NOAA OCEAN AND GREAT LAKES ACIDIFICATION RESEARCH PLAN 2020-2029

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Wilbur L. Ross, Jr., Secretary

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Contents

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 resulting not only from atmospheric CO_2 and organic matter breakdown but also coastal inputs such as runoff, atmospheric pollution and freshwater sources, is re4cognised as the coastal manifestation of OA. Acidification in the Great Lakes is also projected to decline at a rate similar to that of the oceans as a result of increasing atmospheric CO_2 concentrations that may also be confounded by regional air quality and acid deposition via precipitation. Acidification of the open-ocean, coasts and Great Lakes continues to raise concerns across the scientific, resource management and coastal communities as to the ecological impacts and resulting social and economic effects.

In response to legislative drivers and scientific concerns, NOAA's OA mission is to understand and predict changes in Earth's environment as a consequence of continued acidification of the oceans and Great Lakes; conserve and manage marine organisms and ecosystems in response to such changes; and to share that knowledge and information with others. The principle piece of OA legislation, the Federal Ocean Acidification Research and Monitoring (FOARAM) Act of 2009, requires that NOAA has an OA 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 OA 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 requirements. In coordination with international, interagency and external academic and industry research partners, the present NOAA OA Research Plan aims to support science that produces well-integrated and relevant research results, tools and products for stakeholders.

Consistent with the FOARAM Act of 2009 and NOAA's mission, the Research Plan is framed around three research themes;

(1) Document and predict change via **environmental monitoring**, analysis and modeling;
(2) Characterize and predict **biological sensitivity** of species and ecosystems to; and
(3) Understand **human dimensions** and socioeconomic impacts of OA.

These research themes can collectively be used to understand, predict and reduce vulnerability to OA. Environmental monitoring is critical to documenting OA and collecting data that can be used to understand responses 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. Elucidating the human impacts of OA requires translating and synthesizing physical environmental monitoring and biological sensitivity knowledge to study the implications of OA and vulnerability of human communities and economies to OA.

The Research Plan includes regional chapters which encompass the coastal zones around the U.S. and its territories and the Great Lakes, an Open Ocean chapter focusing on deep ocean regions extending 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 monitoring, biological sensitivity and human dimensions). NOAA's OA research goals are to:

(1) Advance OA observing systems, modeling, technologies and data stewardship to improve the understanding and predictive capability of OA trends and processes;
(2) Enhance understanding and prediction of OA as a stressor co-occurring with other prominent ocean and Great Lakes changes;
(3) Improve understanding of the biological response and adaptive capacity of ecologically and economically important species, ecosystems, and communities; and
(4) Increase research to understand the vulnerability of communities and stakeholders to OA and to generate useful data that supports adaptation and resilience plans.

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

Introduction

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Motivation for NOAA's Ocean and Great Lakes Acidification Research Plan

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 and Wickett, 2003; Feely et al., 2004, 2009; Orr et al., 2005; **Figure 1**). The ocean has served as an important "sink" for anthropogenic CO_2, significantly reducing atmospheric CO_2 accumulation (Sabine et al., 2004; Khatiwala et al., 2013; Le Quéré et al., 2015, 2018; Gruber et al., 2019). Acidification also occurs in freshwater systems such as the Great Lakes of the U.S., where pH is projected to decline at a rate similar to the oceans (Philips et al., 2015). OA events have occurred throughout Earth's history whenever the atmospheric CO_2 concentrations have increased, however the present rate of CO_2 release and OA is unprecedented, exceeding the rates of change over the last 56 million years (Gingerich et al., 2019) and likely the last 300 million years (Hönisch et al. 2012). 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.

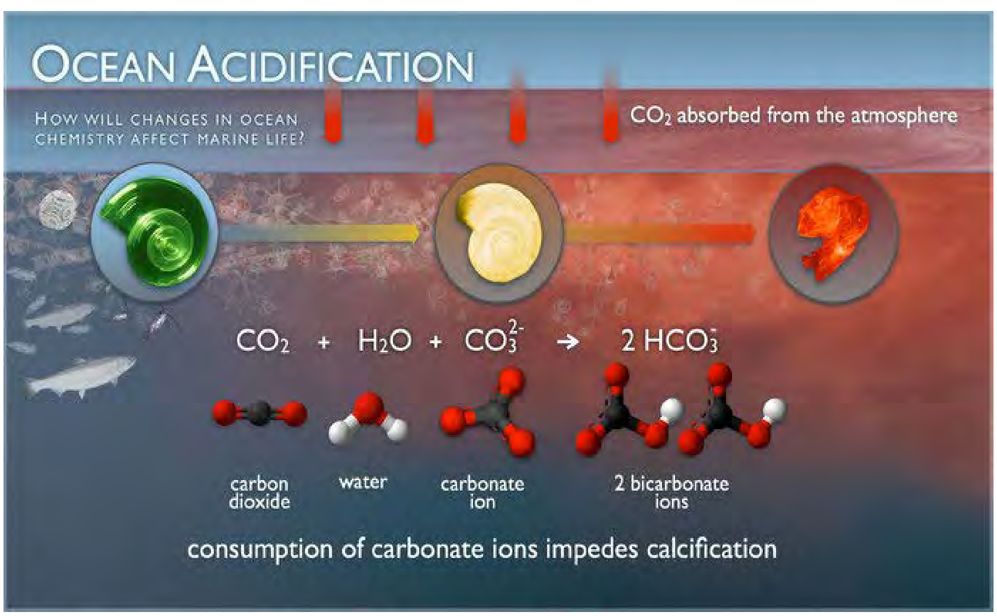

Figure 1. OA is driven by CO_2 from the atmosphere dissolving into the surface ocean. This introduction of new CO_2 into the ocean results in chemical reactions that redistribute the relative concentrations of dissolved inorganic carbon (DIC) species in seawater, ultimately consuming carbonate ions (CO_3^{2-}) and producing bicarbonate ions (HCO_3^-). This redistribution and decline in CO_3^{2-} (and pH) most directly impacts on marine species that depend on this ion to build their hard parts; however, there are additional nuanced impacts OA has on marine ecosystems (NOAA/PMEL).

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, **Figure 2**). Research suggests that the oceans have absorbed approximately one-third 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; Le Quéré et al., 2015, 2018; Gattuso et al., 2015; Gruber et al., 2019). The IPCC concluded that changes in the ocean such as warming, acidification and deoxygenation are already affecting marine life from molecular processes to organisms and ecosystems, with major impacts on the use of marine systems by human societies (IPCC AR5 Working Group II; Portner, 2012).

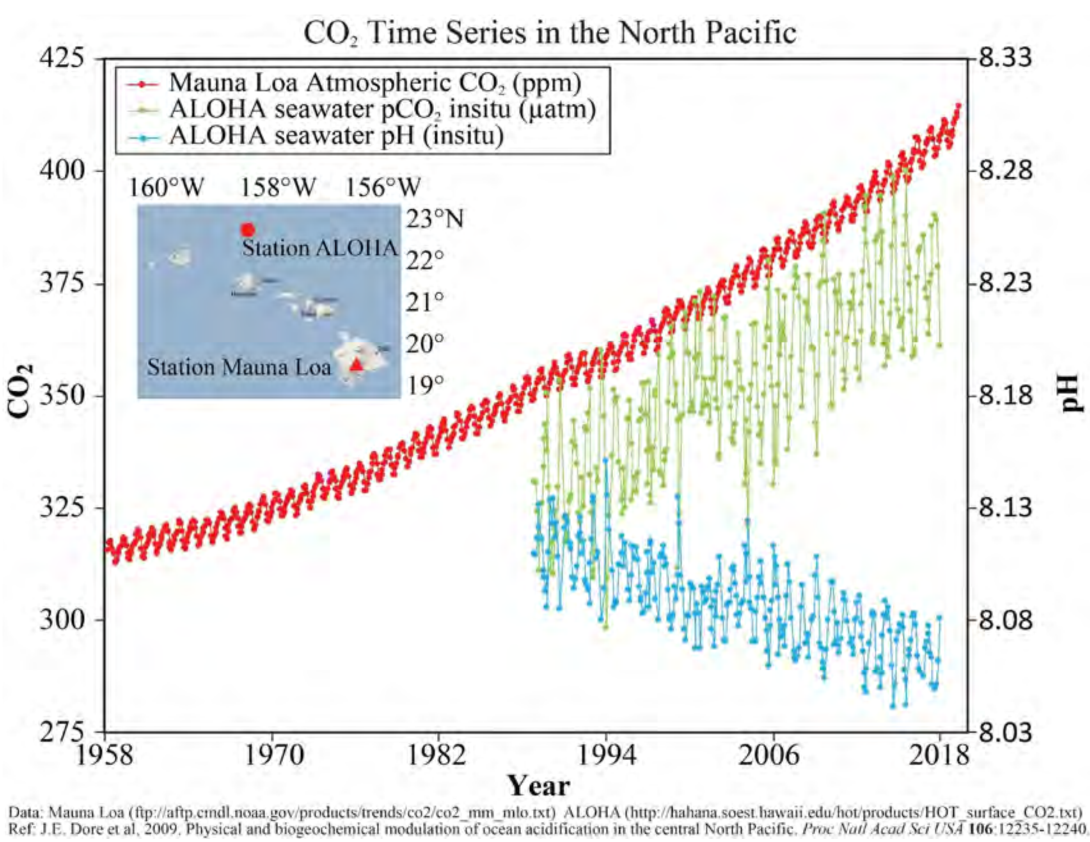

Figure 2. The longest continuous stationary time-series (1958 to present) of atmospheric CO_2 concentration (ppm) measured at the Mauna Loa Observatory in Hawaii. Ocean chemistry measurements of seawater pCO_2 and pH at neighboring Station ALOHA began in 1988. These time-series show that seawater pCO_2 concentrations increase in tandem with atmospheric concentrations, but with much greater annual variability, while seawater pH declines (Adapted from Feely et al., 2009; Additional Data Information).

OA is defined as a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of CO_2 from the atmosphere at rates faster than rock weathering can supply compensatory buffering (which in the geologic past has occurred on timescales of thousands of years). Anthropogenic OA refers to the component of pH reduction that is caused directly by human activities such as combustion of fossil fuels and land use changes (IPCC, 2011). At present, the 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).

Coastal acidification has relatively recently been distinguished from OA as it represents the combined decrease in pH and changes in the water chemistry of coastal oceans, estuaries, and other bodies of water from a number of chemical inputs- including (but not exclusively) carbon dioxide from the atmosphere. Additional chemical inputs that are known to influence coastal acidification include those delivered via advective transport, freshwater input (e.g. riverine influx and ice-melt), surface runoff and coastal atmospheric pollution. Regional coastal acidification can persist or occur episodically based on the nature of local events (i.e. seasonal ice melt, upwelling events, and severe rain events) and oftentimes happen in a complex interplay of processes and reactions. Researchers are highly confident that impacts of coastal acidification, co-occurring with other environmental stressors (e.g. heat waves, sea level rise, deoxygenation), have already been observed in coastal ecosystem habitat area, biodiversity and ecosystem functioning and services (IPCC Special Report on Oceans and Cryosphere in a Changing Climate, 2019).

Ocean acidification results in four chemical changes that can affect marine species: an increase in dissolved CO_2 and bicarbonate and a decrease in pH and the concentration of carbonate ions. Calcifying species, which include many ecologically, recreationally and commercially important marine species, are thought to be especially sensitive to OA as they use CO_3^{2-} 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; Gattuso et al., 2015,Busch et al., 2014; Riebesell et al., 2016). Field collections from high CO_2 locations provide evidence of species impacts of such exposure (e.g., Bednarsek et al., 2017). While some time series examinations find signatures of OA impacts on marine species (e.g., Meier et al., 2014; de Moel et al., 2009), numerous other studies fail to do so (e.g., Beare et al 2013; Thibodeau et al., 2018). Laboratory studies have also shown that physiological processes of finfish are sensitive to OA conditions, in some cases impacting growth, survival, fertilization, embryonic and larval development and behavior (e.g. Long et al., 2013, Hurst et al., 2016, Clements and Hunt, 2018; Williams et al., 2018). 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., Marshall et al 2017, Busch et al 2013). Despite the numerous observations of species sensitivity to OA conditions, some marine organisms and genetic strains within populations have shown resilience and merit future research (e.g. Hurst et al., 2013, 2013; Barkley et al., 2015; Putnam et al., 2017).

NOAA's OA Research Mission

The Department of Commerce's National Oceanic and Atmospheric Administration (NOAA) is the United States' Federal lead 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 ocean warming and acidification. To that end, 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 Plan 2020-2026, *in review*).

OA research at NOAA spans across five of its 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 OA science, referred to as NOAA's OA Enterprise. OAR programs, including the Ocean Acidification Program (OAP), support foundational research that study the marine environment, detect changes in the ocean, improve forecast capability and drive innovative science and technological development (OAR Strategic Plan 2019). The OAP and the OAR Labs 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. Several of NOAA's six Fisheries Science Centers, which are distributed around the U.S., study the biological effects of OA on regionally important fish and shellfish. NOS supports U.S. coastal communities by translating science, tools, and services into action, addressing threats to coastal areas such as climate change and OA to work towards healthy coasts and healthy 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 and the National Estuarine Research Reserve System (NERRS). NESDIS supports satellite-based science that gathers global data to monitor and understand the dynamic planet and provides data services for all of NOAA's environmental data, providing support for the complete lifecycle of data, from collection to archive to dissemination. NESDIS' National Centers for Environmental Information coordinates the data stewardship for all NOAA OA data. NOAA's OMAO plays a critical role in supporting and carrying out OA observing by administering the NOAA fleet of ships and aircraft and trains divers to safely facilitate Earth observation.

While OA research at NOAA responds to numerous legislative mandates and policy drivers (Appendix 1), the primary OA-related legislation is the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM Act). This law specifies that NOAA conduct research to understand and predict changes in Earth's environment as a consequence of continued acidification of the oceans and to conserve and manage marine organisms and ecosystems in response to such changes. Under the FOARAM Act, NOAA's OAP was established to support and coordinate OA research and monitoring across NOAA.

The FOARAM Act also established a cross-agency coordinating body, the Interagency Working Group on Ocean Acidification (IWG-OA) housed within 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 across the Federal government 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 OA Research over the Last Decade: Partnerships and Accomplishments

Following the passage of the FOARAM Act, NOAA has carried out its OA 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 OA, and the underlying data management infrastructure needed to support the OA Enterprise. The present plan serves as an update that identifies research objectives for the next decade of OA science at NOAA and lays a framework for building upon accomplishments made and responding to newly emerging requirements.

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 strategic 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)). Additionally, 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 OA science at NOAA over the last decade have done so both internally by conducting research at NOAA's laboratories and regional 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 grants competitions, awarded to both academic and industry partners, have 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 the NOAA OA enterprise. 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 research, management, or outreach.

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 by the OAP holding a data management workshop in 2012 that established the framework that guides OA data management, including OA metadata and archiving to facilitate the generation of OA data products that facilitate OA science. NESDIS' National Center for Environmental Information (NCEI) established the Ocean Acidification Data Stewardship (OADS) and the Ocean Carbon Data System (OCADS) projects that serve the data management needs of the OA research community with version control, stable data citation, and controlled vocabularies, meeting all NOAA Public Access for Research Results (PARR) requirements. 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 is findable, accessible, interoperable and reusable (FAIR).

The OA Research Plan Framework and Themes

Following a decade of NOAA OA research and interagency and international engagement guided by the 2010 NOAA Ocean and Great Lakes Acidification Research Plan, the agency is entering into the next decade of OA science. OA research draws on a number of scientific disciplines including, chemical, biological, physical and geological oceanography but also sociological sciences such as socioeconomic and human health research. NOAA's OA enterprise aims to produce well-integrated and relevant research results, tools and products. The national research plan and subsequent regional chapters integrate the themes of *environmental monitoring*, *biological sensitivity* and *human dimensions* to understand and, ideally, reduce *vulnerabilit***y** to OA. 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 monitoring* is critical to documenting environmental change in response to OA and represents an important data stream used to enhance predictive capabilities of numerical models. 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 physical environmental monitoring and biological sensitivity knowledge into useful information for studying the implications of OA and specifically the *vulnerability* of communities and economies to OA (**Figure 3**). Vulnerability is defined as the propensity or predisposition to be adversely affected (Intergovernmental Panel on Climate Change (IPCC) 2012 Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation).

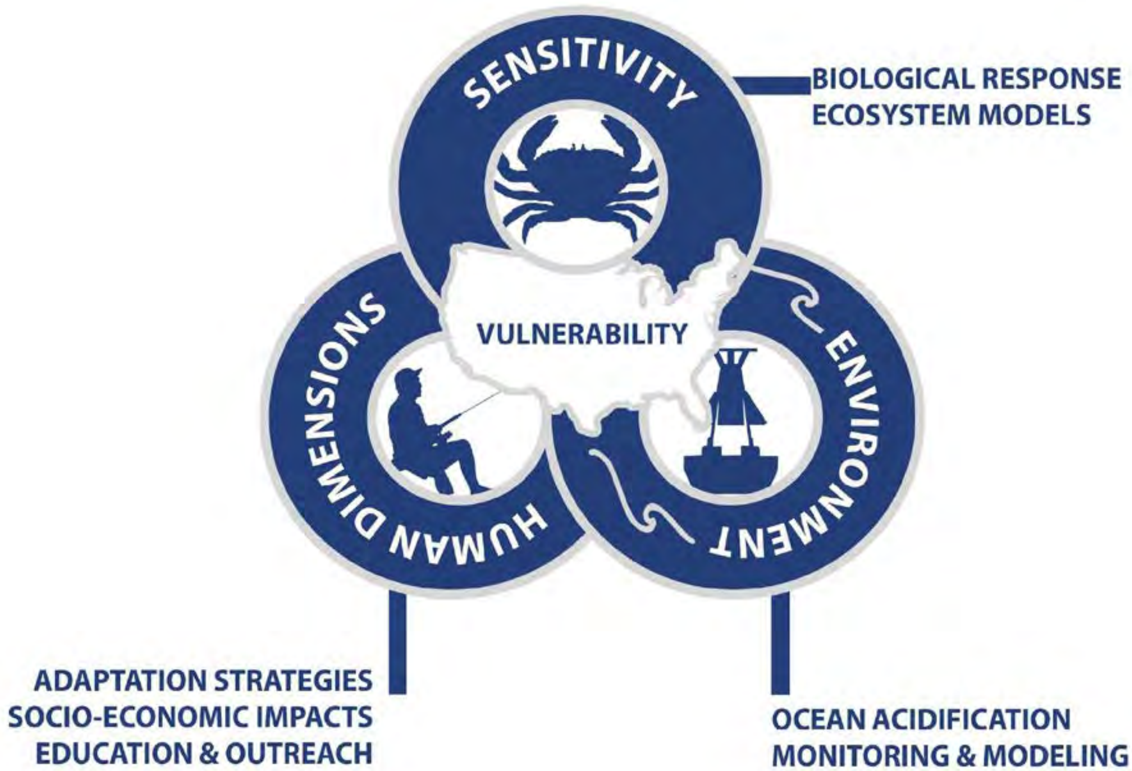

Figure 3. Assessing the vulnerability of the U.S. Blue Economy to OA demands a transdisciplinary approach that simultaneously combines an understanding of how conditions are changing (*Environment*), how living marine resources respond to the changes (*Sensitivity*), and how such impacts affect dependent 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 socio-economic implications of these changes.

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 OA and assessing vulnerability on a regional scale (**Figure 4**). The goal of the plan is to target environmental monitoring, biological sensitivity and human dimensions research aligned with the research needs of the regions and open-ocean, which feed into a series of high-level national research objectives. It is important to note that the agency continues to make major progress on developing OA education and outreach tools and programs (Theme 6 of the 2010 OA 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 toolkits and translated to stakeholder communities.

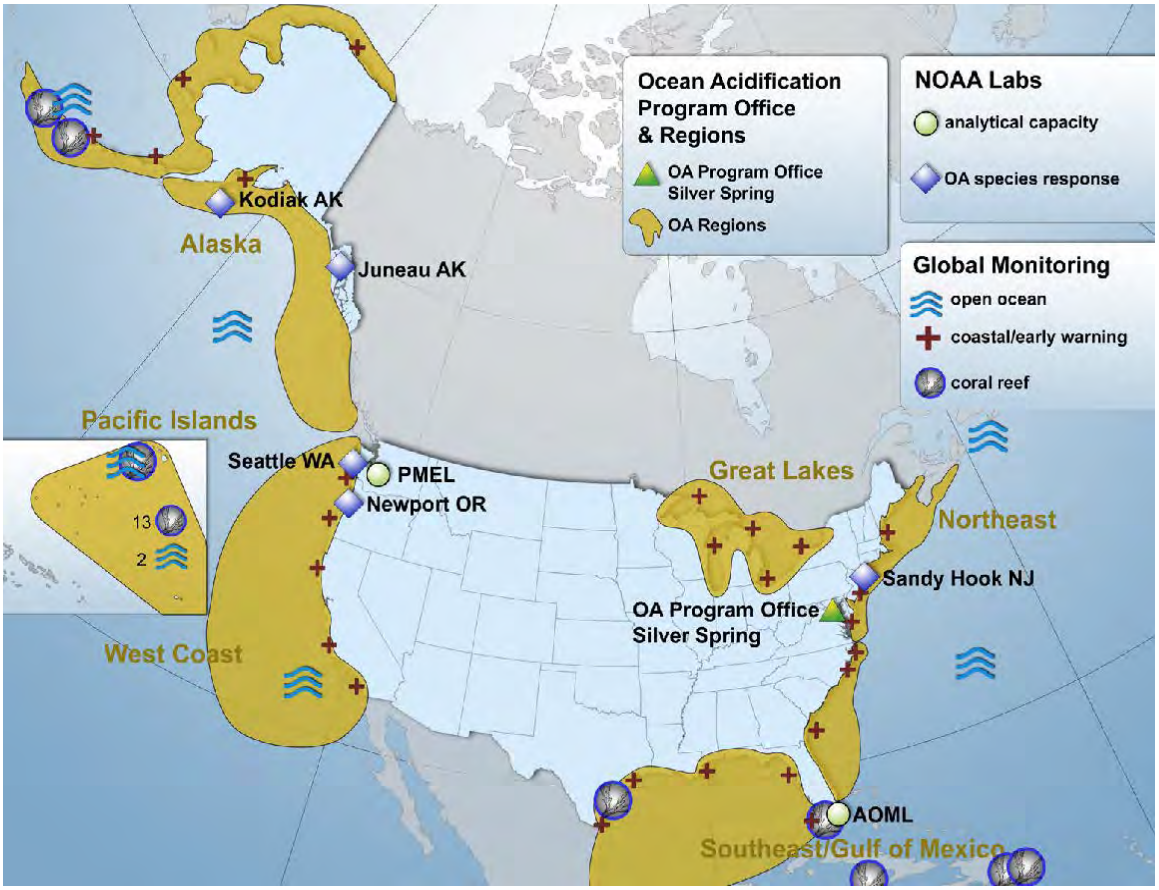

Figure 4. *[Placeholder Figure-Update Underway]* Color coded map showing outlines of the eight coastal regions and the open ocean region included in the 2020 NOAA Ocean and Great Lakes Acidification Research Plan. The coastal regions geographically closely based on the United States' Large Marine Ecosystem (LMEs), which represent areas of coastal oceans delineated on the basis of ecological characteristics that serve as suitable organizational unit to support ecosystem-based management (Sherman and Alexander, 1986).

1. National Ocean and Great Lakes Acidification Research

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Abstract

The National Chapter includes strategic OA research objectives that are collectively relevant to the open-ocean, the continental shelves and coastal zones of the U.S. and its territories and the Great Lakes region. Globally, OA is driven by the growing amount of anthropogenic carbon dioxide absorbed and dissolved in the upper ocean and Great Lakes, and is causing wide-scale changes in both the chemistry and biology of these systems. A number of important regional processes are also at play, influencing regionally unique ecosystems, driving coastal acidification and impacting human communities. NOAA's national OA research goals are to:

- Advance OA observing systems, technologies and data stewardship to improve the understanding and predictive capability of OA trends and processes;
- Improve understanding and prediction of OA as a stressor co-occurring with other prominent ocean and Great Lakes changes;
- Improve understanding of the biological response and adaptive capacity of ecologically and economically important species, ecosystems, and communities; and
- Increase research to understand vulnerability of communities and stakeholders to ocean acidification to generate useful data that supports adaptation and resilience plans.

Ocean and Great Lakes Acidification

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). It is anticipated that the Great Lakes have and will continue to acidify at rates comparable to the ocean (Phillips et al., 2015). In addition to anthropogenic CO_2, climate modes, such as El Niño–Southern Oscillation, are also proving to be important determinants of the state of the marine carbon system (e.g. Feely et al., 2006; Nam et al., 2011). Sub-global scale processes are occurring and driving the regional progression and variability of acidification, particularly within coastal zones. Some of these processes, which can alleviate or intensify coastal acidification, include rising ocean temperatures, seasonal primary productivity and respiration processes, riverine discharge fluctuations that deliver organic carbon and alkalinity-rich minerals, sea ice melt and associated freshwater pulses, and seasonal coastal upwelling that delivers CO_2-rich water masses to the surface ocean.

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. Critical to maximizing the impact of this plan is developing partnerships with other Federal agencies, academia, the private sector, state, local and tribal governments and the international community. 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 online community of the OA Information Exchange has a membership of over 800 individuals, including scientists, educators, resource managers, fishermen, aquaculturists, tribal representatives and citizens from all over the globe. The OA Information Exchange serves as a means to identify emerging issues and priorities for the NOAA OA Enterprise and the IWG-OA.

Beyond the Federal and U.S.-based OA research endeavors, NOAA represents an important voice in international OA research. Given the global-scale of OA and interconnectivity of the ocean system, NOAA and the international research community acknowledge that it is of utmost importance to build wider connections to establish common and interdisciplinary international observing program and data management systems. The Global Ocean Acidification Observing Network (GOA-ON), established in 2013 and co-founded by NOAA, is an international body that aims to develop international collaboration on OA research. Common 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 encourage outreach and education to increase public awareness, appreciation and information sharing to promote informed-decision making with achievable tenable solutions to the implication of OA. The plan's overall approach is ultimately designed to be flexible and adaptive to evolving scientific, technological and societal needs, to deliver results that advance our understanding while maximizing societal impact.

Environmental Monitoring

Ocean and Great Lakes acidification are impacted 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 on regional and global scales. In addition to *in situ* observations, remote sensing assets, such as satellites, provide global-scale synoptic data streams and are powerful tools for studying global surface ocean carbonate dynamics. While satellites are not presently capable of directly measuring carbonate chemistry, they 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., 2019). Sustained, robust satellite observations are central to quantifying changes in parameters through time and space, which together with *in situ* observations, are critical to developing a global-scale observing datasets.

The present *in situ* NOAA ocean observing system (as inventoried in the GOA-ON data portal) is oriented towards routine monitoring of the physical and chemical system (temperature, salinity, oxygen, nutrients, pCO_2, pH, TA, DIC), but lacks coverage of the Great Lakes, and has limited coverage of biological response variables that are measured concurrently. Since the publication of the 2010 NOAA Ocean and Great Lakes Acidification Research Plan, technological advances have greatly expanded non-ship based monitoring capabilities of climate-grade observations of fundamental OA variables (e.g. pH and pCO_2) on ocean moorings and autonomous vehicles, and development is underway for globally deployable biogeochemical profiling floats. Developments of sustained biological measurements are still in need of continued development; however, the field of 'omics research, which uses molecular markers as biological indicators, presents promise for such underway and autonomous biological sampling capabilities (NOAA 'Omics Strategy). Development of such technologies, with the goal of designing both cost-effective and robust analytical systems, observing sensors and unmanned technologies, will be key to expanding the existing observing system within fiscal bounds. Transitioning autonomous technologies from R&D to operational technologies will allow these new tools to serve as key elements of the OA observing system that can be used to better resolve the full water column and environments which challenge conventional technologies including coastal, estuarine and remote Polar Regions.

Continued development and optimization of the OA observing system is central to the research objectives laid out for the coming decade. Optimization means that observing assets are strategically deployed spatially and temporally, designed to answer research questions. While regional observing system configurations will be based on the needs of a specific geographic area, the purpose of the Global OA Observing Network is to (1) identify and document the global scale progression of OA, (2) determine the fraction of anthropogenic carbon in the surface ocean, (3) provide data needed for global biogeochemical model simulations and (4) measure the biological response to OA as technology and protocols become available. NOAA has played an important role in the formation of the GOA-ON. The GOA-ON has made vast progress toward developing the OA observing system via an international design of a coordinated, international interdisciplinary program of ship-based hydrography, time-series moorings, floats, and gliders and sustained support of the GOA-ON program is central to the enhancement of global OA observing.

On regional scales, observing systems must be designed to meet the needs of the coastal regions, which often means capturing a complex interplay of processes driving coastal acidification.

Regional-scale models, which have been developed for many but not all regions, are important to understanding regional impacts to economically important fisheries. Regional models are especially needed for high-latitude open-oceans, coral ecosystems, and coastal regions, which are all vulnerable to coastal acidification and OA in the near-term. The integration and linkage of regional ecosystem models, which represent biological sensitivity of economically important species and their habitats, with biogeochemical model frameworks, will be important to predicting the impacts of coastal acidification in these regions. This progress in model development will inform management actions and is a key example of future work needed in the U.S. regions to fully assess the impact of OA on the blue economy.

OA research investments have generated a tremendous amount of physical, biological and model data sets. Cruise and laboratory based data have to be quality controlled and integrated together in order to better understand the changing water chemistry on a regional to global scale; and the impacts of OA on the broader marine ecosystems. In the coming decade, data management and stewardship will be an integral part of OA research to ensure that data are optimally used and transitioned into useful data products. The transition of scientific data to information product 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. A special emphasis will also be placed on ensuring that data collected by the OA observing system are findable, accessible, interoperable, and reusable (FAIR; Tanua, et. al, 2019, Wilkins, et al, 2016).

In addition to management, data synthesis efforts provide useful products that include integrated time series of chemical, biological, and ecological parameters affected by OA; spatially mapped products utilizing proxies and remote sensing (Salisbury et al., Shutler et al.); predictions at local and regional scales through integration of models and observations; and informational materials based on the OA observations and interpretation. Past synthesis efforts have been focused on the open ocean, when in reality over 90% of the fisheries are from the coastal ocean. Recognizing the importance of coastal OA synthesis activities, concerted efforts are needed to better inform the aquaculture industry and the U.S. population in terms of OA mitigation and adaptation efforts. Such synthesis products could make it possible to produce OA products that can be used by the general public to access information about the OA conditions in their coastal areas, and annual U.S. National OA Reports.

Research Objective 1.1: Expand and Advance OA Observing Systems and Technologies to Improve the Understanding and Predictive Capability of OA Trends and Processes

Continually optimizing and expanding the configuration of observing assets (e.g. ship, mooring, autonomous instruments) is critical to understanding the variability driven by a myriad of processes and progression of acidification in the open ocean, coastal zones and Great Lakes. Maximizing usable observing data streams into model simulations is central to predicting the future of OA and informing management choices and decision makers.

Action 1.1.1: Sustain the development of cost-effective and robust analytical systems, observing sensors and unmanned technologies and transition R&D technologies to serve as operational key elements of the OA observing system, with a special focus on ensuring robus benthic measurements of OA parameters

Action 1.1.2: Collect carbonate chemistry parameters needed to constrain the fraction of anthropogenic carbon present in the open-ocean and coastal environments

Action 1.1.3: Improve leveraging of remote sensing products to up-scale *in situ* observations and routinely produce synoptic estimates of global surface-ocean carbonate chemistry dynamics

Action 1.1.4: Conduct studies based on global and regional observing and modeling needs in order to strategically deploy observing system assets for optimal spatial and temporal coverage

Action 1.1.5: Continue to develop and expand coverage of regional biogeochemical-ecosystem linked models (additionally linked with Earth System Models) with increased geographic coverage on time-scales of days to decades, especially where relevant to local living marine and Great Lakes resources and dependent communities

Action 1.1.6: Continue leadership of and support for the enhancement of the GOA-ON within which the NOAA OA Observing Network is nested

Action 1.1.7: Ensure data collected by the OA observing system have data management plans and are based on standard formats and comply with FAIR data principles

Action 1.1.8: Support data synthesis of open-ocean and coastal datasets to ensure data are transitioned into useful products to be used by the general public and U.S. National OA Reports

Biological Sensitivity

Over the last decade, researchers have improved understanding of how marine species, populations and ecosystems are impacted by OA. This research has been conducted both in controlled laboratory environments and in the field and has examined not only the response to OA but also 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 responses of species, while field studies reflect a magnitude of response that is consistent with present and near future ocean conditions. 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 the inability to disentangle OA from the multi-stressor environment. Despite limitations, evidence of biological response continues to mount and the understanding of OA and biological sensitivity has become deeper and more nuanced.

While numerous species sensitivity studies have been conducted to date, the number of species whose sensitivity has been characterized is small in comparison to the overall diversity of marine and Great Lakes life, and sustained research is needed to close this knowledge gap. Notably, many species that are important to ecosystem function or to commercial and subsistence harvests have yet to be examined (see subsequent regional chapters). Researching these critical species is central to understanding and predicting the impacts OA may have on dependent human communities and economies. In addition to direct impacts, such as reduced calcification efficiency or 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 the reduction in quality and/or availability of a food source due to OA sensitivity of lower trophic species. Such indirect impacts demonstrate the importance of assessing sensitivity through an ecosystem framework among species populations and developing ecosystem-level models.

Understanding biological sensitivity and specifically being able to attribute a species response to a specific variable or stressor would benefit from colocation of biological observations with physical and chemical observing systems in order to collect a suite of variables that can aid in understanding multi-stressor variable interactions. Monitoring plans that integrate biological sensitivity studies and biological surveys with physical observations can coincide with ongoing observations that greatly expand the understanding of exposure and environmental history at a site outside of the bounds of the survey. Promoting concurrent measurements of three of the marine carbonate system (DIC, pCO_2, TA and pH) rather than measuring a single carbonate system variable, will better facilitate attribution of species physiological response to a specific change in the carbonate system. Researchers typically report and correlate calcification response to the saturation state (Ω) of calcite or aragonite of seawater, but recent research has shown that some organisms such as coccolithophores are more sensitive to change in the ratio of bicarbonate to hydrogen ion (e.g., Fassbender et al., 2016; Bach et al., 2015). This nuanced calcifier response highlights the importance of fully characterizing the marine carbonate system when comparing organism response to *in situ* measurements. Constraining the carbonate system with at least three variables will also allow for indirect determination of non-carbonate alkalinity contribution which will be particularly important in coastal environments and in nutrient enriched experiments where many field-based biological studies are conducted.

Field-based biological sensitivity studies are labor-intensive, can be invasive and generally require trained technicians and researchers to collect observations. Recent developments in ‘omics science and sampling collection technologies have the potential to provide powerful new 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 technologies 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 can been used to identify resilient species genotypes and isolate molecular mechanisms that confer resilience with the aim to restore ecosystems.

Researchers expect that there will be emerging and unanticipated phenomena as a result of OA and environmental change. One such example includes the recent correlation between OA and increased growth and toxicity of harmful algal blooms (e.g. Raven et al., 2019). Such multi-disciplinary, including multi-stressor, research will be important in the coming decade, and the OA research enterprise will remain prepared to research unusual and developing phenomena.

Research Objective 1.2: Improve understanding and prediction of OA as a factor co-occurring with multiple stressors

OA is occurring in a multi-stressor framework with other changing environmental parameters, which collectively influence the response of an organism to OA. Understanding the mechanisms that drive physiological responses will inform ecosystem-level predictions of future change.

Action 1.2.1: Co-locate physical, chemical and biological observing systems to collect an array of variables to improve understanding of multi-stressor interactions and attribution of response
Action 1.2.2: Promote the full characterization of the marine carbonate system to better facilitate attribution science of species physiological response
Action 1.2.3: Support research to examine emerging and unanticipated ecosystem changes in response to OA and multi-stressor conditions
Action 1.2.4: Foster new research to clearly define the relationship between frequency, prevalence and toxicity of harmful algal blooms (HABs) in relation to OA
Action 1.2.5: Use new biological sensitivity knowledge to develop existing ecosystem models that can be linked to biogeochemical models and inform scenarios of OA (Action 1.1.5)

Research Objective 1.3: Improve Understanding of the Biological Response and Adaptive Capacity of Ecologically and Economically Important Species, Ecosystems, and Communities

The response of a number of economically and ecologically important marine and Great Lakes species to OA has yet to be examined. Assessing sensitivity as well as adaptation capacity is important to predicting ecosystem response and to developing mitigation and restoration plans.

Action 1.3.1: Integrate biological measurements into long-term biogeochemical observing systems and platforms to incorporate organismal metrics
Action 1.3.2: Assess sensitivity within species populations to evaluate potential for acclimation and adaptation
Action 1.3.3: Assess sensitivity among species, particularly ecologically and economically important species, to improve understanding of differing response
Action 1.3.4: Explore feasibility and benefits of genetically identifying species resistance and resilience to OA and applying active mitigation strategies to foster resilient marine communities and improve habitat restoration success

Human Dimensions

One of the NOAA OA enterprise's goals is to support OA-vulnerable communities by conducting research, developing models and creating forecasts and projections that can be used to quantitatively understand and predict the impacts to human communities, commercial activities and economies. The goal of assessing economic impacts is to weigh the costs of mitigation and adaptation against the costs of unmitigated impacts. NOAA plans to support these goals by conducting research and creating tools and resources suitable for coastal, open-ocean and Great Lakes ecosystem management decisions and using the information to prepare human communities for potential OA-related changes. Related socioeconomic research will be framed based on the needs of and conducted in consultation with relevant stakeholders in order to ensure actionable and relevant research results.

OA will likely affect commercial, subsistence and recreational fishing, tourism and coral ecosystems. A selection of valuable commercial fisheries, according to laboratory studies, that may be directly impacted by OA include West Coast Dungeness crab ($207 million across California, Oregon and Washington in 2017), Alaska King Crab ($81 million in 2017) and New England Atlantic Sea Scallop ($370 million in 2017) along with a myriad of other bivalve species including mussels, clams and oysters. In addition to the deterioration of coral ecosystems that are important recreational attractions, bioerosion of corals, such as those in the Caribbean and Pacific Islands regions (see subsequent chapters), make coastal zones more vulnerable to severe storms and waves that are typically dissipated by the presence of coral structures. Managers at the State, local and regional levels need scientific information to be able to anticipate these and other socioeconomic impacts and develop strategies to address the threats of climate and ocean change.

OA also will likely have impacts on communities that live on the coast and depend on marine ecosystems for their way of life. These coastal communities rely on local marine resources for commerce, cultural identity, and subsistence. Forecasting OA effects on community-relevant species is essential for preparing for and responding to future impacts of OA. Community-based observing and local knowledge can greatly expand the spatial and temporal coverage of monitoring and provide valuable insights to supplement ongoing scientific monitoring of OA.

An important objective to mitigating future OA impacts will be securing coordinated national and international investments to develop effective adaptive 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 balance how effective local adaptation strategies can be in the face of global-scale 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. The Open Ocean Region should pursue efforts to create visualization and educational products and outreach resources targeting diverse stakeholders to promote understanding and awareness of OA.

The FOARAM Act of 2009 calls for educational and public outreach opportunities to improve the understanding of current scientific knowledge and impacts on marine resources. Education, outreach and engagement extends the reach of NOAA's research findings, promotes awareness and provides information on the variety of tools and approaches that can be used by those that are or will be affected by OA. Over the last decade, NOAA's OA enterprise has been dedicated to working with the regions across the U.S. to develop tailored 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 present research plan aims to sustain effective public communication and to work with regions and communities to understand and respond to the needs of the education and communication communities and to support citizen science.

Research Objective 1.4: Increase Research Integration with Vulnerable Communities and Stakeholders to Generate Useful Data that Supports Adaptation and Resilience Plans

Integrating scientific knowledge into a socioeconomic framework is central to understanding the vulnerability of communities to OA. Integrated models and relevant research to develop such models should be framed and informed by the needs and concerns of stakeholders in order to create meaningful and actionable results that can be used for informed decision-making.

Action 1.5.1: Identify the relationships between key social, cultural, and economic drivers to biophysical, fishery, and ecosystem parameters within the open ocean to coastal continuum to predict potential responses from future OA scenarios

Action 1.5.2: Link physical and biological models with socioeconomic models to assess economic impacts, explore adaptive and provide valuable insights to inform strategies for dependent communities and industries (Action 1.1.5 and Action 1.2.5)

Action 1.5.3: Develop (with robust stakeholder input) and operationalize (or transition) data synthesis and data visualization tools based on OA science outcomes most applicable to stakeholder requirements

Action 1.5.4: Support and encourage OA research in partnership with stakeholders via a two-way dialogue to ensure that research is informing needed, local adaptation strategies by continuing to support groups such as the Coastal Acidification Networks (CANs)

Action 1.5.5: Continue to support the OA Information Exchange as a communication platform to incorporate stakeholders into research discussions, foster connections between physical and social scientists and promote the timely exchange of information and knowledge

Action 1.5.6: Create education and outreach resources in partnership with researchers based on regional needs and real data products to promote understanding and awareness of OA and possible response and mitigation strategies (partner goal with NOAA OA Education Implementation Plan)

Action 1.5.7: 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 and biological sensitivity trends to understand areas of coherence

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 interacts with natural variability collectively act on ocean carbonate chemistry and biology, and continue to support and enhance the NOAA Contribution to the Global Ocean Acidification Observing Network (GOA-ON) with new sensors, new autonomous platforms, and new 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. NOAA's Open Ocean Region OA research goals are to:

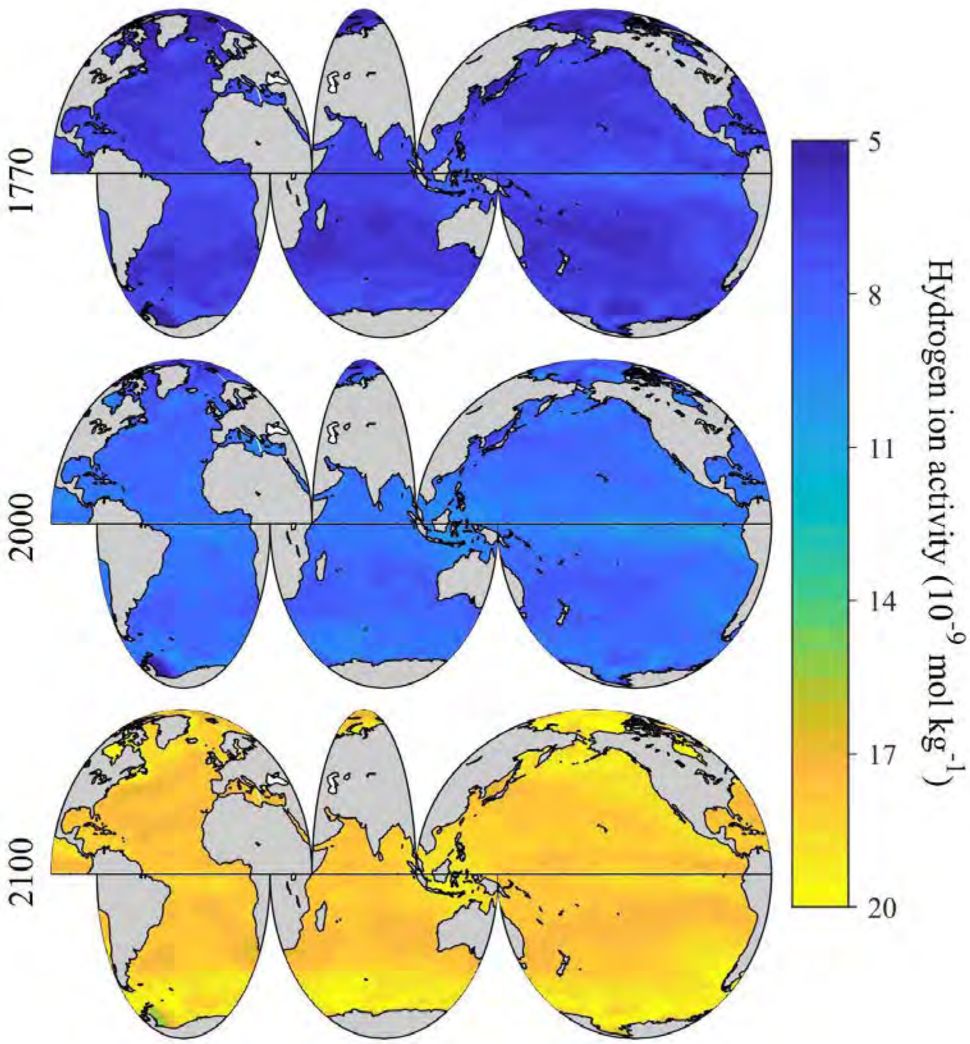
- Maintain existing observations and continue developing and deploying autonomous vehicles and biogeochemical (BGC) Argo floats to measure surface and water column carbon parameters, nutrients, and other Essential Ocean Variables (EOVs);
- Conduct biological sampling (e.g. Bongo net tows) during GO-SHIP 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 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 ocean acidification 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 hydrogen ion activity (H^+) changes from OA because of the combined effects of the anthropogenic CO_2 input, lower temperature, and lower buffer capacity.

Models indicate that with continued atmospheric CO_2 absorption, the ocean is likely to undergo rapid changes in calcium carbonate undersaturation 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; Gattuso et al., 2015; **Figure 1**). Quantifying the relative magnitudes 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 H^+, pCO_2, carbonate ion concentrations ($[CO_3^{2-}]$), and calcium carbonate mineral saturation states, with significant increases in surface ocean H^+ and downward trajectories of surface ocean $[CO_3^{2-}]$, and carbonate saturation states are expected to decrease throughout this century with increasing atmospheric pCO_2 (e.g., **Figure 1**). However, attempts to synthesize H^+ 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 2019). In this chapter we recommend future research objectives, activities, and priorities for the open oceans over the next decade for NOAA ocean acidification research.

a)



1770
2000
2100
5
8
11
14
17
20
Hydrogen ion activity (10^{-9} mol kg^{-1})

b)

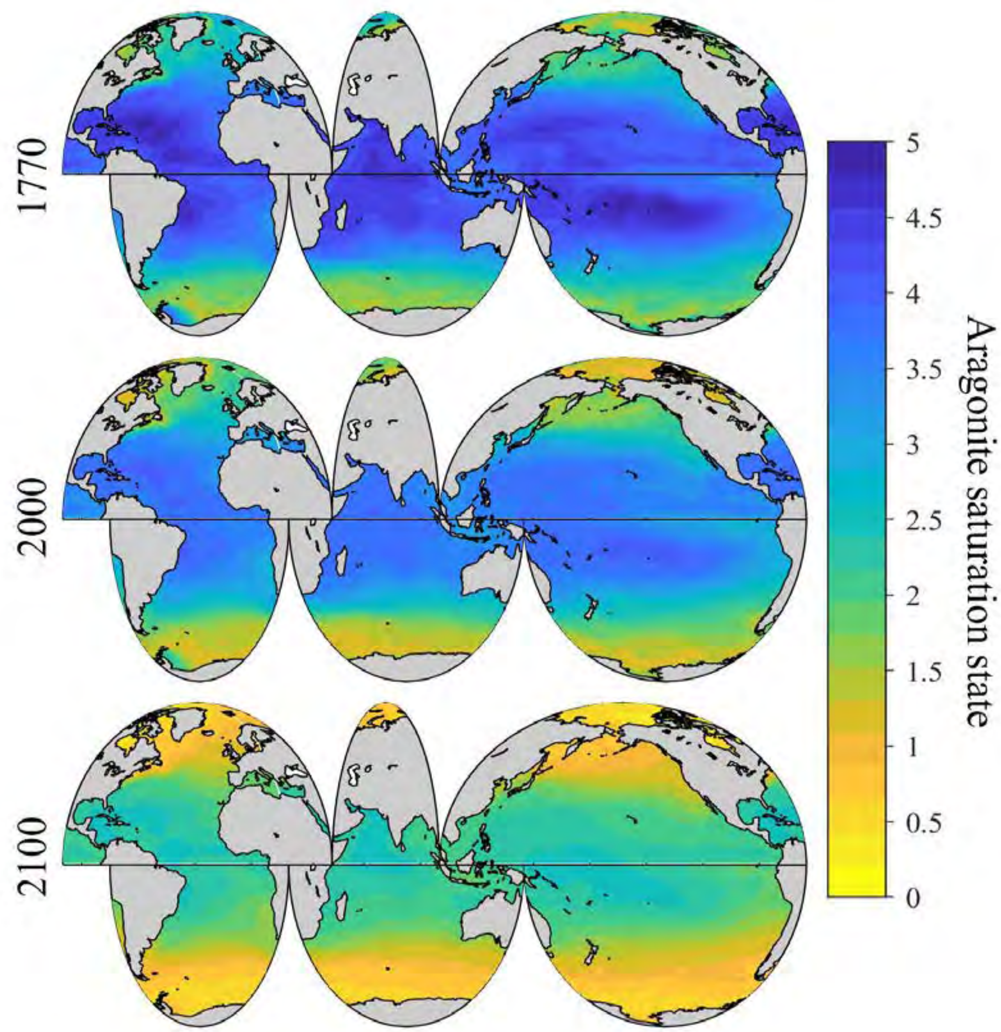


Figure 1. Model output of past, present, and future of: a) hydrogen ion activity changes and b) aragonite saturation state based on global surface ocean pCO_2 observations normalized to the year 2000. The hydrogen ion activity distributions for 1770 and 2100 are reconstructed by extracting the temporal 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., submitted for publication).

Environmental Monitoring

After launching the GOA-ON in 2013, the current observing network is a composite, with several observing networks deployed around the world- including moorings, repeat hydrography lines, ships of opportunity, and fixed ocean time series (**Figure 2**). The existing large-scale global oceanic carbon observatory network of 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 address the problem of ocean acidification (**Figure 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, 2019; Sutton et al., 2019; Gruber et al 2019). At present, many of the existing moored carbon observatories only measure pCO_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.

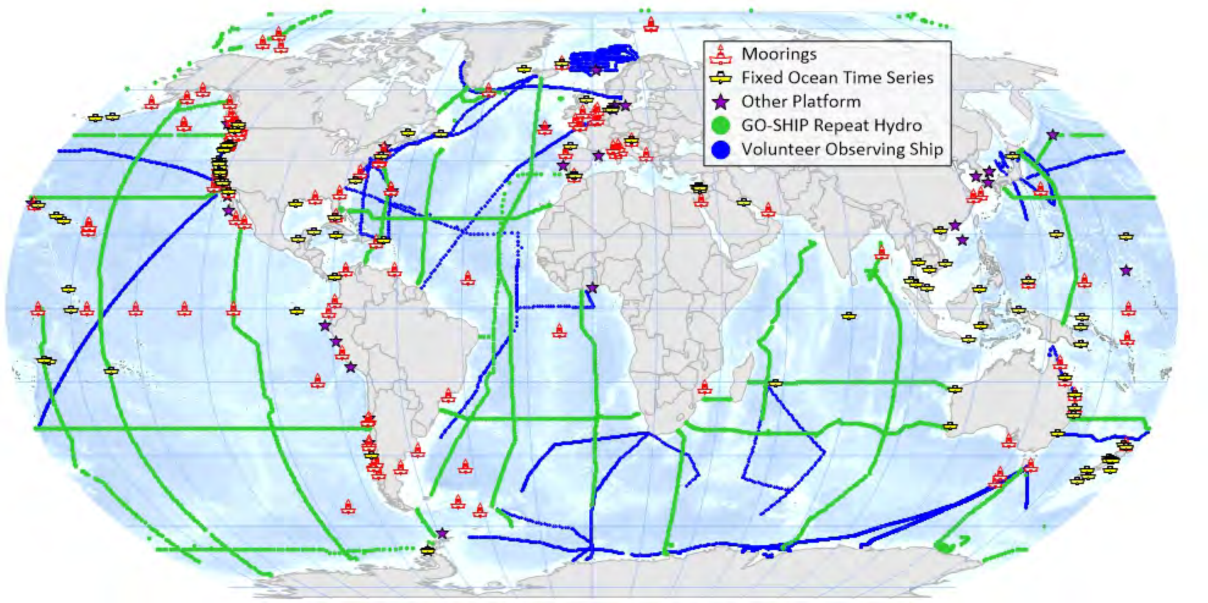


Figure 2. Present-day Global Ocean Acidification Observing Network, which is collaborative with the GO-SHIP, Ocean SITES, SOCONET, SOOP communities, and other open-ocean and coastal observing networks (after Tilbrook et al., 2019).

Efforts to observe and predict the impact of ocean acidification on marine ecosystems must be integrated with an understanding of both the natural and anthropogenic processes that control the ocean carbonate system (**Figure 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 ways by which anthropogenic carbon can be distinguished from natural carbon, but all rely on the repeated, high quality, high spatial density, 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, 2019; DeVries et al., 2014; Gruber et al., 2019). 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., 2019), indicating that repeat hydrographic surveys will remain critical for quantifying ocean carbon storage in the coming decades. Feely et al. (2016) extended open ocean anthropogenic carbon estimates to the coastal ocean, allowing the impacts of OA to be separated from natural processes over a two-decade-long span across several large marine ecosystems. 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 these regions typically lack means to directly quantify the overall anthropogenic impact in regions with air-sea pCO_2 disequilibria.

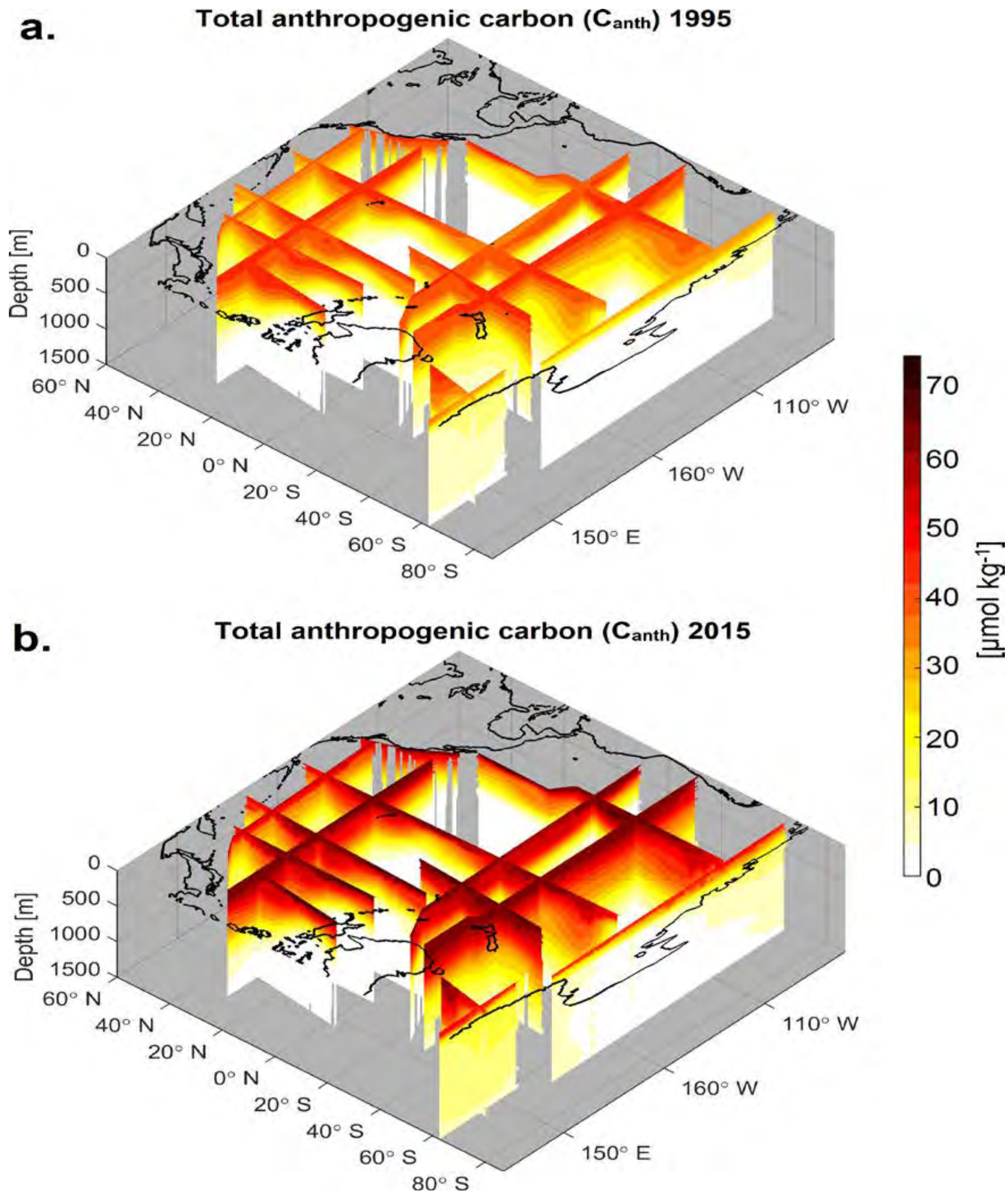


Figure 3. Anthropogenic dissolved inorganic carbon concentrations in μmol kg^{-1} along Pacific repeat hydrographic sections, estimated for (a.) 1995 and (b.) 2015. Darker colors indicate that higher concentrations are found near the surface, and extend deeper into the water column in the subtropical gyres. This figure is adapted from Carter et al. [2019].

Open-ocean time-series observations now exist in nearly all biogeochemical provinces 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., 2014; Sutton et al., 2017, 2019). However, enhanced variability in high-latitude regions can complicate and, at times, obscure detection and attribution of longer-scale 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., 2019; 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. They are a powerful way to quantify the specific UN Sustainable Development Goal 14.3 to minimize and address the impacts of ocean acidification, including tracking rates of change of ocean acidification globally.

Autonomous platforms have demonstrated their potential for revolutionizing the quantity and coverage of OA-related information retrievable from remote regions in all seasons (Bashinsky 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 6 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 4**). Aside from directly determining OA parameters and processes from these programs, the data is increasingly used 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 pCO_2 and pH can be directly measured, with in situ calibration of CO_2 providing high-quality data equivalent to moored pCO_2 time series (e.g. Saildrone). However, even the highest-quality pCO_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.

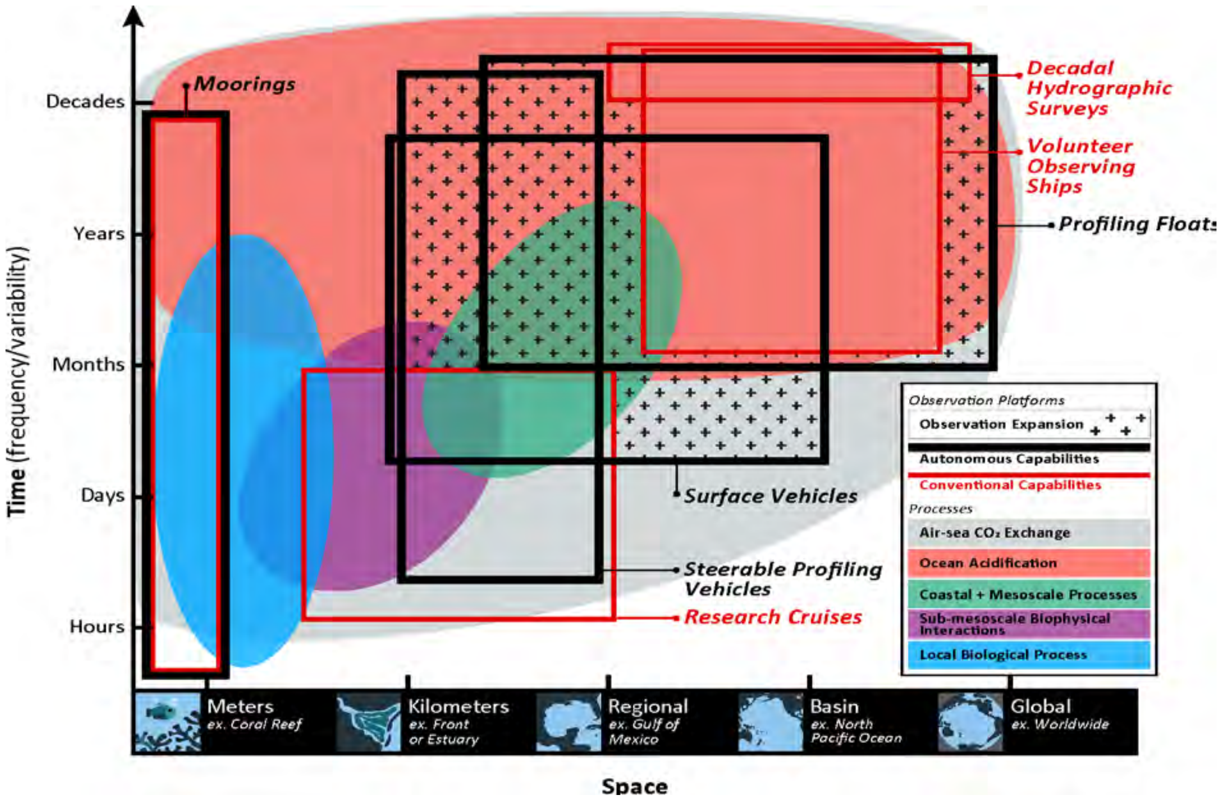


Figure 4. Carbonate system processes and autonomous vehicle observational capabilities as a function of time and space. Ocean processes that affect the carbonate system (solid colored ovals with labels in the caption) are depicted as a function of the temporal and spatial scales over which they must 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 Survey, and Volunteer Observing Ships) indicate the same temporal or spatial boundary but are offset for clarity (after Bushinsky et al., 2019).

Research Objective 2.1: Continue leadership and support for the GOA-ON

The GOA-ON provides a framework to knit together the many of ship-based hydrography, time-series moorings, floats and gliders with carbon system, pH and oxygen sensors, ecological surveys and associated biological responses. Support will assure continuation of the ongoing international observing programs, support augmentation of observation with key biological 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 new observing platforms that provide important information on the changing physical, chemical and biological conditions in open-ocean environments

Action 2.1.2: Enable the development of globally accessible high-quality data and data synthesis products that 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 signal 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 ocean acidification.

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 to characterize rates of ocean carbon change over time, which is necessary to reduce uncertainties in future projections of ocean acidification

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. 2019), 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). 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 data sets 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, 2019).

Open-ocean transects provide valuable insight into source water evolution relevant to coastal ocean 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 ocean acidification. 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 push the state-of-the-art 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 and plans to provide public access to its next-generation Earth System Models 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 activities that must be addressed before these observations can be integrated with established observations in global data synthesis products and used to validate models. Inter-comparisons between established and new observations can help determine uncertainty of new technologies, but a data integration system must also be developed 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. The OA Program should support 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 – dependent on Research Objective 2.2 above. These forecasts are in a state of development and require more research into data assimilation methods, especially considering the new observational assets coming online in the next few years. Global scale historical and future scenarios of decadal to centennial scale 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 on seasonal to decadal timescales (Li et al., 2016; Park et al., 2018). 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 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, 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 requiring further improvements in understanding.

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

Quantifying ocean acidification impacts requires the development of global and regional data products from observational data such as open ocean observations from GO-SHIP, BGC Argo, SOCONET, SOCAT to provide initialization data for model runs and validation data sets for testing model predictive capabilities.

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 to validate models

Action 2.3.3: Continued 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., 2019). 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 ocean acidification, 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 for meeting program requirements.

Recognizing that many satellite-based empirical or semi-empirical algorithms relating observable parameters to ocean acidification 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). Currently, a global beta product exists that incorporates satellite sea surface height, modeled salinity, and satellite ocean color and temperature; however, case studies currently remain limited to the coastal regions as part of the US Marine Biodiversity Observing Network. Thus, there is much opportunity for improvements that include but are not limited to addition of new variables, methodological comparison, and global validation.

Surface ocean gridded data synthesis products of satellite remote sensing outputs (e.g. SOCAT) 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 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_T.

Improved models for quantifying surface biological perturbations to the carbonate system from space is needed. The predominant perturbation arises from net community production (NCP), or the balance between net primary production (NPP) and community respiration (CR). Several existing strategies for retrieving satellite-derived NCP include a space-time accounting of the change in organic carbon inventories (Jonsson et al, 2011; Jonsson and 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: Establish global dynamic classification of pelagic seascapes derived from satellite remotely sensed variables

Action 2.4.2*:* Derive seascape-specific multivariate algorithms for predicting global surface ocean pCO_2 at suitable spatiotemporal scales (e.g. monthly, 0.5 degree)

Action 2.4.3: Incorporate optical measurements supporting satellite algorithm development and determination of biological productivity into on-going ocean acidification surveys

Biological Sensitivity Studies 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; Engstöm-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. Different species often respond differently to OA and other stressors, and have different spatial and temporal dynamics that are crucial for larger organism's food requirements, and in turn for ecosystem services and seafood resources. Changes in biodiversity and lower trophic level species composition are ultimately dependent upon species vulnerability vs. 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 an integration of physical, chemical, and biological data into biogeographic observations 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 the local environment are not always recorded together. More specifically, Habitat Suitability Indices (HSIs) can be used as correlative approaches using multiple regression methods to find the envelope of optimal conditions in which an organism is observed to persist (Bednaršek et al., in revision). CPR data have been collected over time, and some of them now represent unique time-series to 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.

Large-scale OA gradients in the open ocean represent transition zones where genetic pools potentially harbor genetic variability and biodiversity. 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 between community level biological diversity and physical and chemical ocean parameters, in order to understand responses to OA, enabling 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.

***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

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.

Action 2.5.4: Develop biogeochemical tools for assessing the impacts of OA and other stressors on higher-level species

3. Alaska Region Ocean 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. 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. NOAA's Alaska Region OA research goals are to:

- Continue monitoring OA 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 ecosystem and commercial species and use this knowledge to model and predict ecosystem-wide impact of acidification; and
- Evaluate the sensitivity of nutritionally and economically important subsistence and industry species to assess socioeconomic impacts.

Ocean Acidification in the Alaska Region

Ocean acidification poses unique economic, nutritional, and societal concerns to Alaska communities. With a greater area of EEZ waters and a longer coastline than that of the entire contiguous United States, 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 et al., 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, please read "Chapter 4: Arctic Region Ocean 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 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 & 2019). 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 "bellweathers" 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 µmol kg-1 in surface waters as of 2015 (Carter et al., 2017 & 2019). 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., 2014), 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 ocean acidification 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, 2013b, & 2016). The sensitivity of the 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 & 2019). 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 Alaska 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. 2015).

Environmental Monitoring

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. To support understanding 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 and scaling 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 the 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 the M2 and GAK that provide information on the seasonal cycle and interannual variation of OA parameters in the Gulf of Alaska and Bering Sea and expand the mooring network to observing in 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 and 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 to help evaluate the rates and fluxes that are critical to reducing uncertainty in models

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 for commercial and subsistence fishing in Alaska over a broad spatial scale.

Action 3.2.1: Support and validate high-spatial resolution regional ocean models for short and long-term forecasting to inform species response studies and to provide an estimate of OA exposure on shorter timeframes that are relevant to fishery communities

Action 3.2.2: Develop OA indicators that link ecosystem exposure to OA and fisheries population dynamics to improve forecasts of OA ecosystem impacts and create a management-focused OA product for Alaska that can be used by fishery managers

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.

Action 3.3.1: Provide training and technical expertise to local communities to sustain and further develop Alaska's coastal OA monitoring network through establishment of additional OA monitoring sites

Action 3.2.2: Develop the information networks and data management procedures to ensure accurate and timely reporting of OA conditions

Action 3.3.3: Provide high spatial and temporal resolution of 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

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. 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, Long et. al 2016, Swiney et al. 2016) and red king crab (Long et al. 2013a, Long et al. 2013b, Swiney et al 2017) being the most sensitive, whereas blue king crab (Long et al. 2017) and snow crab appear to be more resilient (Long, unpublished data). Among groundfishes, larval and juvenile walleye pollock didn't appear to suffer negative effects of OA (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 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 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, (Mathis et al. 2015; 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 be affected (Clements and 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, submitted), climate-enhanced groundfish assessment models (Holsman et al. submitted) 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, Gains et al. 2018).

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.

Action 3.4.1: Expand research to include under-studied species including Alaska salmon and bivalves that have commercial and subsistence value

Action 3.4.2: 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 adaptation measures.

Action 3.6.1: Integrated climate-biological-socioeconomic models that link the physiology, growth, behavior, and distribution of species to spatial and temporal patterns corrosive water exposure will allow for evaluation of direct and cascading effects of OA on the social-ecological system

Action 3.6.2: Conduct laboratory experimental studies to quantify the effects of OA and *in situ* field observations to validate and parameterize OA to biological couplings in food web and climate-enhanced models

Human dimensions

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 ocean acidification (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, which were treated 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 (Kasperski et al. 2017, Barange et al. 2014, 2018, Holsman et al. 2018). Integrated modeling of OA effects on the coupled social-ecological system, such as technical interactions between fisheries, can help reveal cumulative impacts on specific fisheries and 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. 2019). 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 and the fishing fleets they support.

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: Assess OA sensitivity of 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.

Action 3.7.1: Analyses will include the direct effects of OA on harvested species and OA-induced food web alterations that may impact the production and availability of large marine mammals

Action 3.7.2: NOAA will 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

Research Objective 3.8: Improve assessment of socioeconomic impacts of OA on fisheries

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 3.8.1: 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 3.8.2: Analyze direct and indirect effects of OA, 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 3.8.3: 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 3.8.4: Use integrated assessment models to inform stock assessment status and recovery plans

4. Arctic Region Ocean 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. 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 Alaska Arctic home. While the US 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 OA 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.

Ocean 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., 2015; 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., 2015), 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., 2015) 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, shelf areas that 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 are currently 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's Arctic Action Plan, Sullivan, 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 from Arctic to temperate species 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 and 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 experiences 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 and 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, 2015; Miller et al., 2014; Cross et al., 2018). Estimates of anthropogenic carbon dioxide (CO2) 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, 2015; 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 and Gullands, 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 Monitoring

Over the last 10 years, NOAA's OA research activities in the Arctic have been extremely limited. 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 and Ostrovskiy, 2015). Carbonate chemistry measurements were collected in 2009 and 2012 (Bates et al., 2015; Mathis et al., 209, 2015). 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 and Grebmeier, 2018). While the DBO was formally established in 2010, some time-series observations in DBO date back decades. OA observations were added to the DBO portfolio in 2017.

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, 1985), with the first large-scale carbonate chemistry mapping programs implemented only over the last few decades (e.g., SBI: Bates and Mathis, 2009, Anderson et al., 2010; ICESCAPE: Bates et al., 2014; RUSALCA: Bates et al., 2015). 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 (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 our 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 CO2 flux measurements in an effort to supplement those collected by ships (Cross et al., 2016; Sabine et al*., in prep*). NOAA is also exploring new sub-surface sensors that may be able to seasonally collect autonomous measurements of total alkalinity (TA) from moored platforms. Importantly, collecting TA measurements may help identify OA impacts, including acidification-mediated dissolution. Sensors that measure dissolved inorganic carbon (DIC) are also currently under development. Combining readily available pCO2 sensor data with developing DIC or TA sensor data will also help to generate extended carbonate system data in a time-series setting.

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

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 to 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 Arctic observations in the historical record, time series and process studies can help resolve key unknowns in the Arctic carbonate cycle

Activity 4.1.1: Quantify anthropogenic CO2 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

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 and 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 and Dupont, 2015; De Wit et al., 2015). 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 Ocean Acidification 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, C*hionoecetes 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 and 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.

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 Distributed Biological Observatory 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 ecosystems on which they depend, it is imperative to initiate targeted, Arctic-specific laboratory and field acidification 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 these 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

Characterize baseline physical and biological conditions, monitor changes in these ecosystem attributes, and perform process studies on key species in order to understand and predict ecosystem-level effects of OA.

Action 4.5.1: Establish reference conditions for Arctic ecosystems and invest in sustained ecosystem monitoring of important Arctic species and zooplankton

Action 4.5.2: Perform targeted process studies to quantify important ecosystem pathways

Research Objective 4.6: 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 4.6.1: Use appropriate modeling techniques, including single-species, ecosystem, and qualitative models, to understand the likely effects of OA in the Arctic

Human Dimensions

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 (Sullivan, 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 United States 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 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 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 and 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., 2015; ICCA, 2015; Lam et al., 2016), with these goals expressed in NOAA's Arctic Action Plan (Sullivan, 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 4.7: 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 4.7.1: Design targeted carbonate chemistry products that support the U.S. Arctic Fisheries Management Plan and the FiSCAO Science Plan

Action 4.7.2: Include OA risk information when designing fisheries management strategies for the U.S. Arctic region

Research Objective 4.8: 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 4.8.1: 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 4.8.2: 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 Ocean Acidification Network (AK-OAN) to develop and to transition decision support products

5. West Coast Region Ocean Acidification Research

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Abstract

The West Coast Region includes the US coastal waters off of Washington, Oregon, and California including the continental shelf and inland seas. These waters are influenced by adjacent regions in the Baja and British Columbia regions, and are collectively referred to as the California Current Large Marine Ecosystem (CCLME). This region is an eastern boundary upwelling system marked by seasonal upwelling, which brings old, cold, and low-pH carbon-rich subsurface waters to the surface ocean 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 OA 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.

Ocean 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 climate change-induced processes, like enhanced upwelling, and nutrient additions in some coastal areas to result in a rapid rate of acidification compared to other regions (Rykaczewski and Dunne, 2010, Turi et al. 2016, Carter et al 2019). This 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 CO_2 concentrations, Figure 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). Intensified upwelling supplies deep water to the shelf that is rich in dissolved inorganic carbon and nutrients, but oxygen-poor. Ocean acidification (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., 2016; 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.

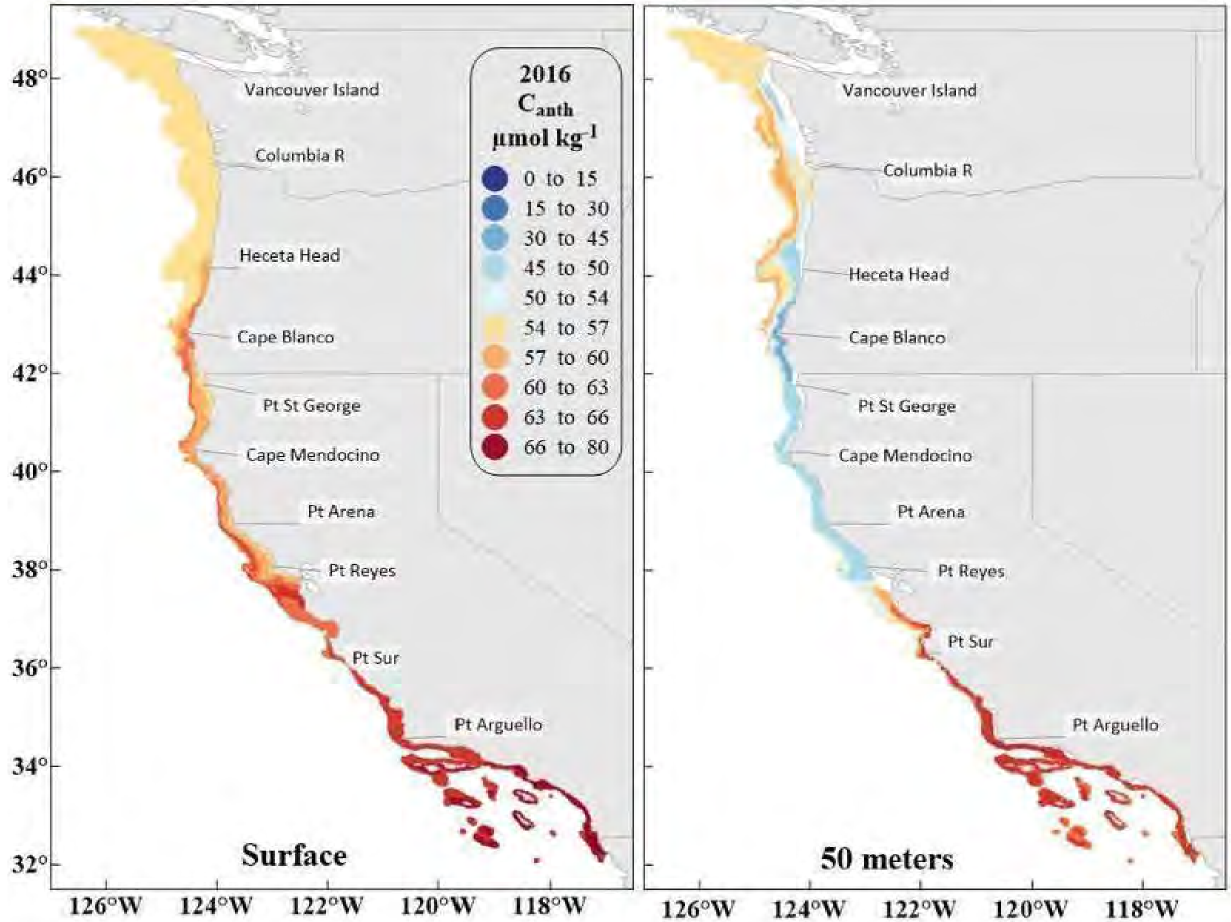

Figure 1. Distribution of anthropogenic carbon in surface and 50 m depth ocean waters in May-June 2016 based on the 2016 West Coast Ocean Acidification cruise. Credit: Richard Feely, Simone Alin, Brendan Carter.

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 pteropods, foraminifera and copepods, important prey in food webs for fin fish including salmon, supports these conclusions (Bednaršek et al., 2014, 2016, 2017a,b, 2018, 2019; Bednaršek and Ohman, 2015; Feely et al., 2016; Osborne et al., 2016, *accepted*; Engström-Öst et al., 2019; Figure 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 et al. 2016, 2017; Davis et al., 2016; Hodgson et al. 2016; Jones et al. 2018, Bednaršek et al., 2019).

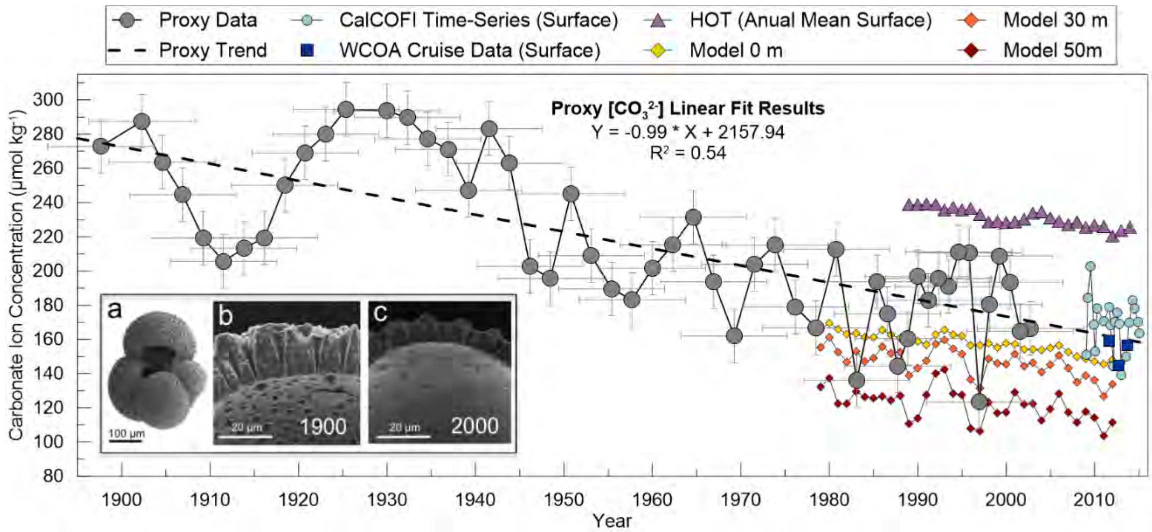

Figure 2. Plot of carbonate ion concentration versus time based on *G. bulloides* shell thickness in sediment cores from the Santa Barbra Basin (after Osborne et al., *accepted*). These results indicate that surface ocean [CO_3^{2-}] in the Santa Barbara Basin decreased by 35% or approximately 98 µmol kg^{-1} ±16 in [CO_3^{2-}] over the 20th century. The proxy-based [CO_3^{2-}] estimates are compared to available *in situ* surface measurements collected in the Santa Barbara Basin and the North Pacific and published hindcast biogeochemical model simulations and are in excellent agreement with the forward projected trend of estimated [CO_3^{2-}] values even though these datasets do not temporally overlap.

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 1; Feely et al., 2008, 2010, 2012, 2016, 2018; Bednaršek et al., 2017; 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 cycle from the coast to the shelf and from benthic to surface waters. There are five National Marine Sanctuaries and numerous Essential Fish Habitats (EFH) 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 human communities economically and culturally dependent on them (Ainsworth et al., 2009; 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 low pH conditions in the region, such as deoxygenation and warming, is seen as crucial for characterizing and understanding OA influence on living marine resources in a way that is ecologically relevant to the CCLME (Bednaršek et al., 2018, 2019, Trigg et al. 2019, Reum et al., 2014, 2016).

Environmental Monitoring

Since the publication of the 2010 NOAA Ocean and Great Lakes Acidification Research Plan, NOAA has supported a range of OA observations and monitoring efforts on existing and NOAA-developed platforms including moorings, cruises, ships of opportunity, the Carbon Wave Glider, undulating gliders in coastal systems, and Saildrone (Figure 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 the OA coastal and the open-ocean, repeat-hydrography cruises (GO-SHIP, Sloyan et al., 2019), remain a strong research priority for OA (Carter et al., 2019a). 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., 2014; 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). West Coast environments experience a large range of marine environmental conditions with respect to carbonate chemistry and boast excellent access to laboratory and ship facilities. In addition, National Marine Sanctuaries and areas designated as Essential Fish Habitat by NMFS provide excellent 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.

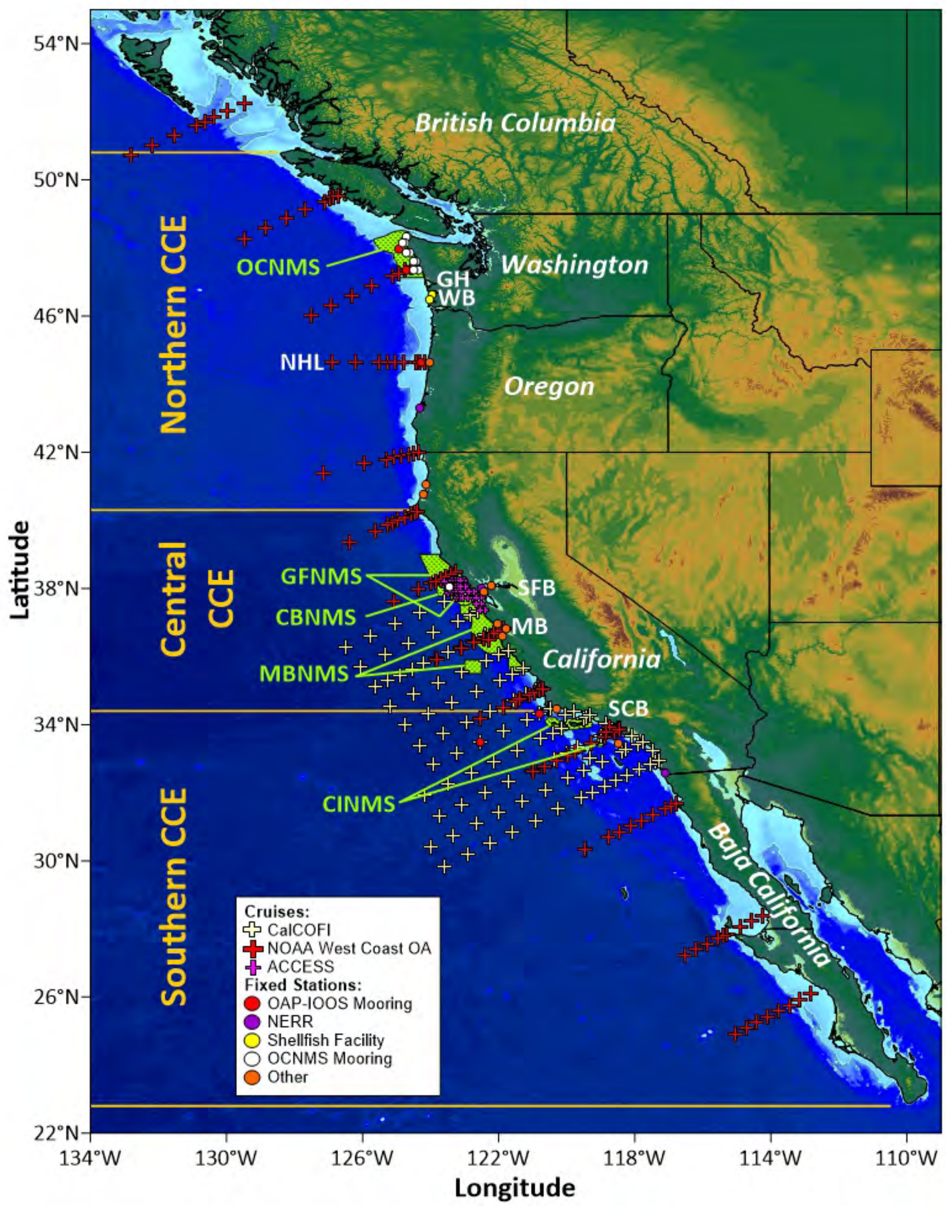

Figure 3. Maps of the California Current Large Marine Ecosystem with National Marine Sanctuary boundaries and current, long-term North American Pacific coast, NOAA-supported OA sampling platforms, as indicated in the legend. Abbreviations include: OCNMS = Olympic Coast National Marine Sanctuary, GH = Gray's Harbor, WB = Willapa Bay, NHL = Newport Hydorgraphic 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, NSF OOI = National Science Foundation Ocean Observatories Initiative, CINMS = Channel Islands National Marine Sanctuary, SCB = Southern California Bight. Credit: Dana Greeley, Pacific Marine Environmental Laboratory.

Economically, ecologically, and culturally important West Coast species such as Dungeness crab, geoduck, other harvested bivalves, salmon, and harvested groundfish use a variety of different habitats throughout 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., pCO_2, pH, aragonite or calcite saturation; i.e., Waldbusser et al 2015), so full delineation of the carbonate system is important at all locations. 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). Integrating physical and chemical time series with time series of species and ecosystem indicators is a priority for oceanographic research globally (Sloyan et al., 2019) 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 and mortality events of sea stars, seabirds, and kelp (Miner et al. 2018, Gibble et al., 2019, 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).

In order to provide decision support at relevant time scales for managers of West Coast species and protected areas, models must continue to be improved to provide skillful estimates of environmental conditions at daily to decadal time scales and beyond. The 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 time scale. 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 decadal timescales (Li and 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, shelf and offshore, and the estuaries and 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 and 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., 2015; 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.

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 harmful algal blooms- 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

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 temperature anomalies, 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 in sentinel sites such as National Marine Sanctuaries, 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

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 time scales and beyond. Development of past-to-future, high-resolution West Coast ocean models should continue in order to provide decision support at relevant time scales 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) 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

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 socio-economically important species yield information useful for management of wild capture fisheries, ecosystems, and aquaculture now and in the future. Species sensitivity studies (Figure 4) 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 (Activity 5.7.2). 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 values, which can be used to identify response thresholds, and 2) with co-occurring environmental stressors known to change with climate change, including temperature, oxygen concentration, and salinity. The experimental facilities at the 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.

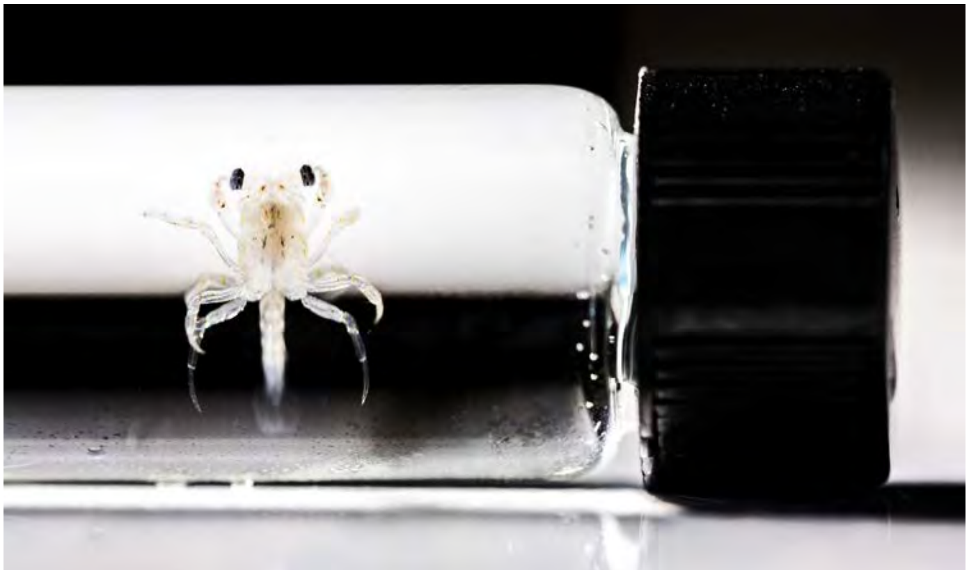

Figure 4. Dungeness crab megalops. Credit: Benjamin Drummond/bdsjs.com.

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 harmful algal blooms, 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 natural 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 vulnerability in natural environments.

However, to date, we have not yet found population changes in existing time series that can be directly attributed to OA, potentially due to the lack of available paired chemical and biological measurements (McElhany 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.

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 rigorously based on lab-based, species-exposure experiments. These HSIs use sensitivity information developed in

Objective 5.3.1 and, in combination with the modeling in Objective 5.2.3, 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 time scales. 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.

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 and state 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.

Objective 5.5: Investigate the potential for species to acclimate and/or adapt to ocean acidification

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 socio-economically 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 and populations of a species in field 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

Objective 5.6: Enable the detection 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

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 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 geographical 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 socio-economic 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 socio-economic data in order to develop models and other tools that may be used to estimate the socio-economic 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 (West Coast Ecosystem-based Fisheries Management Roadmap Implementation Plan, NOAA Climate Science Strategy Western Regional Action Plan).

Improved knowledge of the vulnerabilities from OA on socioeconomic well-being, 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 and 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). 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 harmful algal blooms 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 multi-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.

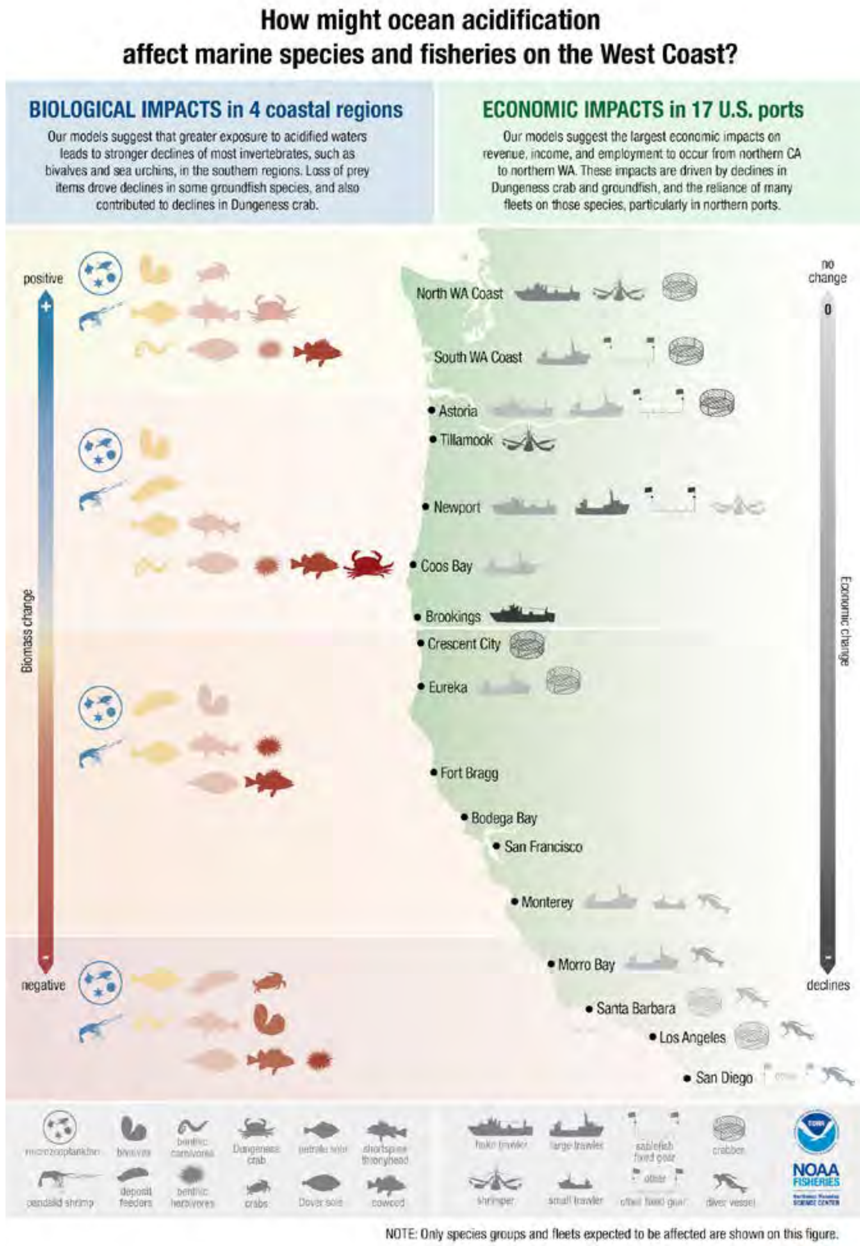

Figure 5. Infographic of model output on how OA could influence West Coast species and the economies of communities that participate in fisheries harvest. The infographic is based on work presented in Busch et al. 2016, Marshall et al. 2017, and Hodgson et al 2018. Credit: Su Kim, Northwest Fisheries Science Center.

Objective 5.7 Improve understanding of the risks to sociocultural and economic well-being of fishing and coastal communities that are dependent on OA-sensitive species, and the associated social-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-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–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 socio-demographics

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

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

Improved knowledge of how communities can reduce vulnerability, including the barriers and capacities for coping with and adapting to OA and cumulative stressors, is critical to developing policies, tools and strategies for mitigating socioeconomic risks (as outlined in 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

6. U.S. Pacific Islands Region Ocean Acidification Research

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Abstract

The Pacific Islands region includes the exclusive economic zones surrounding a collection of small islands and atolls — including the State of Hawai‘i, the Territories of American Samoa and Guam, the Commonwealth of the Northern Marianas Islands, and the U.S. Pacific Remote Island Areas — that are sprawled 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 lower 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 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 validation models to assess OA impacts to human well-being and develop effective management strategies and relevant science communication tools.

Ocean Acidification in the U.S. Pacific Islands Region

The U.S. Pacific Islands region includes the exclusive economic zones surrounding the State of Hawai‘i, the Territories of American Samoa and Guam, the Commonwealth of the Northern Marianas Islands, and the U.S. Pacific Remote Island Areas (**Figure 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.

Figure 1. Map of archipelagic and island areas included under the U.S. Pacific Islands region and U.S. Exclusive Economic Zone boundaries.

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., 2014). 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 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., 2014; Dore et al., 2009; **Figure 2**), and pH has declined 0.0018-0.0026 yr^{-1} in the central equatorial Pacific between 1998 and 2011 (Sutton et al., 2014).

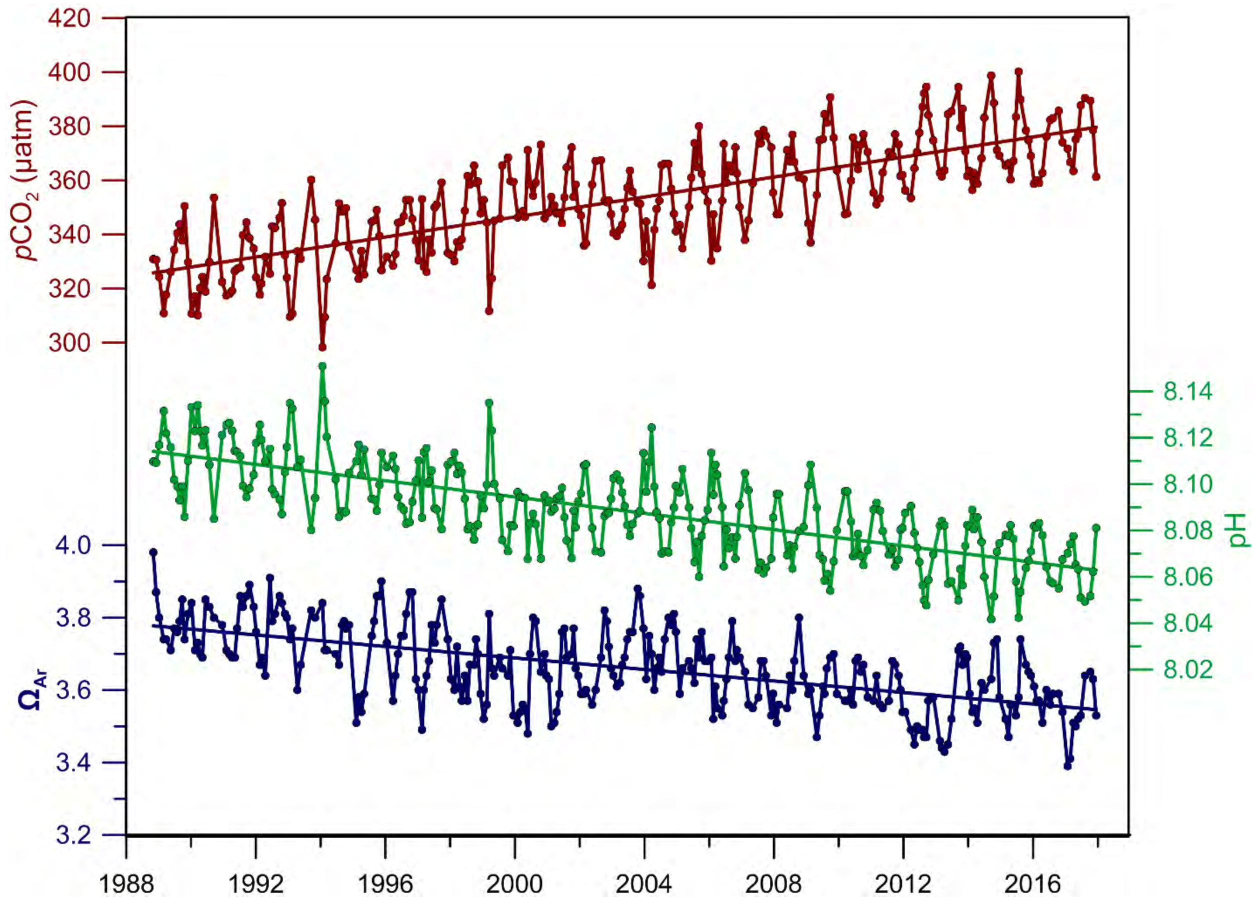

Figure 2. Time series of mean surface carbonate system parameters measured at Station ALOHA, 100 km north of O‘ahu, Hawai‘i (22.75 °N, 158 °W), 1988–2017. Partial pressure of carbon dioxide (pCO_2), pH (total scale), and aragonite saturation state (Ω_{Ar}) were calculated from dissolved inorganic carbon (DIC) and total alkalinity (TA). Linear regression fits are overlaid. Adapted from Dore et al. (2009).

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 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 3**) documented spatial patterns and drivers of reef calcium carbonate accretion around 31 islands (**Figure 4**) initiated assessments of reef bioerosion and dissolution at 13 islands 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.

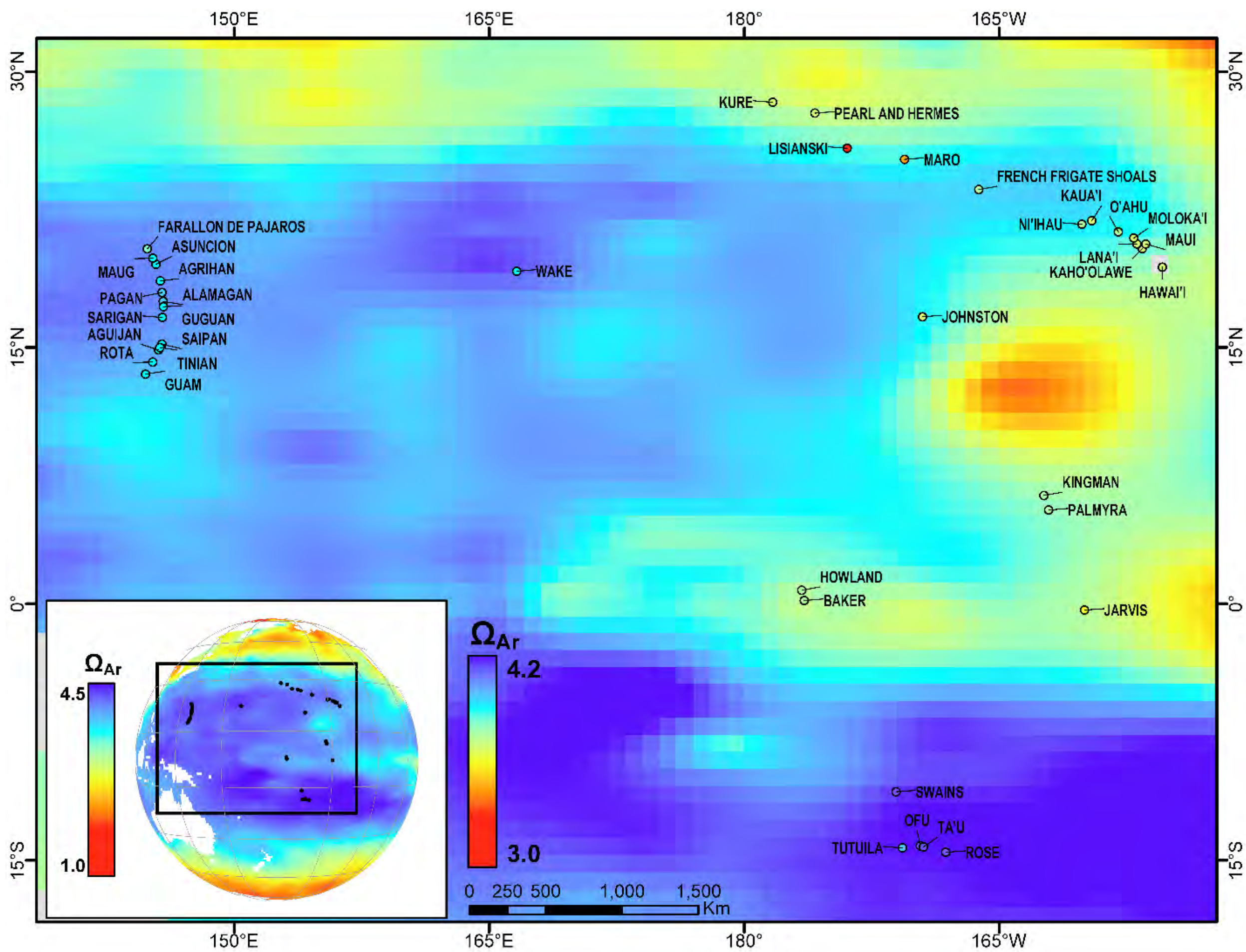

Figure 3. Climatological aragonite saturation state (Ω_{Ar}) for the Pacific Islands region from the GLobal Ocean Data Analysis Project (GLODAP) v2 (Lauvset et al., 2016). Islands that NOAA

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 Ω_{Ar} (calculated from DIC and TA).

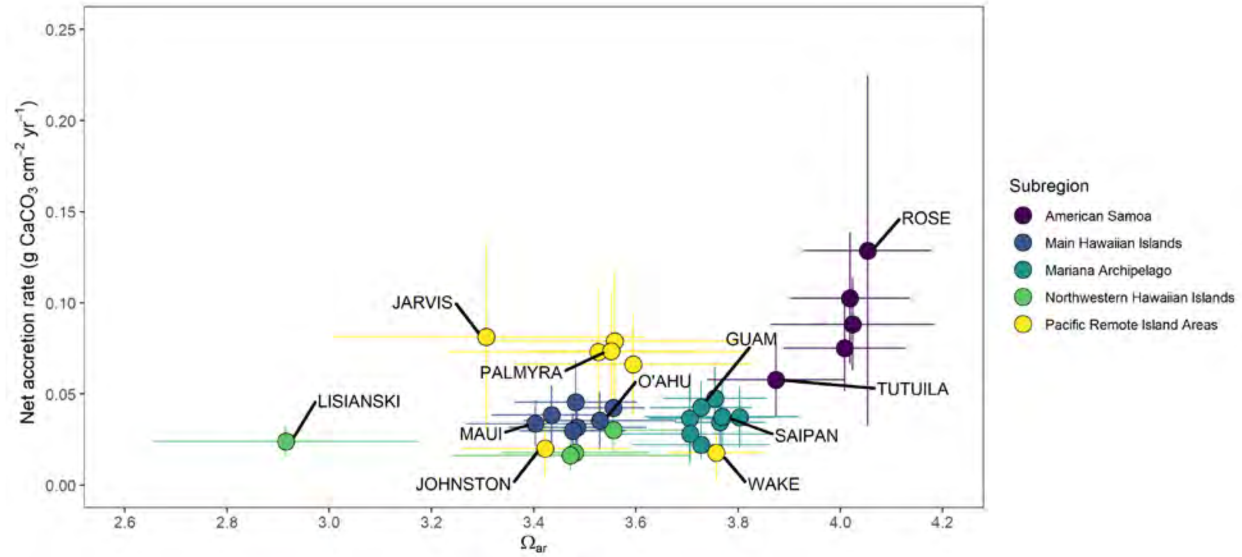

Figure 4. Mean (± one standard deviation) in situ Ω_{Ar} plotted against mean (± one standard deviation) net calcium carbonate accretion rates (measured from Calcification Accretion Units, CAUs) for 31 Pacific Islands from 2010–2017. Islands are colored by subregion, and islands of interest are labelled. See Vargas-Ángel et al., 2015 for additional information on CAUs.

Environmental Monitoring

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 3**). However, there is currently no comparable OA observing network for mesophotic and deep-sea coral reef environments or for the vast pelagic ecosystems that support important commercial fisheries and highly-migratory protected species.

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 Hawai'i have maintained Moored Autonomous $p\mathrm{CO_2}$ (MA$p\mathrm{CO_2}$) buoys at several open ocean stations (WHOI Hawai'i Ocean Time-series, equatorial Tropical Moored Buoy Array) starting in 2004 and at four nearshore sites around O'ahu, Hawai'i (Ala Wai, Kilo Nalu, Kane'ohe 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 data sets 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.

***Action 6.1.1*:** Continue carbonate chemistry water sampling in shallow coral reef environments 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 daytime 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 Pacific pelagic waters and insular mesophotic, subphotic, and deep sea environments 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 $p\mathrm{CO_2}$, total alkalinity (TA), and/or pH analyzers on NOAA ships to measure pelagic surface carbonate chemistry parameters along cruise tracks

***Action 6.2.2*:** Deploy autonomous data collectors (e.g. Saildrones, gliders, biogeochemical-ARGO floats) equipped to measure $p\mathrm{CO_2}$, pH, 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 measure baseline carbonate chemistry levels and monitor OA in mesophotic, subphotic, and deep-sea ecosystems

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

Regional OA maps that leverage available physical and biogeochemical data sets 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.

Action 6.3.1: Construct time-varying insular and pelagic maps of Pacific carbonate chemistry parameters ($p\mathrm{CO_2}$, pH, Ω_{ar}) 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

Corals, crustose coralline algae, 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 baseline data on calcium carbonate accretion and dissolution rates (Enochs et al., 2016; Vargas-Ángel et al., 2015; **Figure 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, spawning grounds, 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 down-scaled OA projections and sensitivities of local taxa to OA (Marshall et al., 2017).

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, pelagic, mesophotic, and deep-sea ecosystems.

***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, 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.

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 (with 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

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 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, 2018; 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 ocean acidification

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 ocean acidification

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 Ocean 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 US Gulf Coast. 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 industry, 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.

Ocean Acidification in the Atlantic and Gulf of Mexico Region

The Southeast Atlantic region is comprised of the coastal areas of North and South Carolina, Georgia, and the East coast of Florida. It is characterized by a shelf width on the order of tens of kilometers and is bound by the Gulf Stream, which flows northeastward along the shelf edge before detaching at Cape Hatteras, NC. The Gulf of Mexico (GoM) includes coastal areas of Florida, Alabama, Mississippi, Louisiana and Texas 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. The Northern and Western GoM shelves are much narrower.

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 ocean acidification (OA) conditions (Wang et al. (2013); (Wanninkhof et al., 2015). Seasonal phytoplankton blooms do not occur regularly, and biologically driven CO_2 uptake is less pronounced than in Atlantic coastal areas farther north (see chapters 9 and 10). 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 OA studies in the GoM have focused in the Northern and East coasts (e.g. Cai et al. (2011); W.-J. Huang et al. (2013); Steven E. Lohrenz et al. (2010); W. J. Huang et al. (2015); Feely et al. (2018); Hu et al. (2018); Robbins et al. (2018)). There is less data 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); S. E. Lohrenz et al. (2018); Chen et al. (2019)).

Environmental Monitoring

Most OA observations in the Southeast and GoM coastal regions have focused on the chemical characterization of the area, particularly through NOAA and USGS efforts. NOAA-supported OA monitoring in the region currently includes: a) synoptic research cruises b) underway pCO_2 systems installed on ships of opportunity, and c) coastal buoys (**Figure 1**). NOAA-led OA synoptic cruises have been carried out in the summertime every four years since 2007 in the East coast (East Coast Ocean Acidification (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 United States Geological Survey (USGS) has participated in several cruises to study the effects of ocean acidification on marine organisms and habitats in the West Florida Shelf and northern Gulf of Mexico regions (Robbins et al., 2018). NOAA funds two underway pCO_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 pCO2 systems through its Ships of Opportunity Program (SOOP). These systems are installed on a variety of ships including scientific and commercial vessels which have also collected data in the Southeast and Gulf of Mexico regions. As a result, over 90% of available surface pCO2 data in the Gulf of Mexico have 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 (pCO2 record started in 2006, pH sensor added in 2011), in the Florida Keys at Cheeca Rocks (pCO2 and pH record started in 2011) and in coastal Louisiana (pCO2 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 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.

Figure 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 ECOA and GOMECC cruises (blue and yellow pins, respectively).

Observing capabilities over the last decade have greatly improved the spatial coverage of carbonate chemistry measurements made in the region and contributed towards 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 2**). Moreover, there are presently no OA buoys in the Western GoM, representing a major regional sampling gap.

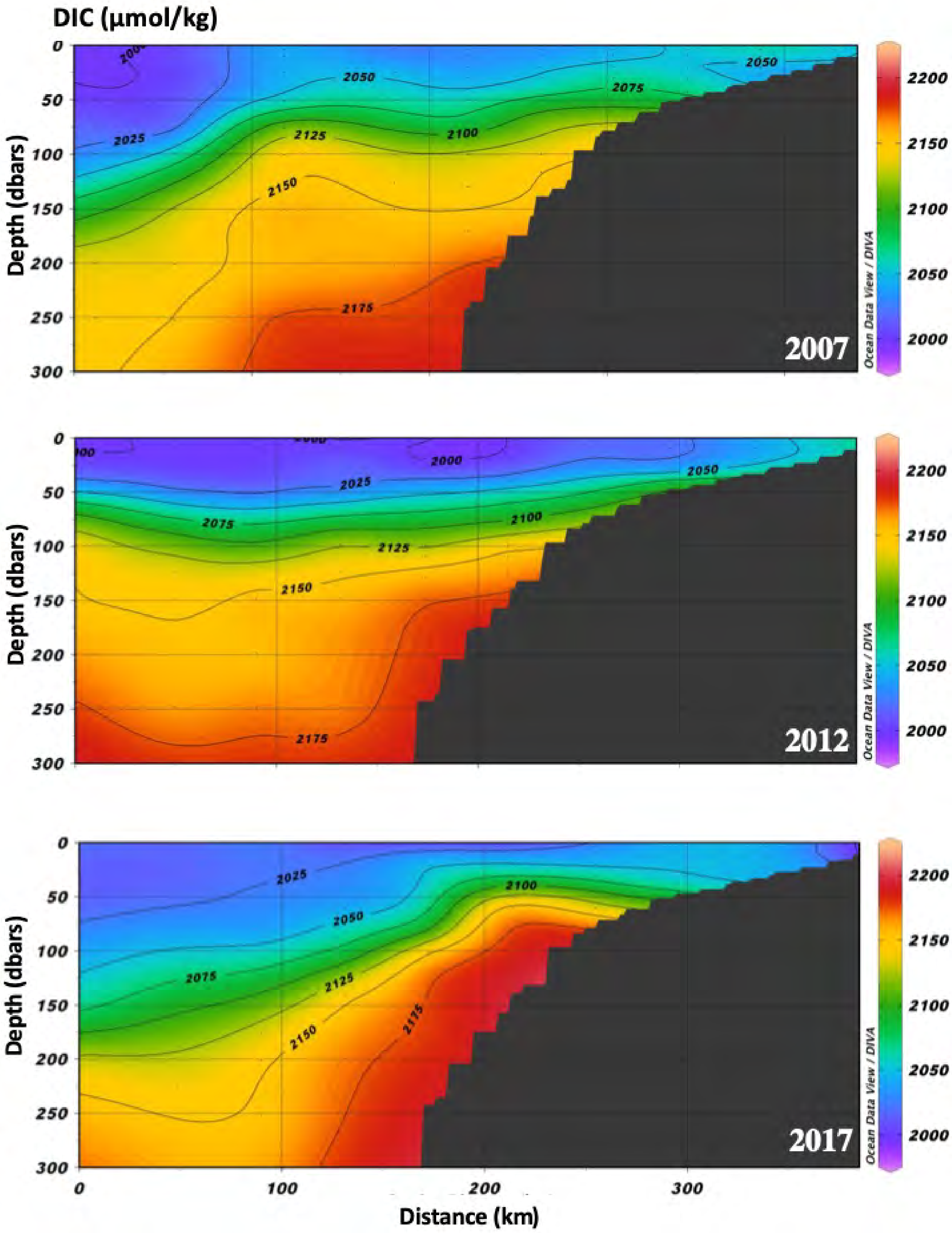

Figure 2: Concentration of dissolved inorganic carbon (DIC) off the West Florida shelf measured during the GOMECC cruises. Increased concentrations are observed in the subsurface over time. Surface measurements cannot capture changes in subsurface waters.

Near-shore 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 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). 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 ocean acidification 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.

The in-situ observing data in the region are used in existing modeling efforts including the Ocean Acidification Product Suite developed for the Greater Caribbean region and now extended to include the East Coast. The Ocean Acidification 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), which showed the GoM to be an annual sink for CO_2 with a flux of 1.11 ± 0.84 10^{12} mol C yr^{-1}, and by Laurent et al. (2017), which 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 near-shore region where most commercial and recreational fishing and tourist industry activities take place. These regions are also home to mangroves, marshes, and estuaries, which are essential habitats within the region's marine ecosystems, play an important role in local carbon balances, and provide a wealth of ecosystems services.

Action 7.1.1: Develop and establish protocols for seasonal or bi-monthly sample collection of pertinent OA parameters at select National Parks, National Marine Sanctuary sites, and essential fish habitats for species predicted to be significantly impacted by OA. These protocols should be complementary to ongoing synoptic cruises to extend the near shore end member of the transects and enhance our understanding of seasonal OA cycles

Action 7.1.2: Explore options to add an OA buoy or alternative monitoring platform in the Western GoM. This additional platform would complete a geographical representation of coastal sites in the Gulf that currently is comprised of buoys in the Florida Keys, West Florida Shelf (a non-NOAA asset), and the Mississippi-Atchafalaya area

Action 7.1.3: Establish OA and water quality monitoring stations at inlets and estuaries in the Southeast Atlantic region and in the GoM to closely monitor eutrophication effects as a co-stressor of coastal OA 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

Coastal OA can be studied by considering a conservative mixing line with a two end-member system: open-ocean and freshwater. Currently, Open Ocean monitoring is only done as part of the OA synoptic cruises, once every four years. Autonomous sensors provide a platform for increasing data availability in deep and shelf waters.

Action 7.2.1: Evaluate the most adequate autonomous sensor(s) to increase deep water profiles in the region, particularly in the GoM, a semi-enclosed basin with water depths upwards of 3000 m and shelf profiles with depths less than 100m and in the vicinity of cold-water coral communities in the northern GoM

Action 7.2.2: Following the rationale in chapter 2, objective 2.3 and action item 2.3.2, establish plan to deploy BGC-Argo floats in the GoM region leveraging 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 (such as the ones from the state/federal Southeast Area Monitoring and Assessment Program (SEAMAP), ecosystem monitoring and restoration, oceanographic, etc.) to increase sample collection in between synoptic surveys

Action 7.3.2: Evaluate methods to measure how upwelling of deep Gulf of Mexico waters onto shelf waters affect OA in shelf ecosystems that are also affected by riverine OA 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, 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. The findings can be used to inform best management practices. Both continued use of existing and development of new models for the region are needed.

Action 7.4.1: Develop, apply, and improve established models for the Southeast Atlantic coast and Gulf of Mexico and validate these models using existing observations to run future scenarios for the GoM

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 in conjunction 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 (see 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 and 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 or links of carbon in the region (Sherr and Sherr (2002); Steinberg and 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 SEAMAP and would provide more power to efforts to depict changes in species ranges and patterns of distribution during the larval (and beyond) life stages.

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. Research to identify indicator species that are sensitive to changes in pH and therefore can be used to track minor changes in the marine carbonate system needs to commence. The Southeast Fisheries Science Center has conducted a climate vulnerability assessment for marine fishery species in the GoM and initiated one in the Southeast Atlantic (Lovett, 2016), which can be supplemented by proposed objectives 7.3 and 7.6 (see below).

Harmful algal bloom events are 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 ocean acidification have shown conflicting results, with some concluding that at higher pCO_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 increased OA conditions and HAB occurrence are happening in other regions, no similar effort is currently taking place in the GoM.

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

Plankton communities are the base of marine food webs and shifts 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 rather than seasonal or other episodic (e.g., tropical storms, flood or drought years) drivers

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

Action 7.5.3: Synthesize existing information from previous cruises and ongoing research and monitoring in the region and coordinate collection of biological data (plankton tows, 'omics-approaches and rate measurements) for future GOMECC, ECOA and other cruises in the study site that will allow for identification of 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 investigate ecosystem impacts that may result from changes in the food web.

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 (add DIC/TA/pH water sampling to the suite of samples that is already being collected)

Action 7.6.3: Conduct laboratory studies to examine OA impacts in combination with other costressors (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 will allow us to hypothesize how changes in indicator 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 in the Gulf and East coast and implement OA sampling in other opportunistic or ongoing cruises organized in relation to HABs already occurring in the Florida coast. Monitoring for potentially toxic species are inherent to the activities described in Objective 7.5; however, more substantial investigations into HAB species or toxins would require additional methods and investment

Action 7.7.6: Support isolation and cultivation-based laboratory experimentation of local HAB species to examine species-specific and community responses to altered 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, even though their marine ecosystem exposure was lower than in other US coastal regions. However, no specific socio-economic studies have been released yet (**Figure 3**).

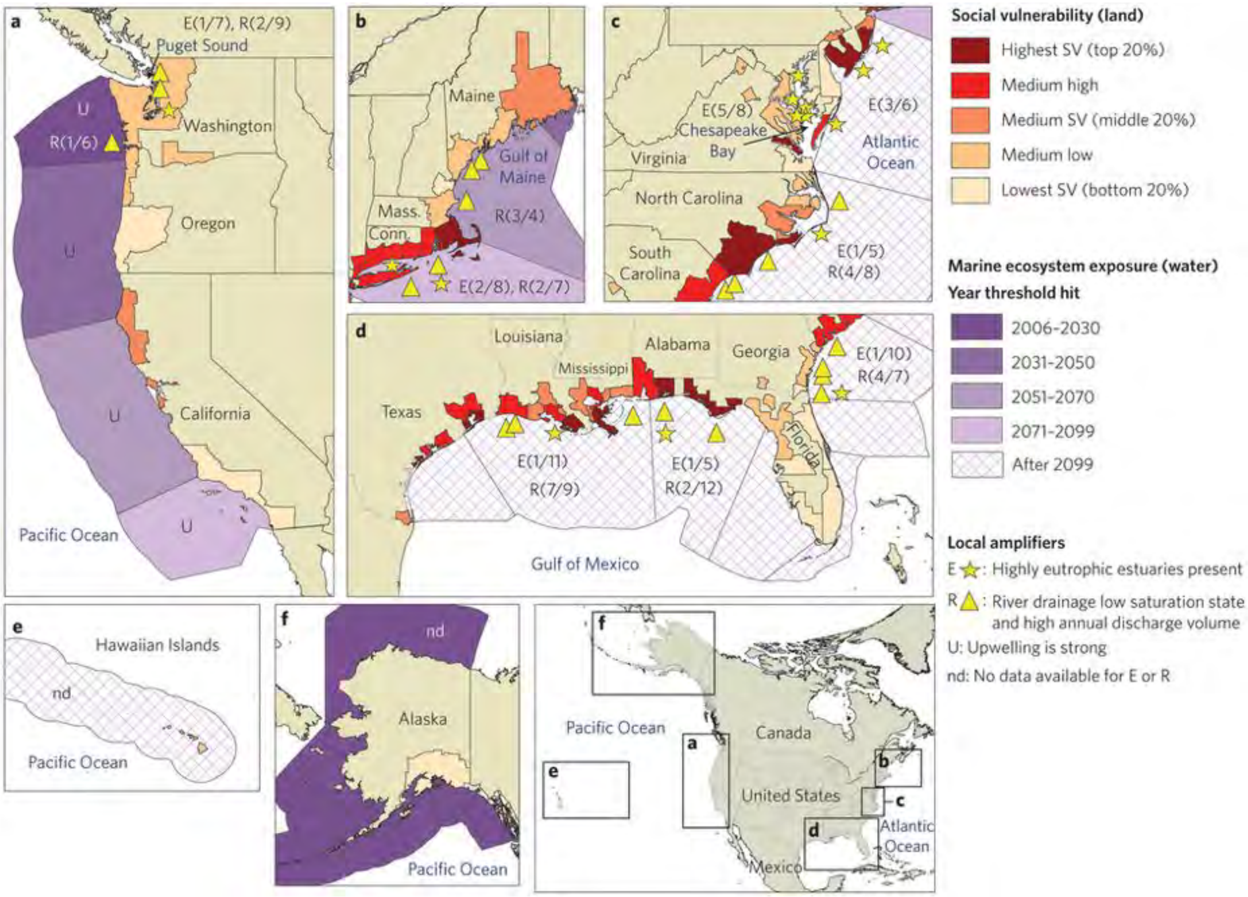

Figure 3: Overall vulnerability of places to ocean acidification. From Ekstrom et al. 2015.

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 socio-economic impacts from impacted key species (*Objective 7.7*) that are due to effects of OA either directly or through food web interactions

Action 7.8.2: Conduct socio-economic 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 the outcome from the above, involve local stakeholders and raise awareness about OA in Gulf and Southeast States that have traditionally disregarded the potential impacts of OA in their economies to increase community resilience and proactively develop OA mitigation plans for affected ecosystems

8. Florida Keys and Caribbean Region Ocean Acidification Research

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Abstract

This region encompasses a large geographic area comprised of the Florida Keys and coastal waters of south Florida, as well as Puerto Rico, the US 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 manifest on time-scales ranging from decades to hours, making holistic characterization a challenging task. There is, however, a great urgency as the region is home to especially sensitive coral reefs ecosystems and commercially important fisheries, which are all inexorably linked to coastal communities and economies. NOAA's Florida Keys and Caribbean OA research goals are to:

- Enhance the temporal and spatial resolution of 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 which have been previously identified as susceptible to or threatened by OA;
- Experimentally investigate the sensitivity and potential resilience of ecologically and economical important species, as well as the underlying molecular mechanisms that drive their differential responses to OA; and
- Develop interdisciplinary tools which integrate socioeconomic data with ecological outcomes.

Ocean 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 ocean acidification (OA), further threatening systems that are already degraded due to warming, disease, overfishing, and eutrophication (e.g., Gardner et al. 2003). The heightened sensitivity of these ecosystems 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 subsequently has experienced among the most rapid rates of decline since pre-industrial times (Gledhill et al. 2008). The carbonate chemistry of the Florida Keys and Caribbean is spatially variable, 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 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. 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 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 Monitoring

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 NOAAwith support from partnering programs (Ocean Acidification Program, OAP; Climate Program Office, CPO; and Ocean Observing and Monitoring Division, OOMD) 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 and East Coast Ocean Acidification (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).

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

NCRMP utilizes a tiered approach of different 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 from stratified, random reef locations by the NCRMP biological teams from 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-Angel et al. 2015), Bioerosion Monitoring Units (BMUs, Enochs et al. 2016), 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, mangroves, and soft-bottom communities)
Action 8.1.4: Expand Ship of Opportunity (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, as well as capture episodic events

Research Objective 8.3: Better understand ecosystems 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, as well as 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 the individual responses of species with clearly documented sensitivities, especially those which have important 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 persistence in future OA conditions.

Action 8.4.1: Develop a habitat persistence (e.g. carbonate budget) model which 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

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. 2015b). Caribbean bioeroding sponges such as *P. lampa* have accelerated rates of biological dissolution under moderate OA scenarios (Enochs et al. 2015c). 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 implication 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 is 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 (Schonberg et al. 2017). These organisms act in opposition to calfcifiers 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. 2015c, 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. 2015c).

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 and 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* (Ros and 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 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., 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 1980's 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. 2016). 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 on 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, 2016). 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 the relationship is poorly understood in the Caribbean.

Action 8.5.1: Conduct experiments to assess the responses of Caribbean bioeroding organisms to OA, and to OA with 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 ecological 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 (e.g., Manzello et al. 2012) 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

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 additional NOAA-supported work within Florida and the Caribbean is limited.

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 in 2010 U.S. dollars (Storlazzi et al. 2019). In Florida alone, over $319 million (2010 USD) of economic activity is protected by coral reefs from flooding, 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 need to be done 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 jurisdictions that rely heavily on Blue Economy drivers such as coastal tourism and shipping.

Combining natural and social science data by mapping indicators is a possible 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 this data may be gleaned from NCRMP and other related social science efforts (NCRMP Florida, NCRMP Puerto Rico). 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 Florida Keys and the Caribbean, and for development of a set of socioeconomic indicators related to climate change. These could then be included into a socioeconomic assessment of any site for which 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.

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 Ocean Acidification Research

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Abstract

The Mid-Atlantic Bight Region geographically includes the eastern United States continental shelf area extending from Cape Hatteras, NC to Cape Cod, MA. Acidification in the region is driven by ocean circulation patterns, particularly influenced by the Labrador Sea current 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 OA research goals are to:

- Expand regional observing system to characterize the full water column and seasonal to decadal OA variability in concert with other environmental parameters;
- Determine how OA and 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 to
- Promote integration OA understanding into regional planning and management.

Ocean 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; Fig. 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 Ocean Acidification Research Plan.

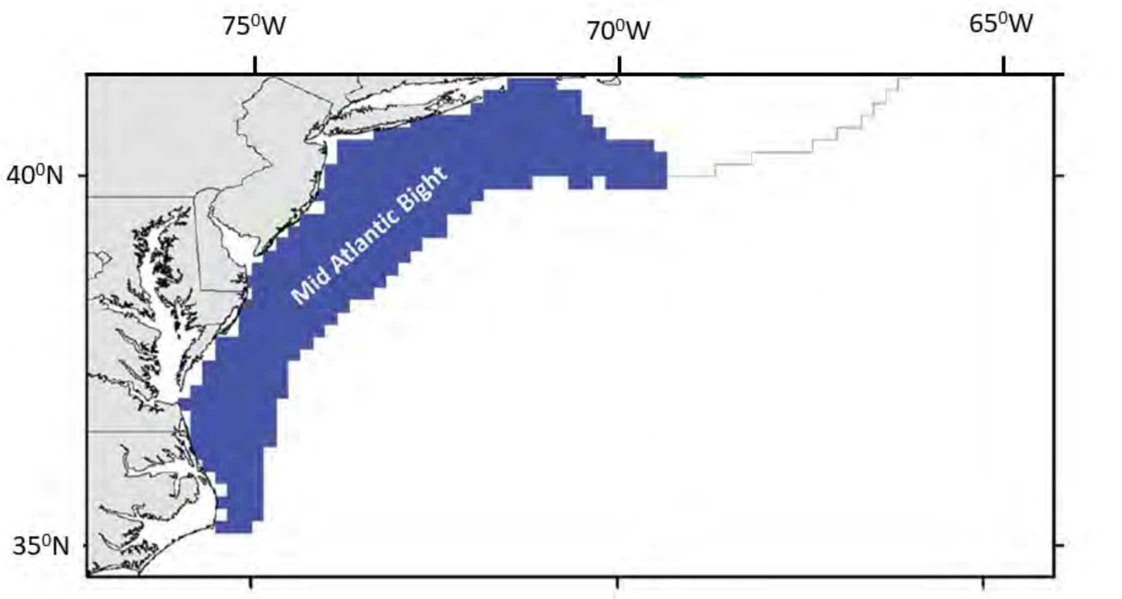

Figure 1. The Mid-Atlantic Bight region from Southern Massachusetts to Cape Hatteras, NC.

The MAB is characterized by a large continental shelf, multiple shelf break canyons, five geographic estuarine ecosystems (Chesapeake Bay, 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 locals. During the fall, storms (i.e., hurricanes, Nor'easters) bring strong winds which lead to a well-mixed water column (Lentz, 2003; Rasmussen, Gawarkiewicz, Owens, & Lozier, 2005). However, during the late spring/early summer strong surface heating and weakening winds lead to the development of a thermocline about 20 m deep, spread across the entire shelf, creating a continuous mid-shelf "cold pool" Fig. 2 (Goldsmith et al., 2019; Haixing 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., 2019; Weinberg, 2005). The MAB is also characterized by regions of upwelling along the canyons, driven by southwest winds associated with the Bermuda High and Ekman forcing (Benthuysen, Thomas, & Lentz, 2015; Brooke et al., 2017; Glenn et al., 2004), which results in areas of enhanced primary productivity, intense fishing activity, and low dissolved oxygen concentrations..

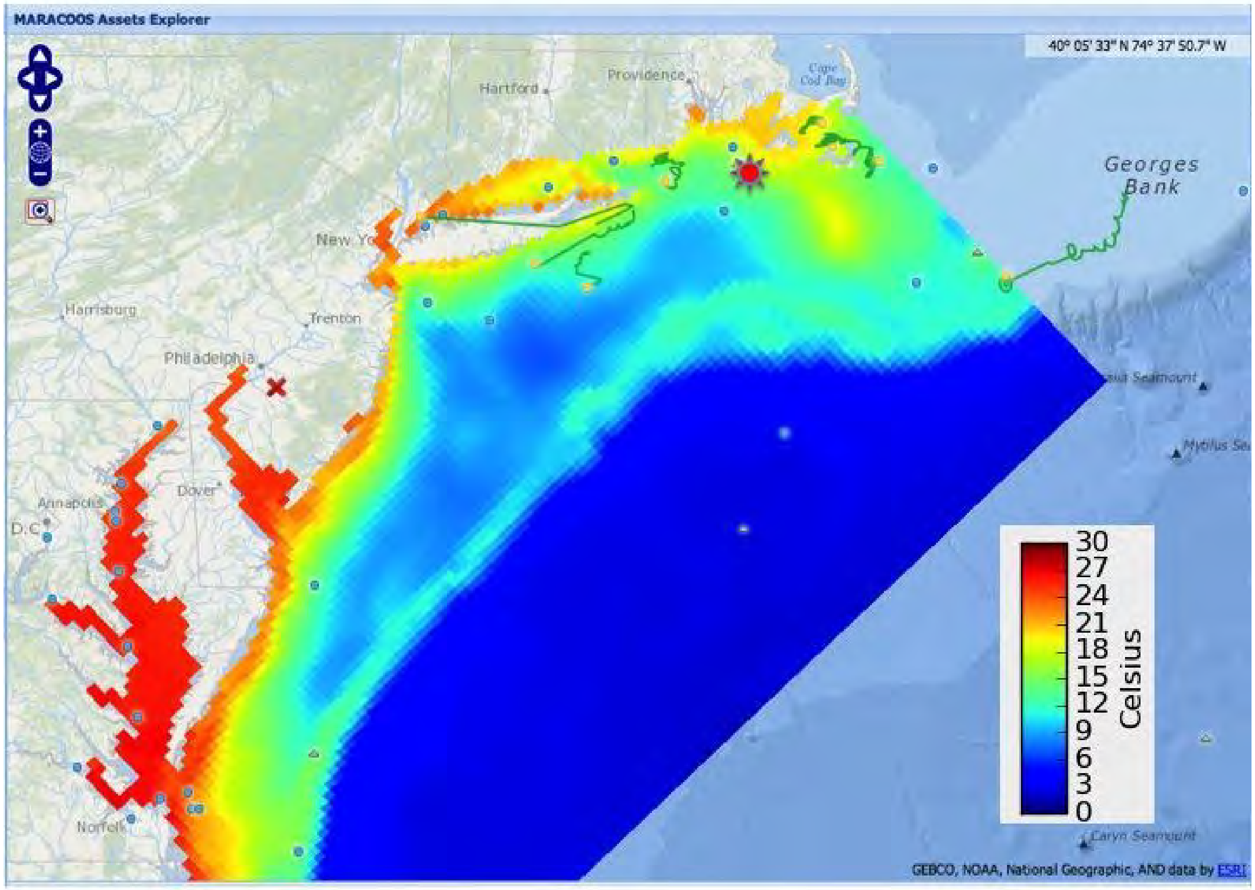

Figure 2. Bottom temperatures for the part of the Mid-Atlantic region, showing the Cold Pool. (courtesy MARACOOS/Rutgers University)

In the MAB region, key physical and biogeochemical drivers that influence OA include: seasonal changes in net-community production, temperature, salinity, physical mixing, and nutrient loading. For example, Gulf Stream waters along the southern portion of the MAB have elevated aragonite saturation (Ω_{AR}). This stands in contrast to the northern regions of the MAB which is influenced by the less-buffered waters and colder southward coastal currents fed by Labrador Sea slope water (Wanninkhof et al., 2015) and the Gulf of Maine (Z. A. Wang et al., 2013) resulting in comparatively lower Ω_{AR}. 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 an area uniquely vulnerable economically to both ocean and coastal acidification.

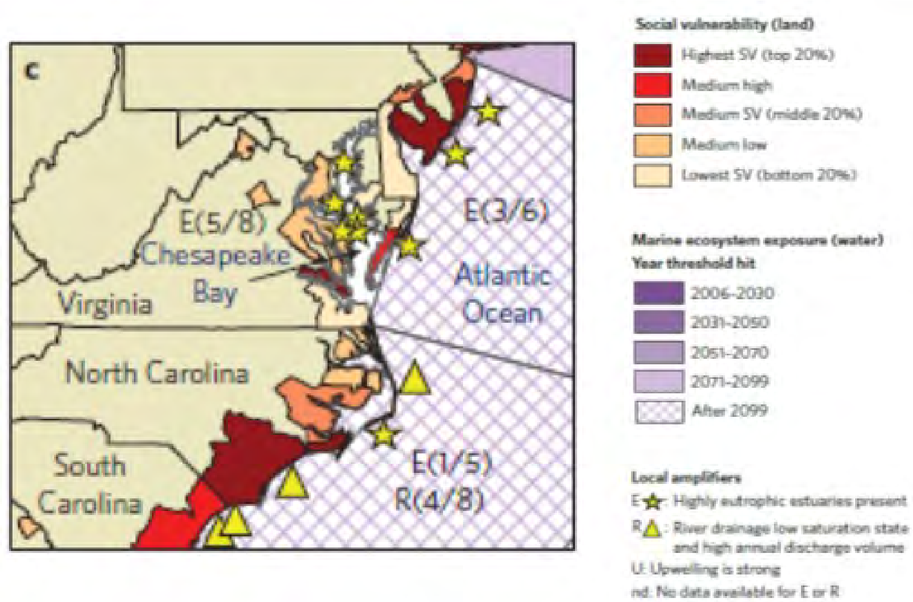

Figure 3. Overall vulnerability of regions within the Mid-Atlantic Bight Region that are vulnerable to OA. The figure is adapted from the figure in Ekstrom et al. 2015. Request permission for Reprint from Journal**

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, Hare, Richardson, & Collie, 2018; Munroe et al., 2016; Narváez et al., 2015; Powell, Ewing, & Kuykendall, 2019; Schweitzer & Stevens, 2019; Waldbusser, Powell, & Mann, 2013). Fisheries in the MAB region totaled $800 million dollars in 2016 with sea scallops, blue crab, and the eastern oyster accounting for 56% of the total revenues (NEFSC, 2018; NOAA FISHERIES, 2019). As in the NE region, marine aquaculture is expanding in every state with the potential of off-shore aquaculture throughout the coastal zone, highlighting the importance of characterizing the drivers 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; Kennish, Sakowicz, & Fertig, 2016; G. K. 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; Hillary Lane Glandon, Kilbourne, Schijf, & Miller, 2018; Hillary L Glandon, Miller, & Woodson, 2016). Consequently, many coastal communities in the MAB have a medium-high to high vulnerability risk to OA, with anticipated effects by 2071 (Fig. 3) (Ekstrom et al., 2015). Understanding the physical and biogeochemical drivers of OA, organism responses to these drivers, and the socio-economic effects on the fishing and aquaculture industries, recreational fisheries, and tourism will help in determining if mitigations strategies may need to be implemented in some communities to reduce OA effects.

Environmental Monitoring

Surveys of surface carbonate chemistry in the MAB conducted by NOAA and other research institutions have shown large natural variability on decadal timescales (Boehme, Sabine, & Reimers, 1998; Z. A. Wang, Lawson, Pilskaln, & Maas, 2017; Z. A. Wang et al., 2013). Regional satellite-derived surface pCO_2 algorithms depict strong seasonal variability with lower pCO_2 values in winter and spring and higher pCO_2 values during the summer and fall primarily driven by seasonal temperature dynamics. Repeated shipboard campaigns have shown relatively low pH, Ω_{AR}, and buffering capacity of waters of the northeastern U.S. shelves which indicates elevated risk to continued acidification compared to southern counterparts Fig. 4 (Z. A. Wang et al., 2013). Limited CO_2 MAB bottom water surveys have shown enhanced seasonal stratification, respiratory DIC production, and lower temperature and salinity conditions brought in from the north as Labrador Sea slope water relative to surface conditions. The complexity of the surface and bottom MAB waters demands simultaneous observations on physical, biological, and chemical parameters within the region.

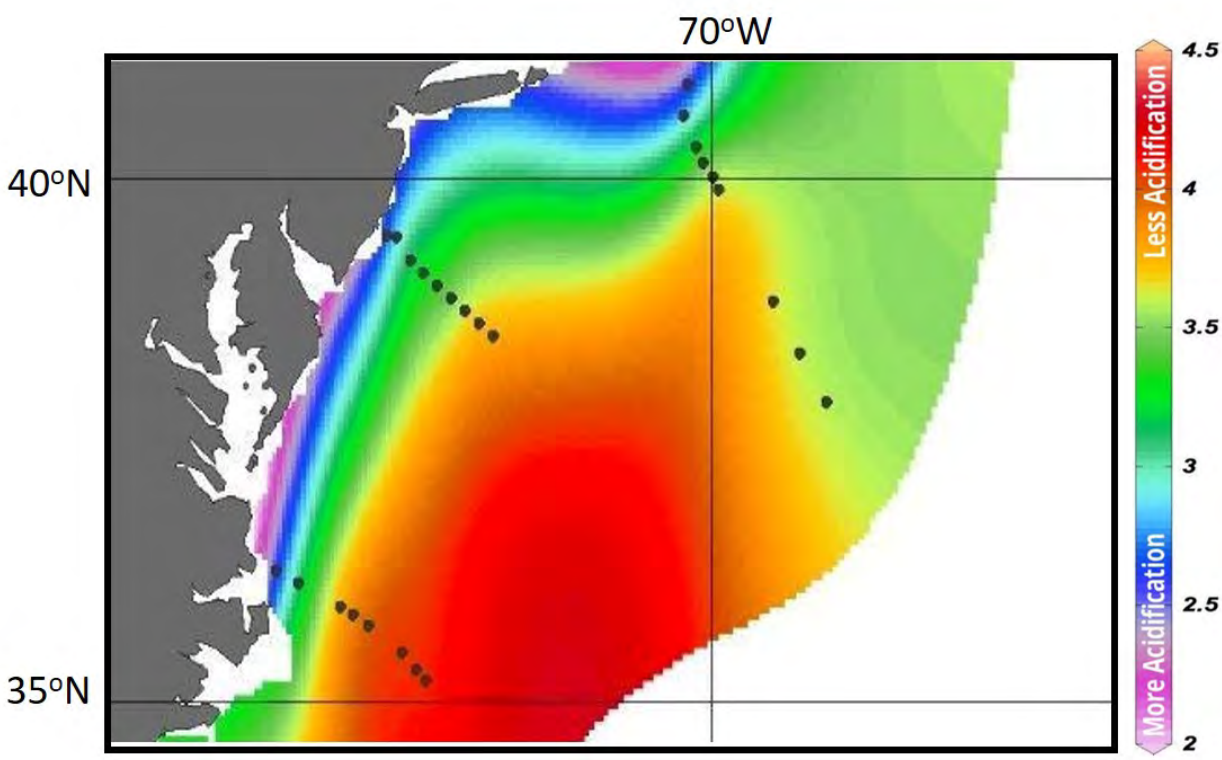

Figure 4. Aragonite saturation state of surface water in the Northeast United States. Dots represent transects where data are collected. Highlighted is in the MAB region the large gradient of Ω_{AR} with more acidic water and lower Ω_{AR} located nearshore and less acidic and higher Ω_{AR} offshore. Concentrations are based on surface water measurements. Source: NOAA Gulf of Mexico and East Coast Carbon (GOMECC) cruises)

Improved biogeochemical models which describe OA conditions and their responses to environmental conditions are necessary. These models should focus on creating accurate short-term and long-term projections that would 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 of OA. Improved models can also be used to generate shorter-term forecast conditions (1-3 years) in estuarine environments as temperature, oxygen levels, and eutrophication change on weekly time scales providing valuable environmental intelligence for use by local stakeholders and managers. Such models must be informed and validated by high quality monitoring data which encompasses direct field measurements of carbonate chemistry and related biogeochemical and physical processes.

Research Objective 9.1- Expand regional ocean observing system to characterize seasonal to decadal OA variability in concert with other environmental parameters

The existing portfolio of OA capable observing assets in the region are sparse and/or are measured 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) have implications for OA that are not well understood.

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

Action 9.1.2: 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

Action 9.1.3: More aggressively adopt the use of autonomous vehicles and newer 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.

With the notable exception of periodic large-scale geochemical surveys (e.g. GOMECC 1, GOMECC 2, ECOA 1, ECOA 2) most biogeochemical observations have been taken at the surface along the MAB. However, since 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: Continue development of biogeochemical models to characterize OA conditions and evaluate our understanding of the mechanisms driving conditions

Action 9.2.2: 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 co-commitment changes in temperature, oxygen levels, and eutrophication

Action 9.2.3: Conduct studies to inform biogeochemical models to evaluate dynamics at the sediment-water interface with increased ocean acidification/eutrophication/hypoxia

Biological Sensitivity

The MAB region is a dynamic area experiencing changes in temperature, precipitation, and eutrophication. From 1977-2016, sea surface temperature increased an average of 0.057°C during the Winter/Spring and 0.047°C during Fall/Winter (V. S. Saba et al., 2016; Wallace, Looney, & Gong, 2018). The MAB region also has coastal areas that are effected by eutrophication (Bricker et al., 2008; Ekstrom et al., 2015; Greene, Blackhart, Nohner, Candelmo, & Nelson, 2015). The increase in temperature and high level of eutrophication has considerable implications on the regional marine ecosystem. A recent vulnerability analysis of 82 species from the Northeast Continental Shelf Region (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*), Atlantic salmon (*Salmo salar*), 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, Reynolds, Sobrino, & Riedel, 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 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, Ghazaleh, Connolly, Westfield, & Castillo, 2016; Speights, Silliman, & McCoy, 2017). For crustaceans, research on juvenile blue crabs have found that OA affects survival, respiration, growth, development, and food consumption, and that higher temperatures amplified this effect (Hillary Lane Glandon et al., 2018; Hillary L Glandon et al., 2016; Glaspie, Seitz, & Lipcius, 2017). 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, Ern, Esbaugh, & Browman, 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.

Action 9.3.1: Develop experiments to address population and life-stage responses with respect to 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 adapt to selective mortality emanating from OA and related stressors
Action 9.3.3: Use experimental physiological and other mechanistic measures to determine the energetic costs of acclimation to OA

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: Experimentalist collaborate with population/ecosystem modelers 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

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) (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 (Fig. 3) (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 valued 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; Chesapeake Bay Foundation; 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 strategies and adapt.

Applications of any OA research findings must fit into existing management structures at the Federal, State, and Tribal level. 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*.). Effective communication of how these resources respond to OA should be included with these other activities.

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 progressing OA.

Action 9.5.1: 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 9.5.2: Estimate the time threshold when changes in the carbonate chemistry will make harvesting or growing shellfish unprofitable in the future 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 (fishermen, shellfishermen, aquaculturists, recreational).

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 (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 fishery members and aquaculturists to alter practices as harvested/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 Ocean Acidification Research

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Abstract

The New England Region geographically includes the Gulf of Maine, Georges Bank, and Scotian Shelf. OA in this region is driven mainly by regional ocean circulation patterns of various water masses as well as precipitation patterns, freshwater influx from riverine sources and eutrophication. This region is experiencing temperature changes three times greater than the global average and increase precipitation. 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 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 incorporate OA into regional management plans and evaluate the cost and benefits of various mitigation and adaptation strategies.

Ocean 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 Gulf of Maine, Georges Bank, and western Scotian Shelf regions within the Northeast U.S. Continental Shelf Large Marine Ecosystem (LME; **Figure 1**). For information on the southern region of the Northeast LME, please refer to Chapter 9 Mid-Atlantic Bight Region OA Research Plan.

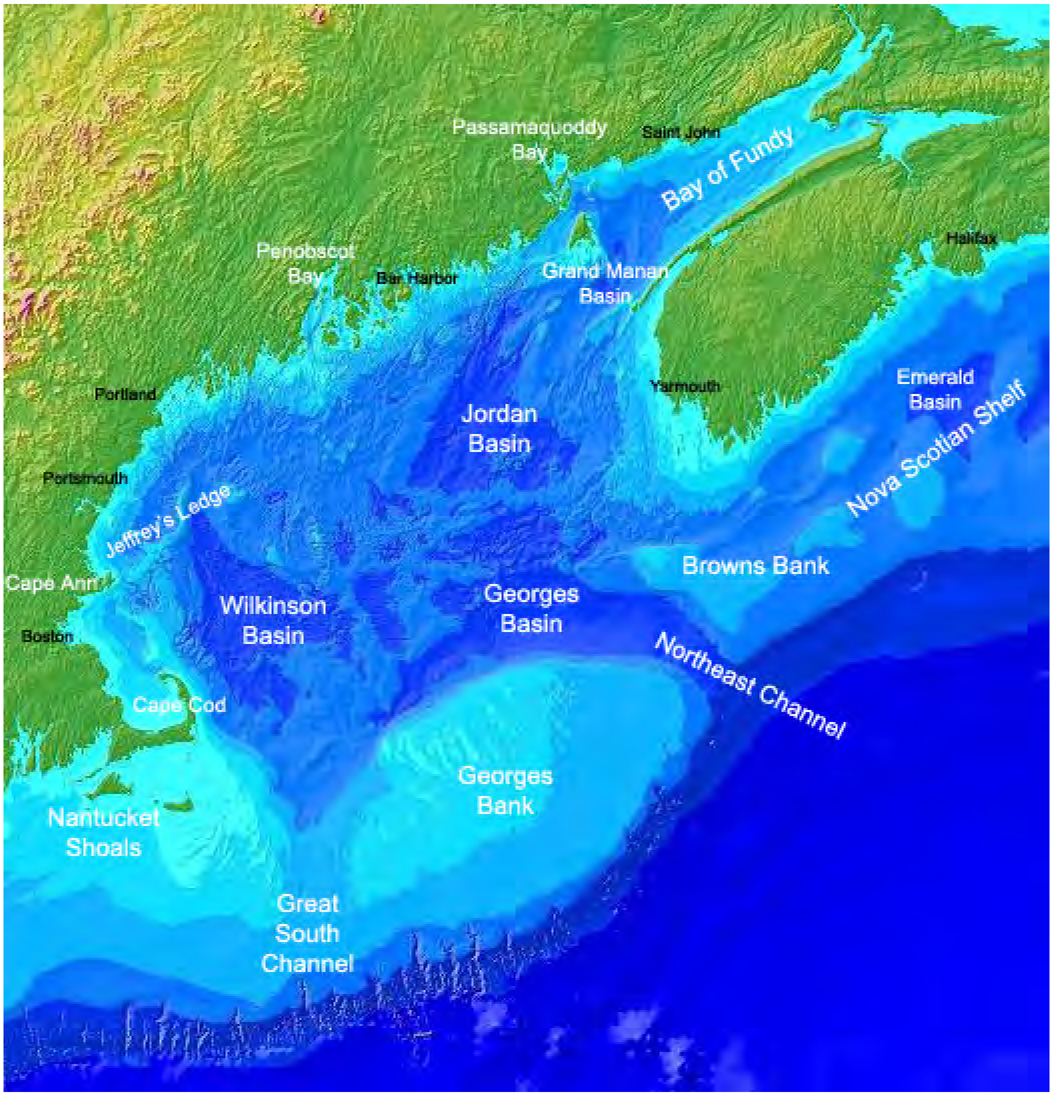

Figure 1. The watershed for the New England Region, which includes the Gulf of Maine, Georges Bank, and Scotian Shelf. Photo Credit: National Oceanographic and Atmospheric Administration and U.S. Geological Survey (USGS) Woods Hole, MA

The highly productive New England Region waters have a long history of extensive commercial fishing (Colburn et al., 2016; Jepson & Colburn, 2013; Townsend, Thomas, Mayer, Thomas, & Quinlan, 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 (see 10.2) (J. Salisbury, Green, Hunt, &

Campbell, 2008; J. E. Salisbury & Jönsson, 2018; Z. A. 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_{AR}), and buffering capacity attributed to inputs of fresh and lower alkaline waters and the accumulation of respiratory products from high primary productivity (Z. A. 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, Link, & Hare, 2017; J. Salisbury et al., 2008; J. E. Salisbury & Jönsson, 2018; Tjiputra et al., 2014). On decadal time scales, the change in pH is dominated by CO_2 from the atmosphere, however, the Ω_{AR} signal is a combination of changes in TA, SST, and salinity (J. E. Salisbury & Jönsson, 2018). With higher precipitation predicted in the future (Guilbert, Betts, Rizzo, Beckage, & Bomblies, 2015; Rawlins, Bradley, & Diaz, 2012; Sinha, Michalak, & Balaji, 2017), increased inputs of fresh water to the coastal zone may increase eutrophication, decrease TA and consequently influence pH and $\Omega_{AR.}$ 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.

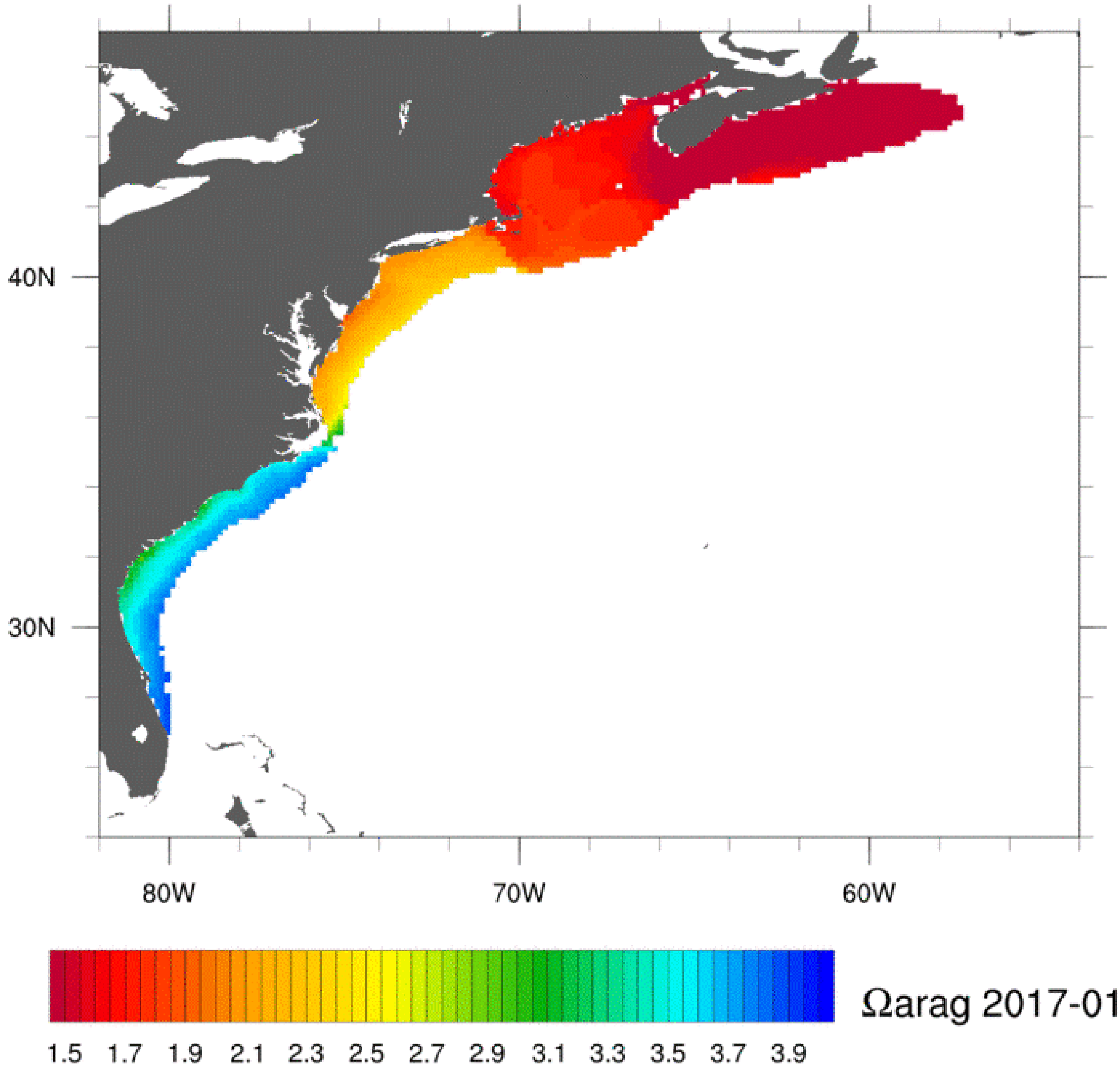

Figure 2. Aragonite saturation levels in 2017 for January for the Northeast United States. The NE region has the lowest Ω_{AR} on the East Coast with levels below 2.0. Image Courtesy of NOAA coral program. https://www.coral.noaa.gov/accrete/east-coast-oaps.html. This is for the month of January with other months being represented on the web page.

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_{AR} (Lapointe, 2013). **Figure 3** shows coastal zones are concentrated with shellfish habitats, which intersects with some of the 2019 fishing grounds for Atlantic sea scallops (**Figure 4**). Marine aquaculture is expanding in every state of the region and the development of off-shore 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, Chai, Wang, & Kan, 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, Waldbusser, Hubazc, Cathcart, & Hall, 2013; J. Salisbury et al., 2008). Consequently, many coastal communities have a medium-high to high vulnerability risk to OA with anticipated effects by 2031 (Fig. 5) (Julia A Ekstrom et al., 2015). Mitigation strategies, such as amending the seawater intake at mariculture facilities to compensate for low Ω_{AR} conditions and nutrient reduction, may need to be implemented in some communities. The 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.

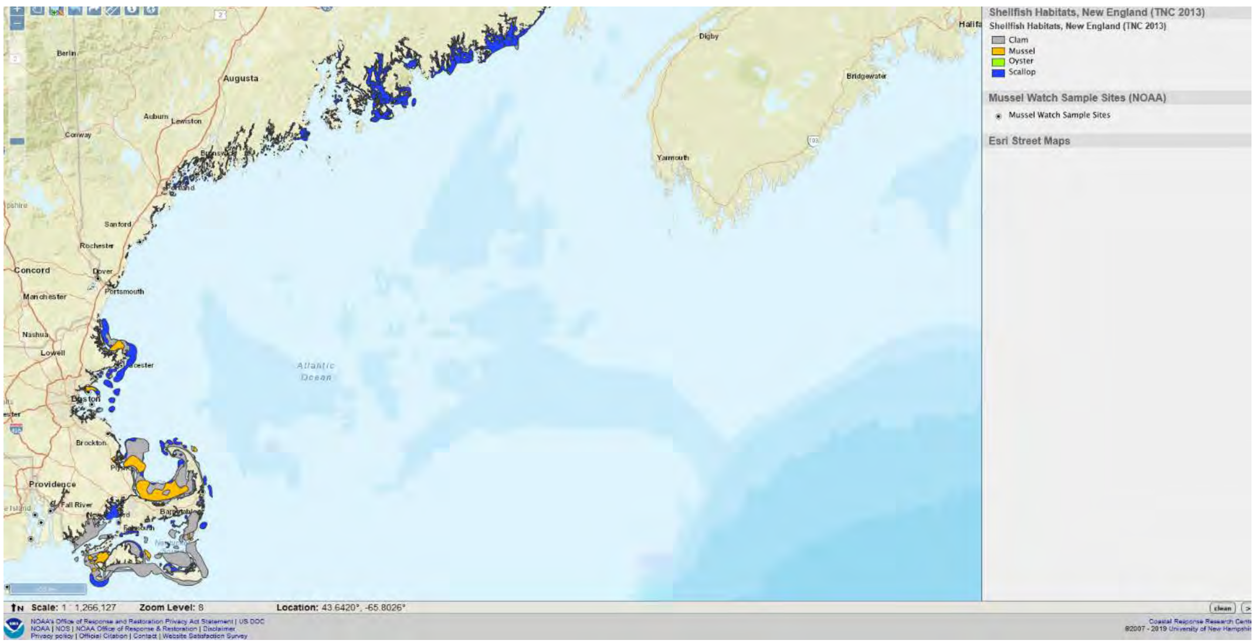

Figure 3. The New England Region with shellfish habitats identified. As illustrated the coastal zone is concentrated with clam, mussel, oyster, and scallop habitats.

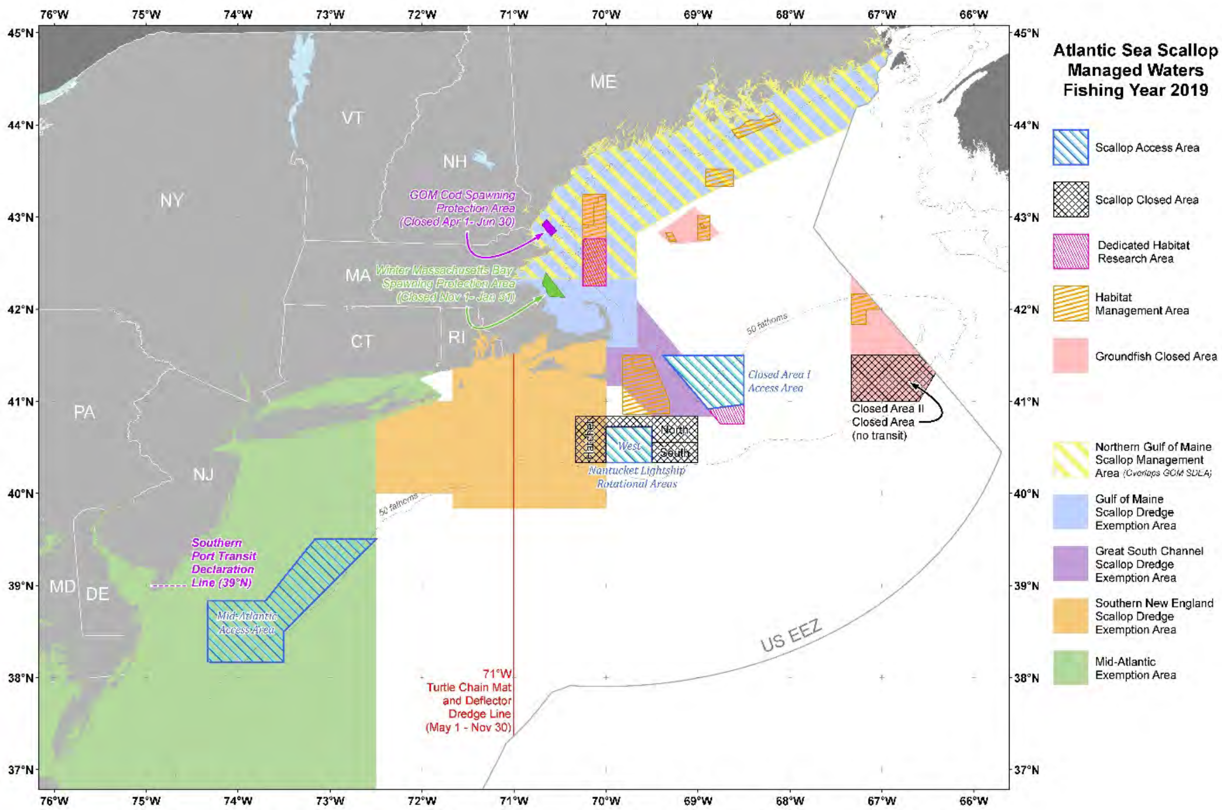

Figure 4. Atlantic Sea Scallop Managed Waters for Fishing Year 2019 (April 1-Mar 30).

Environmental Monitoring

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 spring-time 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.

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 Ocean Acidification (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 inclusive of full life cycle (pelagic and benthic)

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 environment.

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

Action 10.1.2: Conducting 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 benthic monitoring at targeted locations to characterize interactions at the sediment water interface and connections to changes in 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 to the Region and their influence on OA conditions

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 have altered 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, 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. This would include building upon the data synthesis underway and being housed by NERACOOS

Action 10.2.2: Use these time-series for trend analyses to 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 10.1.3: Based on these exercises and analyses, new areas can be identified as important regions 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 time-scales not currently well addressed through 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 (*Objective 10.1*) that reliably account for co-occurring changes including projected temperature changes (NCA4), as well as 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 (*Objective 10.9*)

Biological Sensitivity

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% out 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, Seibel, Feely, & Orr, 2008; Gobler & Talmage, 2014; Green et al., 2013), with a potential minimum Ω_{AR} threshold (> 1.6) needed for survivability and settlement (J. Salisbury et al., 2008; J. E. Salisbury & Jönsson, 2018). Low levels of Ω_{AR} near this threshold can already be found seasonally in the region (Fig. 4). A few field studies found that fewer bivalves settled under OA conditions related to low pH in sediments (Clements & Hunt, 2018; Meseck, Mercaldo-Allen, Kuropat, Clark, & Goldberg, 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, Doney, Cooley, & Hart, 2018). Results on the commercially important crustacean American lobster (*Homarus americanus*) has produced conflicting results to elevated CO_2 (Keppel, Scrosati, & Courtenay, 2012; Ries, Cohen, & McCorkle, 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 organism's responses can be found in Gledhill et al. (2015), but to date most of the research focus on larval stage and an understanding of 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.

Fundamental to our understanding of the consequences of the biological effects of OA is an estimation of the organism's resilience and adaptive potential. The resiliency of the 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 research 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_{AR} 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 OA 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 on shellfish and finfish of aquaculture, wild fisheries, and ecosystem importance

Action 10.4.2: Use these expanded frameworks to evaluate the response 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 New England Region.

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

Action 10.6.2: Joint effort by modelers, field scientists, and experimentalists to develop unified and realistic ecosystem-level models that accurately capture essential biological and biogeochemical details into ecosystem models

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

Human Dimensions

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). 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 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 region was high to medium-high vulnerable to OA especially in the states of Massachusetts (Fig. 5) (Julia A Ekstrom et al., 2015). The analysis further found that in New England Region, high levels of eutrophication may be enhancing OA and if it was possible to reduce eutrophication it might reduce the OA signal. 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. For example, New Bedford, MA is the largest commercial fisheries port in the US in terms of revenue with the American sea scallop fishery generated over $379 million (NOAA Fisheries). Potential strategies that may be utilized by communities to help mitigate the influence of OA may include different 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 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 OA impacts and increase their resilience to changing ocean conditions.

The New England Region has robust existing efforts in ocean planning and regional fisheries management. The understanding and projections achieved in 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 in 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 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 additional 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 10.7.1: 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 10.7.2: 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 fishery members to alter fishery practices as harvested populations change (*Objective 10.6*)

Action 10.9.3: Develop CSVIs with respect to OA to improve the understanding of how communities might respond to OA in a resilient way

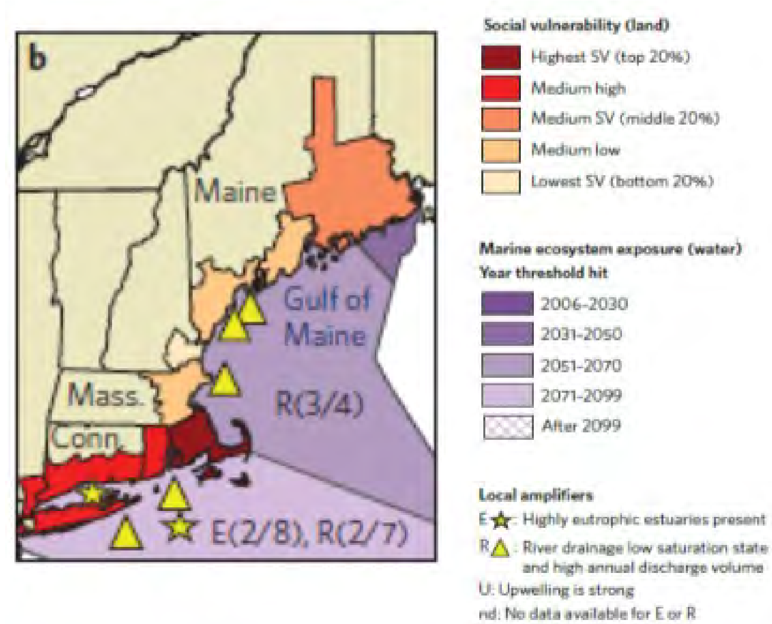

Figure 5. Overall vulnerability of regions within the New England Region that are vulnerable to OA. The figure is from Ekstrom et al. (2015) *Requesting permission for reprint.*

11. Great Lakes Region Ocean Acidification Research Plan

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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 US 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 OA 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 percent of the United States' and 20 percent of the world's surface freshwater (**Figure 1**). The Great Lakes basin is home to approximately 43 million people, 8 percent of the U.S. population, and 32 percent 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 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 pCO_2.

Figure 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).

Great Lakes pH is projected to decline at a rate similar to that of the oceans, in response to increasing atmospheric pCO_2. Phillips et al. (2015) estimated a pH decline of 0.29-0.49 pH units by 2100, assuming current projections of anthropogenic pCO_2 emissions (IPCC IS92a business as usual scenario) and constant alkalinity (**Figure 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 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).

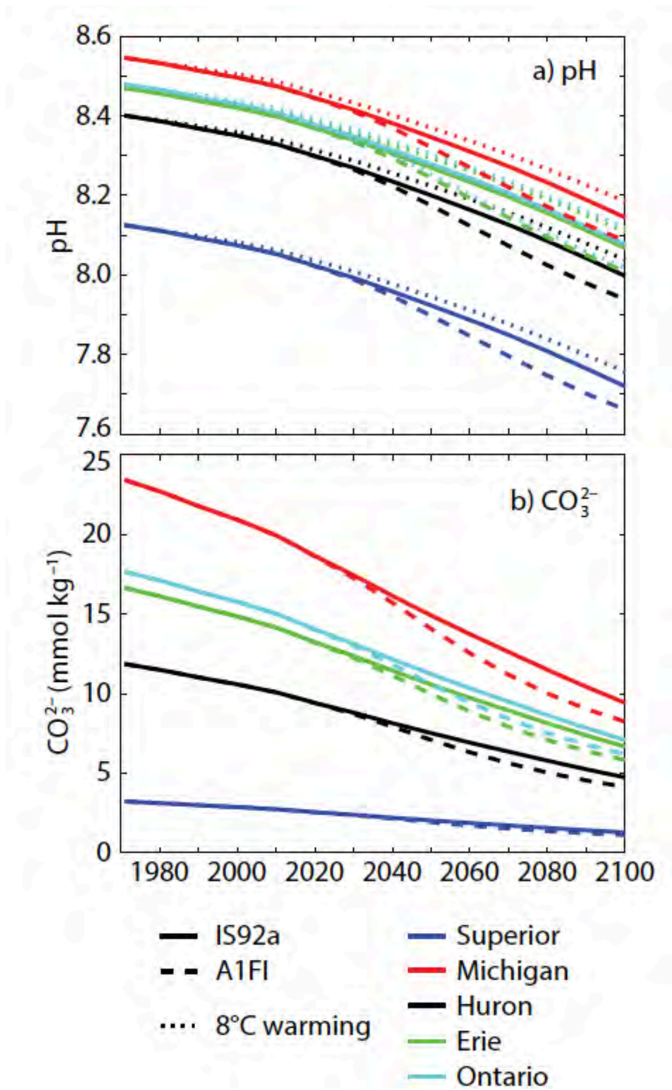

Figure 2. Projected mean annual (a) pH and (b) carbonate ion concentration for the five Laurentian Great Lakes under IPCC atmospheric CO_2 forcing: IPCC IS92a (the business as usual scenario) or A1FI (the fossil fuel intensive scenario). Also shown on (a) is an 8°C warming by 2100 scenario. (Phillips et al., 2015; need to get permission from publisher to reproduce).

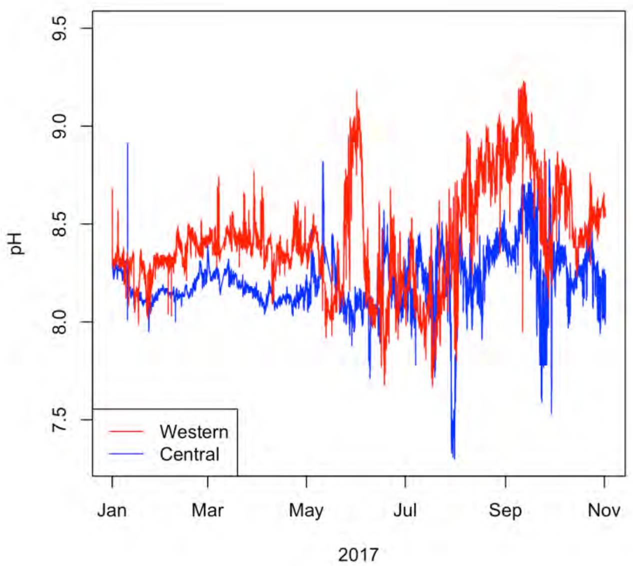

Figure 3. Time series of pH at drinking water intakes in the western and central basins of Lake Erie illustrating short-term variability of pH, which complicates detection of long-term trends. Episodes of high productivity cause pH > 9.0 in the eutrophic western basin, while coastal upwelling of hypoxic water in the central basin cause pH to drop below 7.5 (data source: Great Lakes Observing System, http://habs.glos.us).

Effects of increasing atmospheric $p\mathrm{CO_2}$ 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 ~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).

Environmental Monitoring

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 US 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).

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; website), National Data Buoy Center (NDBC; website), or Great Lakes Evaporation Network (GLEN; website). 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 Ocean Acidification 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

Sensitivity

Effects of weak acidification of freshwater on biota at the organism, community, and ecosystem level is generally not well understood. With increasing pCO_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 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 pCO_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 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 and*

Huisman, 2008). Community shifts in the toxic species present may also be impacted by acidified conditions, as non-toxigenic strains of *M. aeruginosa* are favored at high pCO_2 concentrations (*Van de Waal et al.*, 2011) while toxic strains of *Anabaena circinalis* and *A. eucompacta* dominated at high pCO_2 concentrations (*Shi et al.*, 2017).

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 1990's and 2000's, 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 Ocean Acidification 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 and Claudi,* 2009) and larval settlement may be prevented below pH of 7.1 (*Claudi et al.*, 2012).

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 (Tables 3,4; *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 and 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., 2015 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 sport-fishing 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 Ω_{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

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.

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, 2017; Wolf, Georgic, & Klaiber, 2017; Martin Associates, 2018; Cheng, 2016). Environmental pressures on Great Lakes such as Harmful Algal Blooms 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 adaption 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

[An integrated reference list is in the process of being created, for now please see references per chapter below]

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