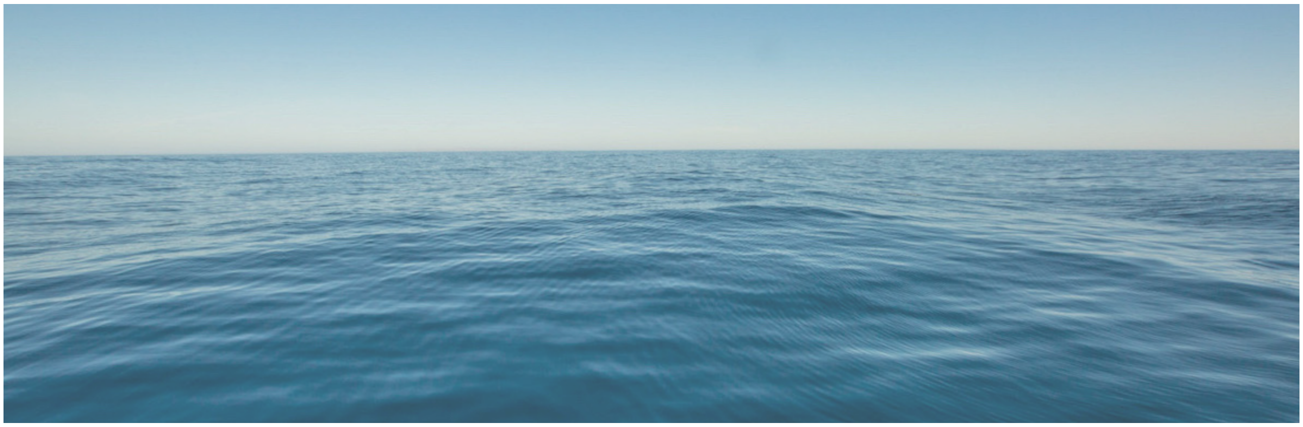

1. National Ocean, Coastal, and Great Lakes Acidification Research

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Abstract

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

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

Ocean, Coastal, and Great Lakes Acidification

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

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

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

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

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

Environmental Change

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

The present *in situ* NOAA ocean observing system is oriented toward monitoring of the physical and chemical system (temperature, salinity, oxygen, nutrients, pCO_2, pH, Total Alkalinity (TA), Dissolved Inorganic Carbon (DIC)), but lacks coverage of the Great Lakes, and has limited inclusion of biological variables that are measured concurrently. Technological advances have greatly expanded non-ship-based monitoring capabilities of observations of fundamental OA variables (e.g., pH and pCO_2) on ocean moorings and autonomous vehicles, including profiling floats. Adoption of sustained biological measurements requires further development; as such, the field of ‘omics research, which uses molecular markers as biological indicators, presents promise for autonomous biological sampling capabilities (NOAA ‘Omics Strategy). Development of such technologies will be key to expanding the existing observing system.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Biological Sensitivity

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Human Dimensions

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

References

[INTRO] = Introduction;

[NAT] = National Ocean & Great Lakes;

[OO] = Open Ocean Region;

[AK] = Alaska Region;

[ARC] = Arctic Region;

[WC] = West Coast Region;

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

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

[FLC] = Florida Keys and Caribbean Region;

[MAB] = Mid-Atlantic Bight Region;

[NE] = New England Region;

[GL] = Great Lakes Region

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