OCEAN ACIDIFICATION MONITORING PRIORITIZATION PLAN

A Report by the

INTERAGENCY WORKING GROUP ON OCEAN ACIDIFICATION

of the

SUBCOMMITTEE ON OCEAN SCIENCE AND TECHNOLOGY

COMMITTEE ON ENVIRONMENT

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

AUGUST 2024

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The Interagency Working Group on Ocean Acidification (IWG-OA) advises and assists the Subcommittee on Ocean Science and Technology on matters related to ocean acidification, including coordination of federal activities on ocean acidification and other interagency activities as outlined in the Federal Ocean Acidification Research And Monitoring Act of 2009 (33 U.S.C. 3701 et seq.).

About this Document

This document was developed by the IWG-OA and published by OSTP. It meets the requirement of the Coordinated Ocean Observations and Research Act of 2020 (P.L. 116-271) to produce a Monitoring Prioritization Report, following the first Ocean Chemistry Coastal Community Vulnerability Assessment, that "develops a plan to deploy new sensors or other applicable observing technologies such as unmanned maritime systems—(A) based on such initial report; (B) prioritized by—(i) the threat to coastal economies and ecosystems; (ii) gaps in data; and (iii) research needs; and (C) that leverage existing platforms, where possible." 33 U.S.C. 3703(e)(5). Any future federal activities will be considered in the broader context of Administration priorities and available resources.

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Executive Summary

The Biden-Harris Administration has made tackling the climate crisis a priority and has delivered on the most ambitious climate agenda in history. Climate change is threatening the health and well-being of people and the environment. As humans continue to burn fossil fuels, carbon dioxide emissions are leading to ocean acidification (OA). OA poses a threat to many marine species through negative impacts to growth, survival, and physiology. This leads to risk for coastal communities and industries that receive economic, social, and cultural value from these species. By monitoring current conditions and forecasting future changes, communities can better understand how marine resources may be impacted by changing ocean chemistry.

This Monitoring Prioritization Plan (plan) details how to guide U.S. government efforts towards monitoring that could be deployed to meet the gaps described in the Ocean Chemistry Coastal Community Vulnerability Assessment. The plan is also complementary to priorities described in the Strategic Plan for Federal Monitoring and Research of Ocean Acidification, the U.S. Ocean Acidification Action Plan, and the Ocean Climate Action Plan.

This plan describes how monitoring could address research needs and provide information on the threat that OA poses to coastal economies, ecosystems, and communities, with an emphasis on leveraging existing assets. The recommended monitoring approaches follow the themes of 1) improving modeling efforts and trend analysis and 2) determining the vulnerability of biological resources.

This plan includes the following opportunities to guide U.S. government efforts:

- Sustain the existing climate-quality OA network, including moored and shipboard time-series, allowing for validation of weather-quality observations.
- Increase subsurface and benthic monitoring through use of autonomous vehicles, profiling instruments, and addition of bottom-moored sensors to existing infrastructure.
- Develop weather-quality regional estimates of OA dynamics derived from proxy observations (e.g., oxygen, salinity), including satellite observations.
- Augment existing water quality programs to measure OA, targeting sites near urban or agricultural areas and major rivers where runoff or pollution may contribute to OA.
- Expand community science observing of OA and biological impacts in coastal areas.
- Build partnerships to improve OA monitoring in significant habitats and managed areas, including estuarine and coastal habitats, and enable real-time sharing of this data.
- Provide technical assistance to states, Tribes, and industries (e.g., hatchery or aquaculture operations) so they can acquire and interpret site-specific OA data.
- Expand co-collection of OA chemistry and biological data through cruises, autonomous monitoring, and moorings, leveraging current biological programs to integrate OA data.

An OA monitoring program must account for additional factors to ensure success. Implementation will depend on availability of a skilled workforce, consideration of the high operating cost, and/or technological limitations. Additionally, as more observations are collected, data management and archiving will be needed to ensure that data meet quality standards and are discoverable by resource managers, scientists, and the public.

Recommendations on how best to monitor acidification will evolve as understanding of the information needs of communities and stakeholders improves. Monitoring networks should continue to be developed at the regional scale with ongoing stakeholder input.

Introduction

Ocean acidification is the increase in seawater acidity over decades due to human activities increasing the amount of carbon dioxide in the atmosphere. OA poses a threat to marine species and ecosystems, as well as the human communities and economies that rely on them. It is a priority to understand how marine life responds to continued changes in ocean chemistry and what socioeconomic impacts will result. Effective adaptation and mitigation strategies require more timely, actionable environmental intelligence regarding event-driven or long-term changes that can disrupt local economies, diminish ecosystem services, and create socioeconomic vulnerability.

Documenting local exposure to conditions is important to understanding ecosystem, economic, and social vulnerability to OA. Acidification varies greatly over space and time, especially in the coastal zone, where factors in addition to carbon dioxide emissions such as nutrient pollution and river runoff influence local ocean chemistry and can cause increases in acidity (i.e., coastal acidification). Monitoring is key to documenting how the frequency and duration of coastal acidification events may change over time within a particular region. This information can serve as an important indicator of local OA stress to habitats and fisheries of regional interest.

Ocean acidification can be measured using four different parameters within the carbonate system: pH (a measure of the relative amount of hydrogen ions), total alkalinity (TA; a measurement of water's ability to resist a reduction in pH), the partial pressure of carbon dioxide (pCO_2), and dissolved inorganic carbon (DIC). The measurement of two out of these four parameters, along with temperature and salinity, can be used to calculate the saturation state of aragonite, a form of calcium carbonate. Aragonite saturation state is a measure of aragonite availability and is thus a useful measure of impacts on species that are rely on calcium carbonate.

Uncertainty in measurements of OA depends on the type of instrumentation used. Different questions require different levels of analytic precision and accuracy. Throughout this plan, there are references to climate quality and weather quality data. As defined by the Global Ocean Acidification Observing Network, climate quality refers to measurements of quality sufficient to detect long-term, anthropogenically driven changes in carbon chemistry over multidecadal timescales. Weather quality refers to measurements that are sufficient to identify relative spatial patterns and short-term variations.

For more than a decade, the United States has made considerable investments in OA monitoring through federal, state, local, territorial, and Tribal governments, as well as by nonprofits, academic institutions, and other partners. The Interagency Working Group on Ocean Acidification (IWG-OA)'s biennial reports contain descriptions of monitoring investments by the federal government. Various agencies play unique roles in advancing OA monitoring based on their mission space; these are described in the table below.

Agency	Mission	Role in OA Monitoring
Bureau of Ocean Energy Management (BOEM)	Manage the development of U.S. Outer Continental Shelf energy. mineral, and geological resources in an environmentally and economically responsible way	BOEM funds studies to characterize ocean carbonate chemistry in areas of interest
Environmental Protection Agency (EPA)	Protect human health and the environment	EPA funds monitoring of coastal acidification in estuaries
National Aeronautics and Space Administration (NASA)	Explore the unknown in air and space, innovate for the benefit of humanity, and inspire the world through discovery	NASA funds satellite-based research on ocean biogeochemistry
National Institute of Standards and Technology (NIST)	Promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life	NIST works to certify reference materials central to quality OA measurements
National Oceanic and Atmospheric Administration (NOAA)	Understand and predict changes in climate, weather, ocean, and coasts, share that knowledge and information with others, and conserve and manage coastal and marine ecosystems and resources	NOAA operates the National OA Observation system, in addition to supporting global measurements of ocean carbon
National Park Service (NPS)	Preserve unimpaired the natural and cultural resources and values of the National Park System for the enjoyment, education, and inspiration of this and future generations	NPS monitors OA at select sites, in partnership with NOAA
National Science Foundation (NSF)	Promote the progress of science; advance the national health, prosperity, and welfare; and to secure the national defense	NSF funds both on-going OA monitoring and technology development
United States Geological Survey (USGS)	Monitor, analyze, and predict current and evolving Earth-system interactions and deliver actionable information at scales and timeframes relevant to decision makers	USGS conducts monitoring of OA in rivers, estuaries, reefs, and carbonate seafloor environments

Table 1: The agencies who are members of the IWG-OA play unique roles in OA monitoring dependent upon their mission space, as described above.

Considerable progress has been made over recent years with expanded geographic coverage and technological innovation. However, regional stakeholders need more data and information that can provide actionable decision support at local scales and in impacted habitats. The 2023 Ocean Chemistry Coastal Community Vulnerability Assessment identified gaps in OA monitoring that should be addressed to better characterize ecological and social vulnerability. This plan builds upon the Vulnerability Assessment by identifying how potential new monitoring efforts might fill these gaps, with a focus on how the information provided by new observations would be used. The opportunities for additional monitoring in this plan are organized under the following monitoring needs:

- Monitoring to Improve Modeling Efforts and Trend Analysis
  - Improving Spatial and Temporal Coverage
  - Understanding Dominant Local Processes that Influence Carbonate Chemistry Dynamics
- Monitoring to Inform Vulnerability of Biological Resources
  - Capturing Short-Term Variability and Acidification Events
  - Understanding Changes in Under-Monitored Vulnerable Habitats
  - Connecting Changes in Chemistry to Biological Impacts

The last section of the report covers other factors that must be considered to build out the monitoring network to 1) better inform OA vulnerability assessments and 2) provide actionable environmental intelligence. Challenges remain in implementing these opportunities, including needs for improved technology, data management coordination, and regional and international collaboration. Additionally, there are moderate cost demands associated with all opportunities in this report.

Monitoring to Improve Modeling Efforts and Trend Analysis

Biogeochemical models are essential tools for understanding the progression and variability of OA. Researchers establish long-term trends through hind-casting to characterize changes in the past, forecast conditions at weekly to seasonal scales, and predict long-term, multidecadal trends. Developing, validating, evaluating, and improving regional biogeochemical models requires carbonate chemistry observational data. These models incorporate a wide range of parameters, including temperature, salinity, nutrients, DIC, pH, pCO_2, TA, and dissolved oxygen (DO). Targeted observations can advance model development and support operational product delivery where data can be integrated to reduce uncertainty. As discussed below, models would benefit from monitoring that 1) better captures spatial and temporal variability, and 2) quantifies the influence of different processes on carbonate chemistry dynamics.

Improving Spatial and Temporal Coverage

Additional observational data are needed to better resolve spatial (including subsurface) and temporal variability at scales most relevant to impacted marine resources. These data provide measurements of real-time OA conditions, are used to forecast acidification events, and inform long-term trend assessments. Each region has unique oceanographic characteristics and capacities that result in differing configurations and prioritization of observing assets. Refining regional models generally requires additional data from the full water column, minimally at sub-seasonal scales. Observing optimization studies are analytical experiments that recommend an optimized sampling design to meet a specific information requirement, such as ensuring collection of data of known uncertainty necessary to track and forecast ocean carbon system dynamics. These studies are presently underway to provide an objective analysis of regional spatiotemporal coverage requirements, and a recently issued call for additional studies requests co-development of the observing design informed by data user needs. Still, further studies of this kind are needed to determine where observing nodes should be located to be most valuable to data users and model developers. Adaptive sampling techniques may also be used to guide the placement and positioning of mobile observational platforms to areas with the most statistical uncertainty. These techniques can also recommend adjustments to sampling frequency. This will better ensure that derived science and data products provide maximum technical assistance to vulnerable communities.

Opportunities:

- Promote the commercial availability of pH sensors that can be integrated into existing glider fleets. This would allow for expanded autonomous subsurface monitoring at sub-seasonal resolution across U.S. coastal systems, with data regularly validated against a climate-quality OA reference network of time-series and shipboard measurements. This technology can capture large- and small-scale signals across wide geographic areas and be targeted for deployments in critical habitats during forecasted acidification events.
    - Saildrones and wave gliders are additional autonomous technologies that collect surface measurements, but their cost remains prohibitive for large-scale operational monitoring. However, they can serve as valuable targeted research platforms where measurements below the mixed layer depth are not needed.
    - Biogeochemical Argo floats may also be used to measure subsurface conditions, but they are best suited for deep-sea applications. They have limited application within large U.S. coastal marine ecosystems, but progress is underway to adapt their use for regional monitoring (e.g., along the California Current).
- Expand use of satellite measurements (e.g., temperature, salinity, ocean color, wind, waves, currents) to provide regional proxy estimates of surface carbonate chemistry. Data from NASA satellite missions (GLIMR, SBG, PACE) have greater potential when coupled with ancillary data and predictive models. Models using these data may need to be refined and validated for offshore surface environments using the climate quality OA reference network, which is comprised of high-quality, fixed time-series stations with internal calibration capabilities and shipboard measurements. NASA also invests in airborne field campaigns and ship-based sampling that can be used to contextualize data.
- Explore the potential for new partnerships with industry to integrate sensors that can measure vertical profiles of the water column onto existing commercial ocean platforms, such as oil, gas, and offshore wind platforms. This will be most successful with industry co-funding, as high costs remain for accessing platforms for routine servicing, maintenance, and data processing and archiving. Sensor access and cross-validation with the reference network can also limit feasibility.
- Expand surface sampling via ships of opportunity (i.e., vessels that volunteer to collect samples during the conduct of their normal business, often through an underway system that passively collects data). This may be particularly helpful where objective analysis (e.g., observing system simulation experiments) demonstrates that additional surface observations will improve model performance or validate and constrain satellite algorithms. Underway systems could be added to additional vessels, such as National Marine Sanctuary boats and regional ferries.
- Sustain existing climate-quality OA network assets, including fixed time-series of internally calibrated sensors and high-quality shipboard discrete sampling that allow for the system-wide cross-comparison of regionally distinct asset configurations. While this could include NOAA's MAPCO2 systems, this technology is nearing obsolescence, and the next-generation system must be finalized or alternate technology options pursued.

- Add new capabilities to existing fixed platform time-series monitoring at select locations. When possible, monitoring should use real-time sensors and leverage existing meteorological and physical oceanographic observing platforms (e.g., National Data Buoy Center moorings and Integrated Ocean Observing System (IOOS) Regional Association physical oceanographic moorings). Vertical profiling sensors could expand the utility of mid-shelf and coastal moorings to provide information on subsurface conditions.
- Sustain NOAA OA Cruises, at a reoccupation rate of no less than every four years, as a key element to a climate-quality OA reference network. These cruises serve as critical validation to anchor regional biogeochemical models and algorithms, assess uncertainties, and reduce bias and drift. Cruises should expand to include all U.S. territories. Additionally, a quantitative assessment should be made to determine how spatial resolution should vary for transect lines.
- Expand existing vessel-based observations (including ships of opportunity and existing cruises) to include winter and fall.
- Expand monitoring of dissolved oxygen to be used as a proxy measurement for carbonate chemistry parameters in instances where data user requirements are such that weather quality measures suffice. This could provide lower-cost alternatives to carbon sensors, where local or regional algorithms anchored by the climate-quality OA reference network allow.

Understanding Dominant Local Processes that Influence Carbonate Chemistry

Sustained, or in some cases targeted, monitoring campaigns are key to quantifying the local and regional drivers of sub-decadal carbonate chemistry dynamics. Improved models demand better characterization of boundaries between land and sea, transition zones in the ocean, and between the ocean and seafloor. Improved model performance relies upon additional monitoring that captures various fluxes, rates, and feedback processes (e.g., net community production, calcium carbonate production and dissolution, decreasing buffering capacity, and sediment biogeochemical alkalinity production).

There is a particular need to understand the processes at play in coastal environments, which are home to ecologically and economically important habitats and species. Nearshore conditions are difficult to model, as these areas can be highly influenced by terrestrial inputs, local pollution, and riverine inflow, among other factors such as multi-stressor interactions. Quantifying the impact of these influences and how they respond to decadal changes driven by atmospheric inputs can improve model accuracy in these dynamic and ecologically and socioeconomically important places; this information is useful for state and local water quality managers. The need for this monitoring will likely continue to grow, as there is emerging interest in deploying marine carbon dioxide removal pilots in coastal waters as a potential OA mitigation strategy.

More observations in the coastal zone will enable better understanding of acidification drivers, track the accumulation of anthropogenic carbon, and deliver more actionable data products to coastal managers and industries. These data can help optimize monitoring by demonstrating time to detection for anthropogenic changes. If the seasonal cycle is accounted for and time to detection calculated, anthropogenic-driven change may be observed in 10-20 years in less variable areas but over longer time frames in more variable areas.

Opportunities:

- Begin continuous long-term monitoring at and around major rivers known or suspected to contribute to coastal acidification. Increase targeted monitoring near urban areas, agricultural areas, and high-flow river mouths and in coordination with state and local water quality monitoring programs. Partner with USGS (which operates long-term river monitoring that includes alkalinity and nutrient measurements), EPA, and other groups to identify where additional carbonate system measurements could be added.

- Augment existing water quality stations to measure additional carbonate chemistry parameters; this could include stations run by state or local agencies, the USGS National Water Information System, EPA's National Estuary Program Sites, NSF's Long Term Ecological Research sites, NOAA's National Estuarine Research Reserves, nongovernmental organizations, or universities. A second carbon sensor such as pCO_2 sensors could be added to existing glass electrode pH sensors, which measure pH at a lower accuracy on the National Bureau of Standards scale.
- Sustain existing nearshore stations collecting carbonate chemistry data, including those operated through the EPA's National Estuary Program, NOAA's National Estuarine Research Reserve sites, and marine protected areas (MPAs). Programs could be leveraged to expand monitoring of the full carbonate system at additional sites, but this is limited to the geographic area covered by the program.
- Partner with Tribes to co-design and expand monitoring at shore stations while elevating Indigenous Knowledge. Agencies should provide technical assistance in terms of troubleshooting, technical advice, and training in community best practices on a periodic basis.
- Deploy autonomous OA stations in 20-30 meter water depths at sites where there is already shore station sampling from IOOS.
- Expand volunteer community science observing to increase spatial coverage of nearshore and estuarine monitoring. Provide technical assistance to improve data quality to meet local needs and cross-validate with the climate reference network.
- Deploy a nearshore array of low-cost OA monitoring stations (20-30 sites) for one-to-two years at a time in different regions to capture smaller alongshore spatial scales in OA variability, which is needed to validate models.
- Expand observations of rates such as net community production, calcification, oxygen utilization rates, and sediment fluxes. This may require expansion of new and existing methodologies, including *in situ* benthic sampling both at the sediment-water interface and within sediments, isotopes, 'omics (i.e., a group of biological sciences that quantify and describe collections of biological molecules, such as the genome)-based methods, and *in situ* observations of benthic organisms and their rates (e.g., O_2 utilization rates). Rate data can be used to inform water mass age and mixing time estimates.

Monitoring to Inform Vulnerability of Biological Resources

A key component of ocean acidification observing networks is the focus on deciphering and predicting impacts to marine life, especially ecologically and economically valuable ecosystems and species. The following sections explain the need to 1) capture short-term variability and acidification events to which species may be exposed; 2) expand observations in under-monitored vulnerable habitats; and 3) co-locate chemical and biological observations to better discern the effects of OA on ecosystems and species.

Capturing Short-Term Variability and Acidification Events

Many ecologically and socioeconomically important habitats are located in coastal areas with high variability and rates of change. Measuring the diel, tidal, and seasonal temporal cycles in carbonate chemistry in these systems would improve understanding of the conditions to which species are exposed. This can both inform biological research and species response studies; the findings of those research studies can be adopted to generate real-time forecasts and seasonal outlooks of impending stressful conditions. This information is valuable to managers implementing restoration and mitigation activities in these ecosystems and industries seeking to limit impacts.

Estuaries and coastal environments provide a variety of ecosystem services that support food security, recreation, tourism, industry, and protection against coastal hazards. The communities that depend upon them or are charged with their conservation or restoration would benefit from actionable environmental intelligence provided by monitoring (or models informed by targeted monitoring) in relevant habitats. Many nearshore and coastal habitats, including marshes, bays, seagrass meadows, mangroves, estuaries, oyster reefs, and shallow coral reefs, need more monitoring to understand their contemporary exposure to OA and other co-stressors, such as hypoxia or harmful algal blooms.

Higher-frequency monitoring captures the magnitude, duration, and frequency of acidification events, informing the vulnerability of marine resources with ecological significance or relevance to industries and marine resource managers. Targeted monitoring can serve as an early-warning system to alert community members to potential acidification events. These early-warning systems could benefit shellfish hatchery operators, subsistence harvesters, and those investing in habitat restoration. When made available on existing platforms, these observations will provide end users the opportunity to evaluate model performance with the existing data. This will help the end users develop trust needed to act on forecasted conditions.

Opportunities:

- Add OA parameters to water quality monitoring conducted by federal and state agencies and watershed groups. This leverages their technical expertise but would require partnerships with laboratories to conduct carbonate chemistry parameter analyses and reference measurements against the climate-quality OA reference network to ensure internal consistency.
- Deploy targeted dock or shore-based moorings to capture high temporal frequency data in places where the data can be used to address mariculture, commercial, or subsistence-related research, or management questions.
- Add new, sustained time series of carbonate chemistry data in estuaries and coastal waters. New, higher-accuracy pH and CO_2 sensors could be deployed alongside glass electrode pH sensor data to leverage historic time series.
- Provide technical assistance to community sampling programs to collect data in habitats or areas of importance for subsistence or other social value; this could include biological measurements such as shell thickness.
- Deploy regular, glider-based monitoring of ecosystem multi-stressors, such as temperature, salinity, oxygen, and pH.
- Sponsor technology development to enable more moorings and gliders to share real-time data in nearshore habitats, which is especially challenging in the subsurface environment. For long-term continuous monitoring that requires instrument maintenance, it is important to choose sites with regular access.
- Create new event response programs to enable rapid detection and monitoring of intensified acidification or hypoxic events.
- Build on collaborations with hatcheries to co-locate water quality and shellfish health monitoring. Collecting carbonate chemistry data will allow hatcheries and local decision makers to mitigate harm and understand the impacts of water quality events on hatchery success.

Understanding Changes in Under-Monitored Vulnerable Habitats

While the subsurface water column and benthic environments may already be exposed to lower pH conditions, monitoring in these areas has been limited. Many ecologically or economically important species occupy benthic environments for part or all of their lives. These include deep sea corals, surf clams, Atlantic sea scallops, benthic fish, and crabs. Seafloor communities such as coastal carbonate seafloor habitats and high-latitude tropical corals are also vulnerable.

Capturing variation in the full water column is important for understanding the environmental conditions to which larvae of sensitive species are exposed. An expansion of sub-surface monitoring in areas of ecological significance for commercial fisheries remains a priority.

Opportunities:

- Leverage existing infrastructure (e.g. National Data Buoy Center, U.S. Army Corps of Engineers, IOOS) to add bottom-moored acidification sensors that are located in benthic fisheries habitats (e.g., surf clam, crab, sea scallop habitat), where cost savings can be demonstrated by the co-locations of these existing assets.
- Add dedicated full water column stations for deep habitats and extend benthic sampling, as appropriate, during ongoing NOAA OA cruises. Dedicated ship-time for deep water sampling is needed to adequately monitor changes in deep sea habitats and ensure cross-calibration across the climate-quality OA reference network.
- Engage fishing fleets in collecting subsurface OA data. Utilize oxygen data of appropriate quality already collected by the industry, along with salinity and temperature data, to develop carbonate chemistry proxies cross-validated with climate-quality datasets.
- Utilize gliders and other autonomous technology (autonomous underwater vehicles, remotely operated vehicles, and bottom landers) equipped with OA sensors to collect high-frequency subsurface data across seasons, leveraging existing programs.
- Leverage existing long-term subsurface stations or benthic sampling programs by adding carbonate chemistry sampling to expand coverage.
- Build upon partnerships with National Marine Sanctuaries, the Marine Biodiversity Observation Network, and NOAA Fisheries, and expand work with the U.S. Fish and Wildlife Service, NPS, state MPA networks, and kelp monitoring programs to collect carbonate chemistry data in significant habitats and managed areas.
- Install continuous monitoring platforms on offshore wind energy platforms and incorporate OA monitoring into the design of new wind energy projects, where appropriate.
- Expand the collection of *in situ* observations in the vicinity of key benthic organisms. These data can be used to estimate metabolic rates in areas where benthic feedback processes impart a major influence on environments important to economically or ecologically important species.
- Target monitoring at sites that have experienced coral mortality and/or chemical erosion of seafloor sediments and structure due to acidification, as well as sites that have proved resilient to major mortality events.
- Build on existing USGS methods and develop new methods for *in situ* benthic sampling both at the sediment-water interface and within sediments to quantify fluxes of chemical constituents across the sediment-water interface.

Connecting Changes in Chemistry to Biological Impacts

Biological data must be co-collected with carbonate chemistry data in areas of ecological significance. This will improve understanding of how acidification impacts species and assist scientists in making predictions of how species and entire ecosystems will respond to increasing OA in the future. Researchers can explore potential impacts of OA to populations and food webs if paired biological monitoring is focused on habitats of commercial and subsistence species, as well as their prey and other key species. It is also important to measure multi-stressors that may impact habitats and species response, such as harmful algal blooms, hypoxia, and warming.

Opportunities:

- Integrate OA observations into co-monitoring and modeling of multi-stressor variables, including hypoxia, harmful algal blooms, eutrophication, and warming.
- Expand time series of carbonate chemistry monitoring to key habitats that support commercially and recreationally important coral, shellfish, and finfish.
- Expand biological measurements, including phytoplankton and zooplankton sampling, environmental DNA (eDNA) measurements, biomarkers, imaging, or fish acoustics, across acidification gradients in coordination with biological monitoring networks, including at nearshore stations, seawater intake systems, stream gauges, and aquaculture facilities. Biological data collected on sensitive species could include growth, metabolic condition, shell strength, or survival.
- Increase subsurface moored and autonomous environmental monitoring paired with ecosystem observations of physical, chemical, and biological parameters of importance (e.g., temperature, salinity, pCO_2, pH, oxygen, Imaging FlowCytobot, chlorophyll, colored dissolved organic matter, and acoustic monitoring of tagged organisms, such as crabs, herring, and salmon).
- Leverage long-term biological monitoring programs and centers of excellence for biological data analysis.
- Integrate phytoplankton and zooplankton monitoring at existing nearshore stations or as a routine part of cruises that collect carbonate chemistry data, including NOAA OA surveys.
- Broaden collection of pteropods and crab larvae, including via light traps for juvenile crabs; refine methods for assessing damage to pteropods (e.g., explore automation).
- Collaborate with ongoing federal and state fisheries surveys to integrate environmental carbonate chemistry sampling.
- Conduct snapshot surveys of OA and biological parameters using community science initiatives.

Other Considerations for Monitoring

Technology, Analysis Capabilities, and Workforce Development

While the opportunities above highlight significant challenges with development and implementation, they also highlight the great opportunity for technology and workforce development and increasing capacity. These challenges may also be exacerbated as the need for ocean carbon monitoring grows to meet the need for verification of marine carbon dioxide removal techniques.

There are few existing carbonate chemistry sensors, and all have limitations and may not be suited for all environments. Improvements to nearshore sensors, in particular, are needed to collect accurate high-frequency data in challenging coastal and estuarine environments with low or highly variable salinity. Currently, nearshore sensors require costly routine visits and significant human labor to maintain high accuracy. Subsurface sensor technology is also underdeveloped; there is a need to improve and develop new seafloor mounted sensors with improved data telemetry capabilities for carbonate chemistry observations.

There is a great opportunity to leverage gliders to advance OA monitoring, but deployment is currently limited by glider manufacturing, payload limitations, and sensor development. Pilot time is costly, and it is challenging to work across different glider manufacturers, models, and biogeochemistry data processing and delivery techniques.

Beyond developing advanced sensors, increased monitoring will require a workforce that includes trained technicians to collect samples and field data, process samples, analyze data, and interpret results. Also, organizations should consider that offshore moorings require routine dedicated ship time for servicing and collecting samples for validation. Even near-shore sensors will require dedicated time for maintenance and addressing bio-fouling, which is a common challenge. Additional research cruises dedicated to OA monitoring would also require the recruitment, training, and retention of skilled crew.

There are a limited number of laboratories capable of high-quality carbonate chemistry analyses; some states do not have any, and many existing laboratories have limited capacity to analyze additional samples. Regular interlaboratory comparisons are needed to ensure proper measurement quality control assurance. Given the current limited laboratory capacity, the feasibility of leveraging water quality programs to expand water sampling for carbonate parameters is low. Carbonate chemistry measurements are also threatened by insecurity in the supply of carbon-in-seawater reference materials.

Industry and Community Engagement

Partnering with marine industries and leveraging their equipment for monitoring presents opportunities to increase the amount of acidification data collected and to engage industry members in acidification research. For example, commercial fishermen have expressed interest in collecting carbonate chemistry observations and contributing to science, but several barriers exist. Current technology is expensive to purchase and install, and other instrumentation does not meet accuracy requirements needed to address research and management questions. Addressing these challenges may open the door for new partnerships.

Partnering with industry requires time to build relationships. For example, maintaining monitoring on ferries requires collaboration with key marine highway system employees. When staff changes, these relationships need to be reestablished. For aquaculture industry collaborations, Sea Grant aquaculture extension agents could be leveraged to start new monitoring programs.

Creating community sampling programs presents an opportunity to include traditionally excluded groups in the collection of OA monitoring information. Impacted communities must be included in every stage of the decision-making process, including data collection. Supporting community-led observing initiatives to build capacity with traditionally underserved or excluded groups should be prioritized. NOAA regional programs could explore opportunities to host capacity building workshops and technological trainings that advance diversity, equity, inclusion, and belonging. This could leverage international capacity-building efforts conducted through the Global Ocean Acidification Observing Network.

Alaska has successfully operated a community sampling program for OA, and the Northeast organized a successful one-day acidification community sampling campaign (“Shell Day”) that had broad regional coverage. Similar programs could be expanded to other regions, but this presents challenges. Community sampler turnover is high in many communities, and sampling can be inconsistent. Community sampling programs also need dedicated support for instrument maintenance and for labs that analyze samples.

Regional and International Collaboration

Acidification monitoring will be most effective where regions build integrated acidification observing networks that leverage federal, state, Tribal, territorial, and local governments’ sustained monitoring and data management efforts. All existing monitoring efforts, including those from individual researchers, community groups, watershed associations, and state and federal agencies, should be coalesced into a coordinated regional plan. Regional coordination can allow members to share technical expertise and troubleshoot equipment among a monitoring community. As resources allow, new monitoring can be supported to augment this network and contribute to the regional perspective. Regional academic partners and collaborators can continue to consult on key locations for additional monitoring.

Fostering international partnerships would also increase monitoring capacity across shared borders. There is substantial chemical, biological, and socioeconomic connectivity among the U.S., Mexican, and Cuban sub-regions, and between the United States and Canada. Facilitated and enhanced international collaboration is required to develop comprehensive monitoring systems in the Gulf of Mexico, Northeast, Pacific Northwest, and Alaska. Multi-national training opportunities could allow for the development and sharing of best practices for data acquisition and management.

Data Management, Analysis, and Synthesis

Sustained data management and coordination capacity is needed to support the successful archiving and use of monitoring data. The differing individual review, formatting, and publication requirements of federal agencies is a large impediment to the timely sharing of data. Across nearshore networks, there is a large need for improved data quality control and coordination.

Development and implementation of a substantive data management plan must be a key component of any project proposing new OA monitoring. Existing data management systems and repositories, including those of the IOOS Regional Associations and NOAA Ocean Carbon and Acidification Data System, should be leveraged to better integrate physical, chemical, and biological data.

Monitoring efforts need to develop and refine data management practices for integrating chemical, physical, and biological data to support biological and socioeconomic risk and vulnerability modeling (i.e., information for industry and management). It is challenging to manage and integrate data from multiple sources and types of collection, especially biological metrics such as community monitoring data, high-frequency moorings, shore stations, and ship survey water column. It is also difficult to process and store imaging and eDNA data, but this methodology is currently being developed (e.g., the National Aquatic eDNA Strategy).

Data analysis efforts must be supported for monitoring to help resolve biological impacts in the context of OA changes or characterize the relationship between salinity and total alkalinity at regional scales. The Global Ocean Data Analysis Project and the Coastal Ocean Data Analysis Product in North America are examples of data synthesis products invaluable for model development and evaluation. A continuously updated Coastal Ocean Data Analysis Product database that ingests new OA data streams in a timely manner, following the standards of the existing collection, could help implement a model-based OA early-warning system informed by observations. Researchers must also evaluate whether data are being used effectively. For example, some states have over two decades of glass electrode pH sensor measurements that could be analyzed and used for a region-wide synthesis. Data analysis should also lead to information delivery and tailored products for diverse end-users.

Conclusion

Filling gaps in OA monitoring will contribute to our understanding of ecosystem and social vulnerability to OA. This plan presents opportunities for how these gaps could be filled with new or expanded monitoring, while also outlining the importance of the information these data would provide. Unique regional requirements emerge as a consequence of the diverse factors controlling local acidification dynamics, the differing species of interest, and the variations in economic and cultural dependence on impacted marine life. However, a number of common needs transcend these regional differences which have remaining technological and cost challenges nationwide. These include increasing coverage in habitats most relevant to economically and culturally important species, such as at depth, and leveraging existing biological monitoring networks to better make use of long-term biological time-series for which OA monitoring would represent a valuable augmentation. As various groups are considering changes to OA monitoring, this plan serves as a guide to federal priorities.

In the future, regional entities such as the Coastal Acidification Networks may be interested in expanding upon this effort by outlining how national opportunities could be implemented on the local to regional scale. The IWG-OA will support those conversations and seek to build partnerships to leverage existing monitoring efforts outside of the Federal Government as well. Federal support for data management will remain crucial to ensure that data from diverse sources are publicly accessible.