing System, http://habs.glos.us.

Environmental Change in the Great Lakes Region

There are presently no long-term monitoring programs in the Great Lakes that are designed to detect long-term trends in pH and inorganic carbonate system variables. This lack of observations represents a major knowledge gap in understanding the past progression of acidification in the Great Lakes region. The U.S. EPA conducts a long-term water quality monitoring program; however, the sampling methodology and frequency are not well-suited to detect trends in pH (Phillips et al., 2015). At least two carbonate system components must be measured to fully characterize the system, for example pCO_2 and pH, and measurements must be made with methods that have sufficient precision in freshwater to detect the predicted trends. Recent developments in Great Lakes carbonate system observing include a long-term monitoring program for pCO_2 in Lake Michigan, using the Lake Express ferry (Milwaukee to Muskegon) and fixed moorings (University of Wisconsin Milwaukee). However, this program only monitors a single carbonate variable and would ideally be supplemented by pH (Harvey Bootsma, personal communication).



A NOAA Realtime Coastal Observation Network (ReCON) buoy being serviced in Lake Erie. Credit: Dack Stuart/Cooperative Institute for Great Lakes Research

Recently developed instrumentation that has the ability to monitor pCO_2 and pH with sufficient precision to document trends in acidification, and are suitable for deployment on remote buoys or moorings, provide a potential means to improve the carbonate chemistry observing gap in the Great Lakes region (https://oceanacidification.noaa.gov/WhatWeDo/Monitoring.aspx). New observations of the carbonate system may build upon existing observing networks, such as the Real-Time Coastal Observation Network (ReCON), National Data Buoy Center (NDBC), or Great Lakes Evaporation Network (GLEN). NDBC buoys may be well-positioned for the purpose of monitoring long-term trends, as these are located in central deep basins of all five of the Great Lakes that would be minimally influenced by local and seasonal variance in pH associated with coastal plumes of enhanced primary production (Phillips et al., 2015). Ideally, buoys with carbonate chemistry sensor packages would be deployed in each of the upper lakes (Superior, Huron, and Michigan) to provide an opportunity to compare and contrast these lakes over a range of alkalinity, carbonate saturation, and watershed geology, and to verify any trends by comparison across sites. In contrast to the upper lakes, the more productive waters of Erie and Ontario have greater short-term variability in pH, which would cause greater difficulty in detection of trends.

While a moored system would be best-suited for detecting long-term trends, mobile platforms such as ships or autonomous instruments would have an advantage in terms of monitoring spatial patterns. Addition of carbonate system observations to a ship-based long-term ecological monitoring program would have the benefit of observing changes in pH and carbonate saturation in conjunction with ecological changes. Long-term trends may be detectable using routine observations made at stations in relatively-deep and low-productivity regions of Great Lakes basins on a near-monthly basis, however the problem of aliasing spatial, seasonal, and diel patterns onto long-term trends would still exist. Novel technologies such as profiling floats could provide insights on the influence of primary production and respiration, by providing vertical resolution and potentially including ecological sensor packages.

Research Objective 11.1: Expand NOAA's OA monitoring network to include sampling sites in the Great Lakes Region

There is currently no existing long-term carbonate chemistry monitoring program in the Great Lakes region, representing a major observing and knowledge gap on how acidification has evolved in the past and continues to progress into the future. Building out an observing network will be critical to understanding the drivers of acidification and predicting future trends in pH.

Action 11.1.1: Leverage existing observing networks in the region to build a carbonate chemistry observing network through addition of sensor packages suited to make high quality measurements.

Action 11.1.2: Strategically identify priority sampling regions in order to best detect trends (relatively-deep basin and low-productivity environments) that can be compared across lakes.

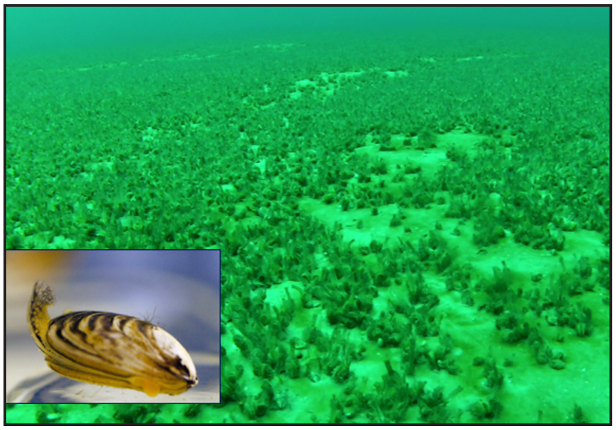
Biological Sensitivity in the Great Lakes Region

Effects of weak acidification of freshwater on biota at the organism, community, and ecosystem level are generally not well understood. With increasing $p\mathrm{CO_2}$, primary producers tend to experience increased individual and community growth rates, while animals, including fish, amphibians, and macroinvertebrates, exhibit reduced growth rates; however, little is known regarding potential effects at the community or ecosystem level (Hasler et al., 2018). Little research has been devoted to the sensitivity of Great Lakes biota to weak acidification.

Phytoplankton community composition is influenced by weak acidification of freshwater. Diatoms are sensitive to pH to the extent that they are used to reconstruct the geologic history of lake pH. For example, statistical diatom models have been developed that can predict lake pH within 0.19–0.46 pH units over commonly-occurring pH range of lakes (6.0–8.5; Finkelstein et al., 2014); thus, we may expect changes in the diatom community to occur over the range of pH change predicted for the Great Lakes. Of particular concern with respect to phytoplankton communities in the Great Lakes is the increased presence of harmful algal species that produce neurotoxins and hepatoxins. In 2014, a Lake Erie harmful algal bloom (HAB) event associated with the freshwater cyanobacteria species *Microcystis aeruginosa* contaminated the public water system and caused a no-consumption advisory that left a half million people in Toledo, Ohio without access to drinking water for 2.5 days (Steffen et al., 2017). It has been suggested that elevated $p\mathrm{CO_2}$ can contribute to the dominance of cyanobacteria within freshwater phytoplankton assemblages (Mooij et al., 2005; Trolle et al., 2011). Warming associated with the increase in atmospheric $\mathrm{CO_2}$ is expected to lengthen and strengthen lake stratification (De Stasio et al., 1996; Peeters et al., 2002), leading to increased lake stability and conditions that favor phytoplankton species that can take advantage of vertical migration in the water column, such as cyanobacteria (Paerl & Huisman, 2008). Community shifts in the toxic species present may also be impacted, as acidified conditions promote non-toxigenic strains of *M. aeruginosa* (Van de Waal et al., 2011) while toxic strains of *Anabaena circinalis* and *A. eucompacta* are favored within a high $p\mathrm{CO_2}$ environment (Shi et al., 2017).

Cyanobacterial harmful algal bloom in Lake Erie near Toledo, Ohio, August 2019. Acidification may alter phytoplankton community composition. Credit: NOAA

Calcifying organisms are sensitive to carbonate saturation states, and have gained an important influence on primary production and trophic connections in the Great Lakes with the colonization of the lakes by the invasive bivalves *Dreissena polymorpha* (zebra mussel) and *Dreissena rostriformis bugensis* (quagga mussel). Dreissenid mussels are an undesirable invasive species that heavily colonized each of the Great Lakes during the 1990s and 2000s, except Lake Superior, which has lower carbonate saturation than the other lakes. The mean aragonite saturation state (Ω_{arag}) varies across the Great Lakes, with Ontario, Erie, and Michigan having values > 2.0, Huron at 0.96 ±0.62 (mean ±std. error) and Superior at 0.15 ±0.08 (NOAA OA Steering Committee, 2010). It is not known whether Ω_{arag} in the main basin of Lake Huron is low enough to stress and limit dreissenid biomass in that lake. Dreissenids may be most vulnerable during their larval veliger stage, as calcium levels below 8 mg L^{-1} lead to significant decreases in larval growth (Mackie & Claudi, 2009) and larval settlement may be prevented below pH of 7.1 (Claudi et al., 2012).



Invasive quagga mussels (Inset photo; also referred to as dreissenid mussels) carpet the bottom of Lake Michigan. Credit: NOAA

Fish are a primary means by which people interact with the Great Lakes, both culturally and economically. Acidification of poorly buffered fresh waters is known to cause mortality, reproductive failure, reduced growth rate, skeletal deformation, and increased uptake of heavy metals in fish. Generally, pH values below 5.5 result in reduced reproductive success of fish, but some deleterious effects on salmonids have been recorded at pH values of 6.5–6.7. Salmonids in the Great Lakes include the native top predator, lake trout, along with important native forage fish, coregonids, and introduced Pacific salmon that are the basis of an economically-important sport fishery. While the pH of Great Lakes waters is not predicted to reach such low levels (Phillips et al., 2015), important spawning and nursery habitats in tributaries and wetlands may be vulnerable. Acid precipitation can also leach Al^{3+} from soils, which has been shown to be highly toxic to certain fish larvae (Haines, 1981). Intense rainfall events, which lead to a sudden decrease in pH (< 5.5), or increase in toxic metal ions (namely Al^{3+}), in poorly buffered rivers may cause mortality of fish early life stages (Buckler et al., 1987; Hall, 1987), and has more severe effects compared to chronic low pH conditions. Indirect effects on fish may result from changes in species composition of lower trophic levels that support fish growth and production (Haines, 1981).

Great Lakes biophysical models have been used to elucidate lake-wide circulation patterns (Beletsky & Schwab, 2008; Bennington et al., 2010), oxygen cycling (Matsumoto et al., 2015), and the effects of invasive dreissenid mussels and changing lake nutrient concentrations on lakewide productivity (Pilcher et al., 2017; Rowe et al., 2017). Such models may be used to determine separate and combined effects of concurrent ecological stressors. Two Great Lakes biophysical models have included carbonate chemistry (Bennington et al., 2012 for Lake Superior; Pilcher et al., 2017 for Lake Michigan). Continued development of biophysical and food web models should be conducted in coordination with observational and monitoring work.

Research Objective 11.2: Conduct research on harmful algal bloom species and the influence of elevated pCO_2, and temperature on bloom toxicity, concentration and frequency

Cyanobacterial harmful algal blooms are a recurring issue in eutrophic areas of the Great Lakes that has had significant economic impacts, and is a human health concern.

Action 11.2.1: Conduct monitoring and experiments to understand the influence of elevated pCO_2 and temperature on bloom toxicity, concentration and frequency.

Action 11.2.2: Incorporate the influence of elevated pCO_2 and temperature into models that can predict HAB occurrence in short-term forecasts and in longer-term scenarios to inform nutrient management decisions.

Research Objective 11.3: Conduct research to understand the sensitivity of dreissenid mussels, plankton, fish, and other biota to changes in pH and carbonate saturation states, including early life stages

The influence of elevated pCO_2 on Great Lakes biota is relatively unknown at the organism, population, and ecosystem level, causing an unknown level of risk to an ecosystem that supports a multi-billion dollar tourism and sportfishing economy.

Action 11.3.1: Given its marginal Ω_{arag} values, and gradients in Ω_{arag}, Lake Huron dreissenid distributions may be most sensitive to acidification, and could serve as an early indicator of changing trends in pH and Ω_{arag}. Compare and contrast dreissenid distribution over time and with other lakes as a function of $\Omega_{arag.}$

Action 11.3.2: Conduct monitoring and experiments to understand the influence of elevated pCO_2 on Great Lakes plankton community composition.

Action 11.3.3: Conduct monitoring and experiments to evaluate the influence of elevated pCO_2 on early life stages of fish and dreissenid mussels.

***Action 11.3.4*:** Focus research on nursery habitats for fish early life stages, such as poorly buffered tributaries and wetland habitats that currently experience fluctuating pH levels, and will be most at risk to anticipated pH declines.

Research Objective 11.4: Incorporate carbonate chemistry into biophysical and food web models to project the impacts of changing pH and carbonate saturation states on important ecological endpoints

Current biophysical models for the Great Lakes region often do not include effects of the carbonate system and pH on ecological endpoints.

Action 11.4.1: Develop biophysical models capable of simulating the carbonate system, pH, and Ω_{arag} in the Great Lakes.

Action 11.4.2: As understanding develops regarding the influence of elevated pCO_2 on Great Lakes biota, incorporate these mechanisms into biophysical and food web models.

Human Dimensions in the Great Lakes Region

Potential impacts of Great Lakes acidification are largely unknown at this time. If ecological impacts of acidification are documented in the Great Lakes, then it will be important to engage with stakeholders in the region and evaluate economic impacts. Human dimensions of environmental stressors can be described as three points of interaction between human and environmental systems, 1) including human actions as causes for environmental changes, 2) impacts on society, and 3) effective responses (NRC, 1992). NOAA in the Great Lakes Region engages with a wide range of stakeholder groups including drinking water system managers, hydroelectric power managers, commercial shipping industry, coast guard, recreational and charter anglers, and environment protection agencies. These relationships can serve as a foundation for human dimensions work related to Great Lakes acidification.

Researchers at NOAA's Great Lakes Environmenatal Research Laboratory, Lake Michigan Field Station use seine nets to monitor larval white fish abundance for use in recruitment models for the lake whitefish fishery. Credit: NOAA

NOAA and its academic and government partners use social science methods such as needs assessments, focus groups, and surveys to learn about the human dimensions of issues facing the Great Lakes. In 2018, the International Joint Commission (IJC) conducted a binational poll of residents of the Great Lakes basin, and identified over fifteen top of mind problems faced by the Great Lakes, which included pollution in general, invasive species, nuisance algae, and water levels (IJC, 2018), but acidification did not appear as a top of mind issue for the public. Recent studies have evaluated the economic impact of the Great Lakes through fishery, shipping, and beach visits (NOAA, 2019; Wolf et al., 2017; Martin Associates, 2018). Environmental pressures on Great Lakes such as HABs in Lake Erie can cause $2.25 million to $5.58 million in lost fishing expenditures (Wolf et al., 2017). In addition to economic studies, there is a need to measure impacts of environmental changes on quality of life, sense of place, and community wellbeing. Studying how stakeholders address uncertainty and long-term changes and take precautionary actions fit NOAA's vision of building healthy ecosystems, communities and economies that are resilient in the face of change. For example, a focus group study documented the influence of Lake Erie HABs on decision making by recreational and charter anglers and the potential utility of a HAB forecast to these stakeholders (Gill et al., 2018). While acidification is not currently a focus among Great Lakes stakeholders or the research community, policy makers and resource managers should be informed about ongoing research directions. The sooner stakeholders and the public are engaged in research, the more likely they will be to trust the scientific information and to accept new management goals (Bauer et al., 2010).

Research Objective 11.5: Engage stakeholders and public in the knowledge production process

The scientific research on Great Lakes acidification can have greater impact with better understanding of stakeholders' and public needs and strengthened public trust and awareness of NOAA's efforts.

Action 11.5.1: As research activities are undertaken, develop engagement, communication, and training programs to increase stakeholder and public awareness of NOAA's acidification research as a scientific frontier. Test hypotheses about best ways to engage stakeholders and public.

Research Objective 11.6: Evaluate economic and social impacts of ecological outcomes or mitigation actions

Well-documented economic and social impacts help policy makers and the public to prioritize adaptation tasks and select mitigation actions.

Action 11.6.1: As the ecological impacts of Great Lakes acidification are identified, conduct vulnerability assessments to identify sectors of the economy that are vulnerable to Great Lakes acidification, and measure economic and social impacts of acidification.

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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