Ocean and Coastal Acidification Monitoring Priorities for the Northeast US and Eastern Canada

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Executive summary

The Interagency Working Group on Ocean Acidification Monitoring Prioritization Plan 2024 calls for Coastal Acidification Networks to identify the ocean and coastal acidification (OCA) monitoring needs most important for their regions. The Northeast Coastal Acidification Network (NECAN) organized a webinar series to study regional needs, which culminated with a workshop in November 2023. This workshop led to the identification of six priority new Monitoring Needs in addition to the maintenance of current monitoring efforts:

- ☐ **Improve spatial and temporal scale of monitoring co-located OCA variables and biological measurements to better resolve variability of acidification dynamics in concert with biological processes**
- ☐ **Increase subsurface monitoring to understand how conditions vary at depth**
- ☐ **Increase the number of high-frequency monitoring assets that measure at least two of four carbon parameters**
- ☐ **Increase near-real-time and rapid response observing capacity to capture episodic events**
- ☐ **Determine fluxes and rates that would help parameterize and constrain regional modeling efforts to understand past conditions and project future trends**
- ☐ **Increase spatial coverage of "climate"-quality observations**

This report presents monitoring needs and opportunities for consideration by coastal managers, decision makers, researchers, and monitoring groups. It offers options to apply new capacity or funding to the expansion of OCA monitoring in the NECAN region. Writing the report led to the identification of a number of cross-cutting actions which will lead to the implementation of these Monitoring Needs:

- Expand monitoring beyond carbonate chemistry to provide a complete assessment of OCA, its effects, and future trends.
- Enhance or leverage existing monitoring platforms for a cost-effective and collaborative approach to creating a more complete OCA monitoring system in the NECAN region.
- Expand the NECAN membership to include protected area experts, terrestrial biogeochemists and hydrologists, fisheries experts, social scientists, Tribal liaisons, project leads from large assessments, and other important stakeholders, rights holders and decision makers.
- Increase funding in the Northeast to both sustain currently-stretched efforts and grow a more robust ocean acidification monitoring program.
- Pursue immediate implementation of proxy approaches or interim strategies for measurements with technological or capacity limitations, while new technologies are being developed.
- Synthesize monitoring information to advance the collective understanding of OCA in the NECAN region.

- Deploy monitoring assets strategically, with end-user needs in mind, ensuring that the collected data is accessible, relevant, and useful for decision-making.
- Share NECAN's experience in developing these recommendations with other regional CANs.

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Goals of the monitoring plan

The Northeast Coastal Acidification Network (NECAN) monitoring plan identifies highly-rated, specific actions that will improve both (1) the monitoring and understanding of regional ocean and coastal acidification and (2) future decision making regarding this issue in the Northeast region. Due to the size of the NECAN region and the high variability of conditions in the coastal zone and shelf waters, this monitoring plan cannot consider and make specific recommendations for every locality in the region. To allow this plan to be used more broadly across the region, this plan also outlines the criteria that were used to identify specific monitoring recommendations. These criteria provide a framework which can be applied to efforts beyond those recommended here. This allows decision makers to identify monitoring actions that can be implemented in other areas of the NECAN region (or other regions) that were not considered in this plan.

Introduction

NECAN is leading the synthesis and dissemination of ocean and coastal acidification information in the Northeast US and Eastern Canada. Established under the Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS) in 2013, NECAN is a partnership among government agencies, industry members, and the scientific community to advance the collective understanding of ocean and coastal acidification (OCA). NECAN serves as a conduit through which decision makers and stakeholders can receive recommendations on OCA monitoring and understanding. The NECAN region encompasses the coastal ocean from the high-water line to the shelf-break from Long Island Sound to Nova Scotia.

The Northeast Regional Ocean Council (NROC) is a Regional Ocean Partnership of New England states, federal agencies, Tribes, New England Fishery Management Council, and regional partners, including ocean industries, academia, and environmental organizations to coordinate and collaborate on regional approaches to support balanced uses and conservation of the Northeast region's ocean and coastal resources. NROC's Ocean and Coastal Ecosystem Health Committee works closely with NECAN to improve the scientific understanding of OCA, advance spatial data to inform decision making, and support outreach to managers, planners, scientits, and industry representatives to better understand data requirements for permitting, siting, and monitoring related to OCA specific variables. Many of the state and federal partners in NROC have robust monitoring programs to provide information for coastal management, and addition of OCA monitoring is of interest to these partners.

Since 2014, several states across the United States (US) have focused on OCA, enacted policies and, at times, legislation to better understand the impacts of OCA on industry, environment, and coastal communities. In each of the state-level final reports, enhanced monitoring for OCA parameters is a key recommendation. National reports and Congressional direction have consistently recommended additional monitoring, both for ocean acidification (OA) (*i.e.*, atmospheric carbon dioxide-driven acidification absent the influence of coastal processes) and coastal acidification (CA) (*i.e.*, acidification including the influence of freshwater from land and coastally located biological growth and respiration). However, these reports lack specifics on what form this monitoring should take. NECAN is called out to lead the effort to create a region-wide monitoring plan in many New England state reports and in the reauthorized Integrated Coastal and Ocean Observation System Act (ICOOS). Additionally, the Interagency Working Group on Ocean Acidification (IWG-OA) Ocean Acidification Monitoring Prioritization Plan specifically calls for regional coordination of monitoring efforts. With its experience and expert Steering Committee, NECAN is the logical entity in the Northeast to provide this leadership. Working in partnership across the Northeast, NECAN, the Northeast Regional Association of Coastal Ocean Observing Systems (NERACOOS), and NROC are working to collectively advance OCA in the region, drawing on each organization's strengths to develop and support a Monitoring Plan for the region.

The NECAN Region - Background oceanography and OCA

The NECAN region includes coastal and shelf waters from the urbanized estuary of Long Island Sound in the southwest, to Nantucket Shoals to the southeast, into Canada and the Scotian Shelf to the north. The Gulf of Maine (GoM) resides in between, acting as a large estuary mixing the fresher Labrador current waters from the north, oceanic water from the continental slope and shelf (including increasing imports offshore waters from the Gulf Stream), and local river inputs. Georges Bank sits on the offshore and southern edge of the Gulf of Maine and serves as an important fishing ground for the region's many fisheries. The regions are interconnected by a broad cyclonic circulation pattern where a general northeast–southwest flow of water from the Labrador and Newfoundland Shelf areas extends through the Gulf of St. Lawrence, Scotian Shelf, and GoM to the Mid-Atlantic Bight (Figure 1).

Water properties indicative of ocean and coastal acidification similarly track this latitudinal gradient. Calcium carbonate saturation state (Ω) and pH both decline to the north in the NECAN region as the temperatures decline (Cai et al. 2010, Wang et al. 2013, Salisbury and Jonsson 2018). Temperature and salinity each impart important influence on the variability of Ω and the partial pressure of carbon dioxide (pCO_2), as do changes in the inputs and proportions of the various water masses that influence the region (Salisbury and Jonsson 2018).

The carbon system is impacted by more than atmospheric CO_2 concentrations, and in the NECAN region these processes include eutrophication, low alkalinity river discharge, atmospheric deposition of acidic and alkaline compounds (Doney et al. 2007), and sedimentary fluxes (Fennel et al. 2008). Over the last decade, research has identified drivers of ocean acidification in the GoM (Salisbury et al. 2008, Wang et al. 2013, Strong et al. 2014, Gledhill et al. 2015, State of Maine Legislature 2015, Salisbury and Jonsson 2018, Siedlecki et al. 2021), however the relative contributions of each driver, and in particular the mixing of water masses, remain poorly understood and constrained.

High resolution observations in the region have identified that surface conditions often include Ω values below the biological threshold of 1.6 in coastal embayments as well as on the shelf at the long term observing location, Buoy D (Siedlecki et a. 2021). Preindustrial conditions, however, did not show such low Ω levels (Sutton et al. 2016), suggesting the region is experiencing long-term ocean acidification. Despite this, over the last decade, the Ω at a sentinel monitoring site off the New Hampshire coast (Buoy D) has increased. A well-characterized and intense warming alongside salinity increases has buffered the changes in pCO_2 and Ω (Salisbury and Jonsson 2018), showing that changes in water masses are critical for decadal change in the region. In contrast, pH was found to decline over 2005 to 2014 and was largely in agreement with North American surface water decline rates measured in Bermuda (Siedlecki et al. 2021).

Overprinting these long-term trends in regional carbon chemistry are strong seasonal and episodic signals, which correspond to shifts in the factors controlling short-term regional OCA conditions. These signals include seasonal biological production and respiration, stratification and overturn, and mixing (Vandemark et al. 2011, Wang et al. 2021, Hunt et al. 2022), as well as episodic events such as large freshwater storm fluxes, blooms of unusual or harmful algal species, or episodic water mass intrusions (i.e. Grodsky et al. 2018). Long-term climate trends are expected to impact these short-term signals in ways that are difficult to forecast (Li et al. 2024a,b), and new phenomena such as marine CO_2 removal (mCDR) activities pose unique challenges to monitoring and anticipating OCA changes in the region.

The purpose of regional OCA monitoring and establishment of webinar themes

While federal agency reports identify national OCA monitoring goals, in this report NECAN establishes some specific regional monitoring goals. These goals fit within the national OCA monitoring plan, but are tailored to the regional needs that NECAN established in the process outlined in more detail below. Monitoring serves several purposes, and the type, location and timing of monitoring done need to be optimized for different uses (Wright-Fairbanks et al., in review). Most state OCA commissions in the Northeast US were unsure about the current impacts of acidification to their resources, and recommended monitoring to understand the status and trends of acidification in their state waters. Local OCA monitoring would be most useful in collaboration with existing state efforts that include other water quality parameters (i.e. dissolved oxygen, nutrients, temperature), and coordinated with monitoring of resources that are likely to be affected by acidification, such as shellfish beds and aquaculture facilities. Another use for nearshore monitoring is identifying the areas most prone to acidification ("hot spots") or relatively protected from acidification and its impacts ("refuges"). This could include areas where CO_2 remediation is being undertaken, such as seaweed farms or marsh restoration or areas where nutrient remediation has been enacted, such as watersheds with advanced nitrogen remediation of wastewater. As above, monitoring in these areas would be most useful if it includes other water quality and biological data. Ongoing monitoring is essential if states are implementing actions to alleviate acidification. Knowing about conditions before and after interventions can provide justification for effective actions and is crucial to encourage public support. Furthermore, an ability to project future conditions for OCA, or hindcast conditions to understand past events, requires monitoring data to develop and tune biogeochemical models. Ongoing monitoring also serves as an evaluation for model outputs and when paired with assets that end users rely on, enhances end user trust in model results (Siedlecki et al. 2021).

Monitoring is also used to understand long-term trends for ocean acidification, and to attribute the drivers of dynamics in ocean acidification (Li et al. 2024a, b). Ocean acidification signals may be amplified or masked by changes in other regional conditions (Salisbury and Jönsson 2018), underscoring the need for long-term monitoring data, and in particular the drivers of OCA conditions in coastal regions and estuaries may change seasonally or episodically (Cai et al. 2011, Hunt et al. 2022).

To help identify the current state of the science and identify regional OCA monitoring needs, NECAN organized a series of webinars that were broadly available to the scientific, academic, and regulatory community. NECAN's steering committee established eight webinar sub-themes around the theme of monitoring the Northeast coastal ocean for OCA, which included:

(1) **Current Assessments:** included the ecosystem status reports produced by the National Oceanic and Atmospheric Administration (NOAA) fisheries, climate reports from National Marine Sanctuaries, and reports and publications from academic and research institutions in the region that include OCA variables in their monitoring activities and work to distill those into regularly delivered products.

(2) **Climate:** covered discussions of monitoring to support the attribution of long term (multi-decadal) trends and support mitigation strategies like marine Carbon Dioxide Removal (mCDR).

(3) **Modeling**: recognized the various modeling efforts in place in the region working toward reconstructing historical patterns, extending observations in time and space, and developing forecasts and projections. These models have specific needs which can shape monitoring activities.

(4) **Biological Impacts**: identified needs from the biological community in support of establishing impacts from OCA in the field.

(5) **User Needs and Products**: provided descriptions of regional monitoring tools and data offerings, as well as an overview of a state OCA Commission's activities and needs.

(6) **Indigenous Interests**: was established to clearly identify the unique needs of this important group.

(7) **Rapid Response to Emerging Events:** provided an understanding of how a flexible observations unit could be deployed to understand compound events as they emerge in the NECAN region.

These themes provided the foundation for the webinar series and subsequent in-person workshop which NECAN used to establish the monitoring priorities for the region presented in this report (Figure 2).

Approach to establishing monitoring priorities for this report

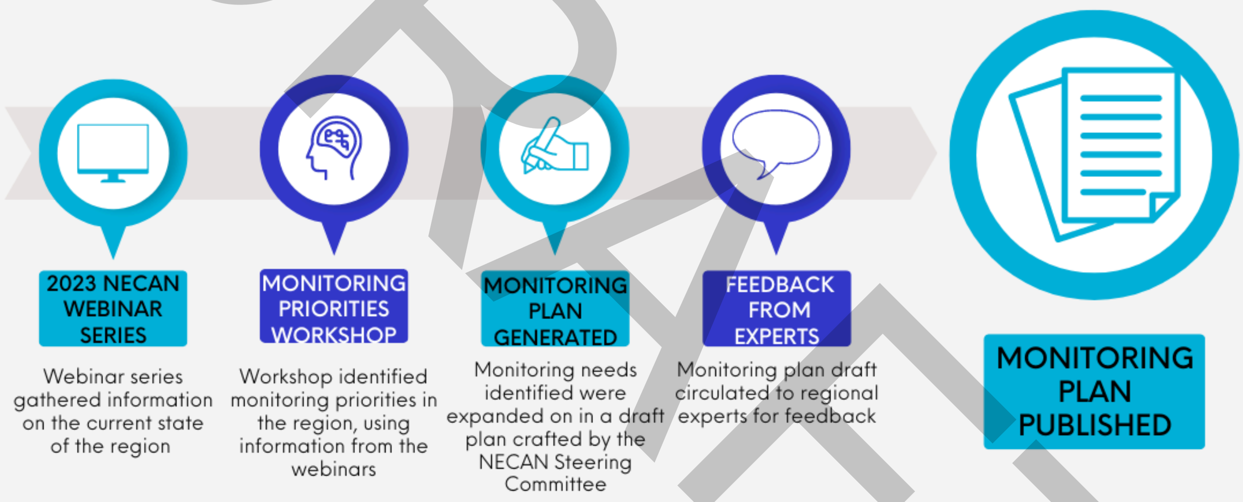

Figure 2- Conceptual diagram illustrating the development process for this report.

To develop a more integrated and effective OCA monitoring strategy, NECAN held a series of webinars to solicit insights from the regional network of OCA experts including researchers, data generators, and user communities, culminating in a workshop to identify and recommend monitoring priorities for the region. Each webinar was a part of one of the themes identified by the NECAN steering committee in response to the question -“why do we monitor?” A total of 12, 90 minute webinars were held and archived on the NECAN website and the NERACOOS YouTube Channel. The NECAN Steering Committee is grateful to webinar speakers (see Appendix A) for their discussions and insights.

This webinar series culminated in the “Monitoring Priorities in the Northeast Workshop” held in November 2023. The goal of this workshop was to identify and explore OCA monitoring priorities in the NECAN region (the northeast US and eastern Canadian Atlantic). By combining the information from the NECAN webinar series with monitoring recommendations produced by the NECAN Steering Committee for an earlier report to the IWG-OA, the NECAN Steering Committee and local OCA experts endorsed six Monitoring Needs for the NECAN region (Table 1).

A poll was circulated to the workshop participants to complete after the regional monitoring priorities were identified on the second day of the workshop. This poll asked the participants to rank each of the identified monitoring priorities across three categories: Importance to end users (Imp), Feasibility (Feas), and Cost. Importance to end users was defined as the direct usefulness of the information generated to decision makers, such as area based managers, fishermen, aquaculture operators, and coastal communities, with more useful information for groups receiving a higher rank. The feasibility category focused on the availability of resources needed to realize the monitoring priority, such as personnel availability, access to technology, existence of technology, data processing ability, and timelines, with easier tasks receiving a higher rank. The cost category took into account the monetary value of the need including cost of equipment, personnel time, and operations and maintenance, with lower cost receiving a more favorable rank. The workshop participants then ranked each Monitoring Need, with a rank of 1 indicating the most favorable score (most important, most feasible, and lowest cost) and a rank of 6 indicating the least favorable score (least important, least feasible, highest cost). Once each monitoring priority had been ranked in each category, the totals were added up and averaged to give a ranking relative to all of the other identified monitoring priorities (Table 2, Figure 3). In this way the workshop participants developed a consensus that balanced the importance, feasibility and cost of each identified monitoring priority. Ideally each need identified will be realized, as they are all extremely important to the understanding of OCA in the NECAN region; however, this ranking is intended to provide a rough map of priorities which should be targeted first. For more information please see the NECAN Monitoring Priorities in the Northeast Workshop Report (available on the NECAN Website).

Monitoring priorities for the NECAN Region

Below is a summary of the outcomes of this ranking exercise (Table 1). A workshop report was produced by the NECAN Steering Committee and is available on the NECAN website.

Table 1. This table expresses the relative priority ranking of the identified monitoring needs as ranked by the participants of the NECAN Monitoring Priorities in the Northeast Workshop. They are ranked in 3 categories: Importance of the activity to end users of the data (Imp), Feasibility of the monitoring based on personnel, and technology (Feas), and total monetary cost of the activity (Cost). These relative rankings for each category were then averaged to give an overall average ranking of the Monitoring Priority (Avg). For all rankings a lower score is equivalent to a higher priority and therefore a higher ranking.

Monitoring need	**Imp**	**Feas**	**Cost**	**Avg**
Improve spatial and temporal scale of monitoring co-located OCA variables and biological measurements to better resolve variability of acidification dynamics in concert with biological processes	1st	1st	2nd	2
Increase subsurface monitoring to understand how conditions vary at depth	2nd	1st	2nd	2.7
Increase the number of high-frequency monitoring assets that measure at least two of four carbon parameters	3rd	3rd	1st	3.1
Increase near-real-time and rapid response observing capacity to capture episodic events	4th	5th	5th	3.9
Increase spatial coverage of "climate"-quality observations	6th	4th	4th	3.9
Determine fluxes and rates that would help parameterize and constrain regional modeling efforts to understand past conditions and project future trends	5th	6th	6th	4.7

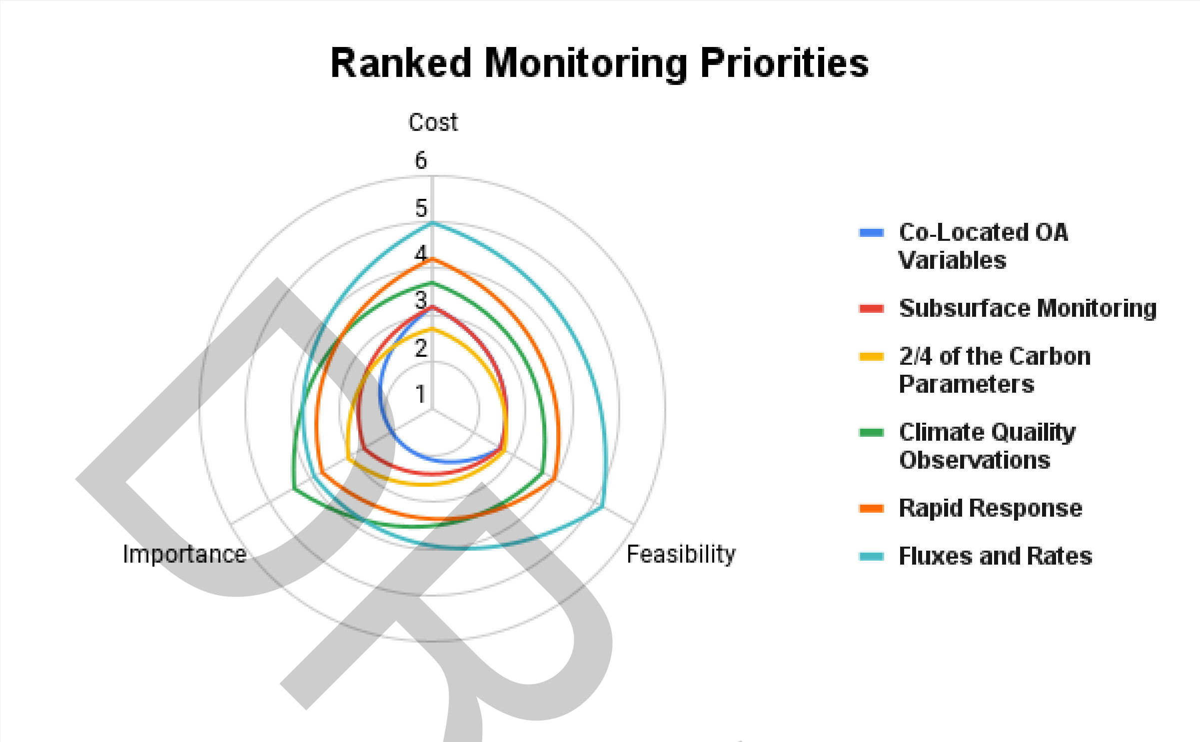

Figure 3. This radar plot shows the average ranking of each identified Monitoring Need in three categories: (1) Importance of the activity to end users of the data (Imp) (2) Feasibility of the monitoring based on personnel and technology (Feas), and (3) Total monetary cost of the activity (Cost). The smaller the shape area the better the score.

Preserving existing OCA monitoring capacity

For nearly two decades NOAA has engaged in high-quality carbon monitoring throughout the NECAN region, most notably with the deployment of the Coastal Western Gulf of Maine Mooring (Buoy D) in 2006 followed by the first Gulf of Mexico and East Coast Carbon Cruise (GOMECC-1) in August of 2007 and the expanded East Coast Ocean Acidification (ECOA) cruises beginning in 2015. Since the establishment and continuation of these sentinel monitoring efforts, there has been a considerable expansion in the number of carbon observations collected on a routine, sustained basis. Over the years these observations have grown in complexity and involve increasing federal and state level interagency partnerships. It is important to understand that the gaps identified in the later sections of this report assume preservation and recapitalization of existing observing efforts (e.g. timeseries observations at Buoy D, ECOA cruises throughout the region, and others described below). These observations serve as a critical backbone towards resolving regional changes in ocean acidification and impacts. The following OCA monitoring programs represent the foundation of the NECAN regional OCA monitoring network, offer important contributions towards each of the monitoring needs identified in Table 1, but are alone presently insufficient to meet the needs called for by the user community.

NOAA Ocean Acidification Observing Network (NOA-ON) - The NOA-ON represents a national ocean acidification observing network composed of 15 coastal moorings that serve as nodes within the wider network of sustained OCA observing assets. The Gulf of Maine node (43.02ºN, 70.54ºW) represents the longest continuous mooring in this network providing surface observations every three hours for nearly two decades. NOA-ON moorings are a NOAA Pacific Marine Environmental Laboratory (PMEL) Carbon Group project, sponsored through the NOAA Ocean Acidification Program in partnership with Integrated Ocean Observing System (IOOS). Each node in this network provides data appropriate for full constraint of the surface carbonate system at high-temporal frequency, while meeting GOA-ON “climate”-quality standards (see Monitoring Need D). Data quality are verified by calibration with reference gasses and quarterly discrete validation sampling.

Coastal Large Marine Ecosystem Ocean Acidification Surveys - NOAA’s Ocean Acidification Program supports coastal and ocean acidification research cruises along the U.S.’s major coastlines. These essential cruises supply coastwide “climate”-quality information on ocean conditions. Beginning in 2018 cruises collect and connect biology and ecology to the biogeochemistry of these marine ecosystems. The information from these research cruises, which generally occur on a 4-year cycle for each coastline, help us track long-term ocean change and evaluate our monitoring network of buoys, gliders, and other tools. They serve as an anchor for research in the region not only by collecting these data, but by bringing together ocean acidification researchers from across the region and beyond. Within the NECAN region these are termed the East Coast Ocean Acidification (ECOA) cruises with the next anticipated to be executed in 2026.

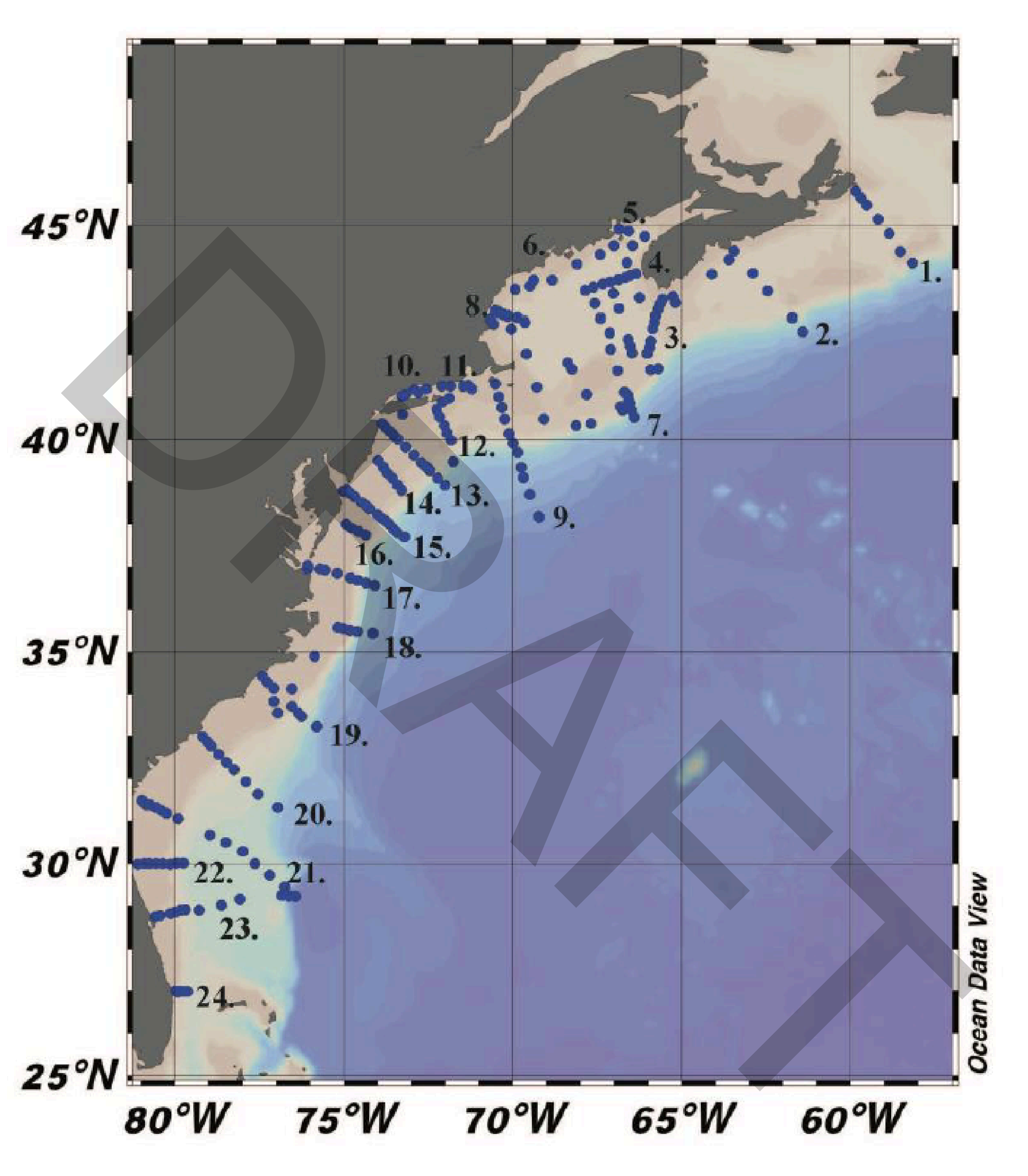

Figure 4. Sampling station map from the 2022 East Coast Ocean Acidification cruise report. Numbers identify transects in order of occupation, from north to south.

ECOA-3 (2022, Figure 4) was the third iteration of the East Coast Ocean Acidification Cruise and marked 15 years since the first NOAA coastwide sampling of the region. The cruise provided high quality data for monitoring the carbon system along the U.S. East Coast and covered fishing grounds for the nation's most valuable fisheries and outlined this information in a cruise report available on the NOAA ECOA website. This cruise not only monitored ocean chemistry, but also documented co-occurring marine biological and chemical processes improving our ability to model and forecast ocean change. The information gleaned from these cruises help us track long-term ocean change and evaluate data from our monitoring network of buoys, gliders, and other tools. The cruise was led by scientists from the University of New Hampshire and the University of Delaware, with participation from the University of Connecticut, University of Miami, North Carolina State University, Lamont-Doherty Earth Observatory, NOAA and others.

Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) - The international GO-SHIP surveys provide approximately decadal evaluations of the changes in ocean basin heat, freshwater, carbon, oxygen, nutrients and transient tracers. These surveys cover the major ocean basins from coast to coast and surface to bottom, with measurements of the highest required accuracy to detect these changes. The GO-SHIP principal scientific objectives are: (1) understanding and documenting the large-scale ocean water property distributions, their changes, and drivers of those changes, and (2) addressing questions of how a future ocean will increase in dissolved inorganic carbon, become more acidified and more stratified, and experience changes in circulation and ventilation processes due to global warming and altered water cycle. Several Atlantic reference sections (A22, A20, A02, AR07W, Davis) are of direct relevance to the NECAN region and provide important end-member characterizations needed to inform regional biogeochemical models.

Ship of Opportunity CO_2 (SOOP-CO_2) consortium - NOAA Atlantic Oceanographic and Meteorological Laboratory's (AOML) Ocean Carbon Cycle group leads the largest Ship of Opportunity CO_2 (SOOP-CO_2) consortium in the world. Currently there are 11 ships outfitted with automated instruments taking surface water measurements, several of which regularly transect through the NECAN region on approximately seasonal frequency. The data from SOOP ships provide critical information necessary for not only documenting surface OCA conditions across a broad spatial domain at relatively high frequency, but also make a significant contribution towards reducing uncertainty of global carbon budget assessments that inform national and international policy considerations.

Other OCA observing efforts are underway in the NECAN region as well. Discrete sampling and spatial pCO_2 data are collected during the seasonal NOAA Ecosystem Monitoring (ECOMON) cruises, while the local Long Island Sound Study (LISS, operated by a consortium of New York and Connecticut organizations) and a coastal cross-shelf Gulf of Maine transect operated by the University of New Hampshire are conducted seasonally. The National Estuarine Research Reserves located within the NECAN region (i.e. Wells ME, Great Bay NH, Waquoit Bay MA, Narragansett Bay, and Connecticut NERRs) have decades of experience in collecting time-series data, including OCA-relevant parameters such as pH, and are increasingly including expanded OCA parameters as part of their monitoring programs. Additionally, National Estuaries

Programs (i.e. Casco Bay Estuary Partnership) and Long-Term Ecosystem Research sites (i.e. Plum Island LTER) are increasingly adding OCA parameters to their monitoring and research efforts.

Monitoring Need A: Improve spatial and temporal scale of monitoring co-located OCA variables and biological measurements to better resolve variability of acidification dynamics in concert with biological processes

In prioritizing NECAN regional Monitoring Needs, the necessity of more closely coupled OCA and biological monitoring rose to the forefront. This urgency reflects the reality that climate shifts and OCA are affecting biogeochemical conditions in the region. Changes in conditions can potentially lead to poorly understood effects on ecosystems and individual species, including species of key ecological and fisheries significance. Development of this report led to the identification of several opportunities to increase the integrated biological and OCA monitoring capacity: incorporating OCA monitoring into fisheries management processes, leveraging areas with significant monitoring investment, focusing on biologically relevant stress thresholds and parameters, and utilizing diverse monitoring platforms and new technology.

Integrating OCA monitoring with fisheries management (i.e. New England Fishery Management Council, the Mid-Atlantic Fishery Management Council, state fishery programs) can ensure that the collected data is directly applicable to important biological resources and increases the opportunities to acquire long-term collaborative datasets. The design of fisheries surveys leverages modeling, long term study, and episodic comprehensive ecosystem reviews incorporating environmental and fishing pressure factors and in consideration of life history stages across species and trophic relationships. Those conducting fisheries surveys already have interest in developing OCA monitoring strategies. For example, the Mid-Atlantic Fishery Management Council (MAFMC) has set a precedent by incorporating OCA indicators into their ecosystem approach to fishery management. The MAFMC considers OCA sensitivity thresholds for key species such as sea scallops and longfin squid, demonstrating how OCA data can be directly applied to fisheries management decisions. Similarly, NOAA's Northeast Fisheries Science Center's bottom trawl surveys and Cooperative Tagging Program offer excellent opportunities to combine OCA monitoring with assessments of fish populations and distributions, providing a comprehensive view of ecosystem health. Initial focus of OCA work in these contexts should focus on direct impacts to commercial species across stages of life-history (i.e. surf clams, scallops, lobster and cod), species with critical importance to ocean food webs (i.e. sand lance and phytoplankton population dynamics), and endangered species. Other opportunities to enhance fisheries surveys with OCA monitoring capacity include NOAA Ecosystem surveys, the Marine Recreational Information Program, state-specific fisheries surveys, independent fisheries surveys (i.e. university and research institution efforts), Northeast

Ecosystem surveys, the cooperative Maine-New Hampshire Trawl Survey, and the Lobster Settlement Survey.

Another effective strategy is the establishment or enhancement of sentinel sites. These dedicated locations for comprehensive monitoring of both OCA and biological parameters can yield invaluable long-term datasets. For instance, the Stellwagen Bank National Marine Sanctuary is a sentinel site which has proposed creating a climate sentinel mooring. This mooring would monitor ecosystem dynamics, including OCA parameters, alongside ongoing biological surveys of sand lance, seabirds, and marine mammals. Such an approach allows for a holistic understanding of how OCA impacts various trophic levels within the ecosystem.

Enhancing the capacity for comprehensive co-located biological and OCA monitoring in locations with existing monitoring infrastructure is an efficient strategy to identify targeted and cost-effective methodologies for expanding ecological impact research in less studied areas. In locations where OCA monitoring is robust, research should expand to impacts on organisms, with particular focus on commercial, endangered, and keystone food web species. In locations of survey transects where biological sampling is robust, NECAN partners can work to provide accompanying OCA instrumentation for in situ measurement and facilitate specimen collection for laboratory study on topics including organismal stress, fecundity, and genetic plasticity across ocean climatological predictions. There are some examples of sub-regions that are thoroughly studied through collaborative efforts involving multiple partner institutions and state agencies. The Long Island Sound Study, which aims to develop a long-term coastal acidification monitoring program alongside existing biological (plankton)monitoring, is one such example. Another is the multi-institutional water quality and biological monitoring initiative in Casco Bay, Maine. There are also locations that benefit from intensive research investment by specific institutions with coastal laboratories. The National Estuary Programs (NEPs) and National Estuarine Research Reserve System (NERRS), for example, exemplify how existing monitoring efforts can be leveraged for comprehensive OCA studies. The EPA has established a network of 30 coastal sites that already conduct extensive biological monitoring. These programs have expanded their data collection to include OCA parameters such as pH, total alkalinity, and dissolved inorganic carbon. A comprehensive report, "Measuring Coastal Acidification Using In Situ Sensors in the National Estuary Program," provides valuable insights into each NEP's objectives, sensor deployments, findings, and data management strategies, and can serve as a good reference for planning new estuarine monitoring initiatives. Many other examples exist across the NECAN region. In Maine, for instance, the Damariscotta River is closely monitored by the Darling Marine Center, while areas adjacent to Bigelow Laboratories receive similar attention. While these programs are examples of existing co-located biological and OCA monitoring, there are numerous efforts in the NECAN region which are primarily focused on biological (e.g. Stellwagen Bank National Marine Sanctuary) or OCA monitoring (e.g. ECOA cruises), and which could benefit from the synergistic monitoring of both types.

When co-locating OCA and biological monitoring, it's crucial to focus on parameters and thresholds that have direct biological relevance for managed species and ecosystem processes. An example of a biologically-relevant parameter is calcium carbonate saturation state (Ω), which is crucial for calcifying organisms. While monitoring programs increasingly calculate Ω to inform management decisions, research indicates that many species can tolerate episodic low saturation states. This suggests that studies and monitoring should focus on the long-term chronic stress of exposure to low Ω conditions over time, particularly during key life stages, while also considering food availability. Effectively co-locating biological and OCA monitoring will require attention to survival and fecundity of species in relation to species-specific synthesis of OCA conditions over time. This approach has critical implications for metadata collection and data synthesis. For instance, mean daily values for OCA parameters or averages of Ω may be less informative than data on daily extremes and the total duration of stressful versus tolerable conditions across organisms. These data are not necessarily collected by programs focused on ocean climatology which often identify mean daily values for climatological assessment.

To expand the development of diverse monitoring platforms for OCA and biological observations, consideration should be given to gliders, other emerging platform technologies, ships of opportunity, and new fixed stations. The integration of pH sensors into gliders by Rutgers University and the University of Delaware represents a significant advancement in OCA monitoring. These autonomous underwater vehicles offer high-resolution depth data alongside biologically-relevant observations, providing a comprehensive view of water column dynamics. Glider paths can be coupled with existing fisheries transect surveys and deployed in concert with trawls or fishing activity. There is also potential to explore and develop new monitoring platform technologies. For instance, autonomous surface vehicles like Saildrones could be equipped with OCA sensors to cover vast ocean surface areas. Programs like eMOLT that deploy oceanographic sensors on fishing equipment could be expanded with OCA monitoring and real-time biological data collection. This approach leverages existing maritime traffic to gather widespread data. To enhance this platform, efforts could be made to develop more robust and user-friendly sensor systems suitable for non-scientific crew operation, standardize data collection protocols across different vessels, and create a centralized data repository for rapid analysis and dissemination of findings. The EPA Surface Water Monitoring Program (SWMP) demonstrates how existing monitoring efforts that collect biological data can be augmented with OCA parameters. To further develop this platform, NECAN Partners could focus on increasing the spatial coverage of OCA instrumentation, particularly in areas identified as OCA hotspots or of high biological significance. Additionally, efforts could be made to improve the temporal resolution of measurements and to integrate advanced sensor technologies that can withstand long-term deployment in harsh marine and estuarine environments.

A crucial aspect of developing these diverse platforms is improving unified data management systems. This would involve improving meta-data for comparability across data formats, developing quality control protocols, and creating user-friendly interfaces for data access and analysis. Such systems facilitate the integration of data from various sources, enabling a more comprehensive understanding of OCA impacts on marine ecosystems.

Monitoring Action: Current biological monitoring programs (e.g. fisheries surveys) can work with NECAN partners to add complementary OCA monitoring; conversely, OCA efforts (the ECOA cruises, for example) can incorporate relevant biological measurements. Data collection should incorporate seasonality most important for specific life stages, annual shifts in phenology, and timed phenomena such as coccolithophorid and diatom blooms which affect both food availability and carbonate cycling in marine systems.

Monitoring Need B: Increase subsurface monitoring to understand how conditions vary at depth

Two large and understudied areas of the NECAN region which are particularly susceptible to ocean acidification (and hypoxia) are shelf waters deeper than 50 m and bottom waters impacted by benthic exchanges (Siedlecki et al. 2021). Deep water OCA conditions are affected by processes which can be different from those at the surface or in well-mixed water masses. Organic matter produced at or near the surface is exported to depths, where it can be respired aerobically or anaerobically (Wang et al. 2017). Vertical fluxes of water and chemical constituents to and from sediments may carry different chemical properties than the rest of the overlying water, while conditions within the sediments themselves may be dramatically different from those of the overlying water (Cai et al. 2011, Mucci et al. 2011, Brenner et al. 2011). For instance, the pH of porewaters (the water contained within bottom sediments) can be as much as 0.5 units more acidic than the overlying water. The biogeochemical characteristics of deep basins in the Gulf of Maine (Jordan, George's and Wilkinson Basins) are affected by changing relative amounts of inflow water from several water masses, including Scotian Shelf, Labrador Current and North American Intermediate and Slope water (Townsend 2006, Townsend et al. 2015), as well as variations in biogeochemical processes regionally and with depth (Wang et al. 2013, Li et al. 2024).

Bottom water masses in shallower, seasonally stratified areas less than 50 m deep are also understudied in the NECAN region, particularly when considering that they are critical in sustaining coastal habitats, such as eelgrass and shellfish beds, and might also be impacted by upwelling of deeper acidified waters or by local processes that exacerbate OCA effects (i.e. Beal and Otto 2019). For instance, some of these areas are prone to warmer waters and low dissolved oxygen, including Long Island Sound, and Massachusetts Bay, both areas sustaining a shellfish industry (e.g. Tomasetti et al. 2021; Casey et al. 2022). Data from the 30-year water quality monitoring program in Massachusetts Bay conducted by the Massachusetts Water Resource Authority shows a characteristic decline in dissolved oxygen in late summer and early fall (Libby et al 2020), which never reached hypoxia levels until as recent as 2017 (Scully et al. 2022). In this case, changes in wind patterns have been a key contributing factor (in addition to warming bottom waters), which has also been linked to recent changes in water biogeochemical conditions within the upper 200 m in other geographic regions (Burgers et al 2024). The relative contribution of fluxes of shallow and deeper waters, and of more local conditions, such as extended stratification events and organic matter imports, remain largely unknown for the resulting OCA conditions in bottom shallow waters in the NECAN region.

In shallow areas, critical species spend a portion of their life cycle or seek refuge from predators in bottom waters (e.g. lobster, flounder) or within the sediment itself (e.g. sand lance). These bottom areas may have very different OCA and oxygen conditions than the overlying water column. In the NECAN region, the few studies which characterized the sediment conditions at the sediment-water interface suggest that oxygen and dissolved inorganic carbon fluxes are primarily coupled to primary production, that they decrease with depth, and that DIC release from sediments tends to exceed O_2 consumption (e.g. Hopkinson et al. 2001; Tucker et al. 2014). Enhancing the NECAN network's monitoring of bottom water (and more challenging, porewater) with measurements of pH, pCO_2, dissolved oxygen, TA or DIC will help to constrain the assessment of regional changes in these important parameters.

Monitoring Action: Deploy bottom-water sensors (pH, pCO_2) in deeper basins of the NECAN region, or in seasonally stratified shallower waters of interest. Alternatively, implement discrete sampling and lab analysis of bottom water OCA conditions (TA, DIC, pH).

There are numerous examples of programs in the NECAN region sampling subsurface OCA conditions, however, the vast majority of sites are sampled during seasonal cruises (i.e. NOAA-NMFS ECOMON cruises, UNH Wilkinson Basin cruises, or are comprehensive regional surveys conducted on a 3-4 year timescale (i.e. NOAA ECOA cruise). The infrequent collection of subsurface OCA data may lead to masking of seasonal or longer-term trends (Wang et al. 2017, Siedlecki et al. 2021), and is at least in part due to logistical and instrumental challenges in monitoring these areas. Underwater sensors are only commercially available for a limited suite of OCA parameters (pH and pCO_2), and near-bottom sensor deployments as part of buoy systems are especially challenging. To avoid equipment damage, discrete samples taken on cruises are also often collected 5m or more above the benthos, which may not completely capture conditions at the sediment-water interface where many organisms live (see Monitoring Need A which discusses the need for co-located biological and OCA monitoring). Gliders, ARGO floats and uncrewed surface vessels represent new autonomous platforms which can sample on a more frequent basis throughout the water column and over a wide spatial extent, but also are limited by available sensor technology and must still remain above the benthos by several meters at best, and may not be deployable in shallower shelf and coastal waters. The development and deployment of autonomous profiling systems (i.e. Zheng et al. 2023), benthic "lander" systems which can be placed on the bottom by a ship to collect sensor readings and water samples, or the placement of long-term platforms for bottom-water data collection, could greatly expand the data available from this area. Further, the development of an autonomous flux chamber or subsurface sampler would mark a valuable technological advancement. Addressing this Monitoring Need may require investment in new technologies, partnering with other groups placing equipment in bottom waters (e.g. acoustic monitoring programs), or the emergence of new commercial sensor technologies.

Closer to shore, there are several examples of groups monitoring OCA variables , which have systems already collecting data at or very near the benthos (i.e. the eMolt program, Friends of Casco Bay). The Massachusetts Water Resource Authority has conducted comprehensive water quality (including OCA) and biological monitoring for over 30 years in Massachusetts Bay, a region with seasonal stratification, which includes coastal, and offshore habitats in the Stellwagen Bank National Marine Sanctuary. The instrumentation used by some of these programs often does not meet “climate”-quality criteria (refer to Monitoring Need E), but when collected using best practices these data might be highly valuable for detecting relatively large changes and might serve to identify sites or times deserving more detailed, specific studies. Support for coordination among these groups should lead to greater data consistency and possible expansion of monitoring activities.

One example from beyond the NECAN region is the Bedford Basin Monitoring Program in Nova Scotia, Canada, which has successfully integrated carbonate system parameters into its existing time series. The program conducts weekly measurements, including CTD casts and bottle sampling for nutrients in both surface and near-bottom waters. In 2019, they expanded their efforts to include regular measurements of pH, TA, and DIC. This comprehensive approach allows researchers to track changes in water column chemistry while also considering the influence of benthic processes on overall ecosystem health.

OCA monitoring in the NECAN region can benefit from expanded subsurface and near-bottom sampling and measurements at a number of locations as discussed below. There are resources available to inform the choice of potential monitoring sites. For example, the Northeast Ocean Data portal provides spatial information on seafloor sediments, benthic habitat, and existing observing assets. However, ongoing effort is needed to complete data holdings and expand this tool to offer a comprehensive inventory of regional OCA efforts and available data.

Some sites may be already identified as candidates for expanded subsurface monitoring. For example, the Northeast Channel is a key area of deep water inflow to the NECAN region, while NERACOOS Buoy A01 provides critical boundary conditions for the Massachusetts Bay region, and Buoy M0133 provides monitoring of the same conditions far from coastal influences and down to 250m. Cape Cod and nearby islands, as well as Downeast Maine, are important shellfish areas. Stellwagen Bank, which includes a National Marine Sanctuary, is an important habitat area for several fishery species (Suca et al. 2022) and protected species (Silva et al. 2020) with demonstrated sensitivity to ocean acidification (Baumann et al. 2022). George’s Bank represents an enormous habitat area for acidification-vulnerable benthic species such as the Atlantic sea scallop (Cameron et al. 2022) and the Atlantic surf clam (Pousse et al. 2020). The list of sites above is not exhaustive or intended to be prescriptive, but merely a collection of examples where enhanced subsurface monitoring could add to the understanding of ocean acidification and its effects on species and ecosystems within the NECAN region.

Monitoring Action: *Opportunistically expand OCA monitoring of bottom or near-bottom waters in deeper shelf waters (e.g. buoy M0133) or shallower areas (e.g. the eMolt program). Invest in new technologies to allow access to bottom water measurements (e.g. bottom water profiling lander or bottom-deployed sensor array).*

Monitoring Need C: Increase the number of high-frequency monitoring assets that measure at least two of four carbon parameters

Understanding acidification in the coastal waters of the Northeast US and Eastern Canada can be improved upon by expanding the number of assets that are able to concurrently monitor multiple carbonate system parameters at high-frequency (hourly to daily). The four major measurable carbonate system parameters are dissolved inorganic carbon (DIC), total alkalinity (TA), the partial pressure of carbon dioxide gas in seawater (pCO_2) and pH. Investigators can tailor monitoring efforts towards achieving high quality measurements (see Monitoring Need E for the criteria for "climate"-quality data) and equipment for at least two parameters. In order to calculate out the remainder of the carbonate system, high quality measurements of temperature (T), salinity (S) and pressure (P) are also needed for the equilibrium constants utilized in carbonate system calculations. Detailed descriptions of these constants, and their appropriate usage have been developed (Millero 2010, Riebesell et al. 2010). Analysts can then use their chosen carbon parameter pair along with T, S, and P to calculate out other parameters of interest including the aragonite saturation state.

Dissolved inorganic carbon (DIC), is the sum of the inorganic carbon species that are dissolved in a solution. The majority of DIC in seawater exists as bicarbonate and carbonate ions. At the surface, open-ocean equilibrium conditions, the DIC pool consists of (~1%) carbon dioxide, (~10%) carbonate ion, and (~89%) bicarbonate ion.

Total alkalinity (TA) quantifies the ability of substances in seawater to react with the addition of a strong acid and convert it to an uncharged species. For this reason, it is sometimes informally referred to as "buffering" or "acid buffering capacity" of seawater. Alkalinity tends to be pseudo-conservative with salinity; generally, higher salinity waters (containing a greater concentration of salt and carbonate ions) will have higher alkalinity (Millero et al. 1998) and a greater ability to neutralize acidic inputs.

The partial pressure of carbon dioxide gas dissolved in water (pCO_2) is a measure of aqueous CO_2 concentration. While pCO_2 may only make up approximately 1% of the total DIC pool, it is biologically important as the pCO_2 concentration is directly affected by photosynthesis and respiration.

pH measures the concentration or activity of hydrogen ions in solution. The two main pH scales in use in coastal and oceanic studies are pH_{NBS} and pH_T. The NBS (or IUPAC) scale is optimized for glass membrane electrodes and uses NBS or similar buffers. This method measures the free hydrogen ion activity, but the low ionic strength buffers may not be suitable for non-freshwater systems (Dickson 1984). pH_T measures both the H^+ and HSO_4^- concentration, making it well suited to working in seawater. However, the instrumentation available to measure pH_T is both less available and more expensive.

Carbonate Parameter Pairings:

The decision of which pairings of carbon parameters to use is influenced by several factors including monitoring goals, desired frequency, biogeochemical characteristics of the site, or whether the monitoring is intended to be carried out via autonomous platforms or by user groups with access to lab facilities containing carbonate chemistry instrumentation.

DIC and TA: DIC and TA are large, stable pools and measurements of these parameters benefit from a number of factors. Importantly, collected samples for DIC and TA can be preserved and stored for analysis at a later date. For DIC and TA, certified reference materials with known DIC and TA concentrations are available (Certified Reference Materials Laboratory - Andrew Dickson). These two parameters are mostly suited for laboratory analysis although there are options emerging for in-situ and underway analysis. The ability to include these two variables in high-frequency determinations might be possible as technology evolves and commercial products become more widely available.

DIC and pCO_2 or DIC and pH: Pairing DIC and total pH can potentially be more easily validated (i.e. CRM availability, preservation allowing side by side bottle sampling lab analysis, ease of calibrating deployed instruments in tubs prior to deployment) compared to pairing DIC and pCO_2.

Alkalinity and pCO_2 or alkalinity and pH: The pairing of total alkalinity and either pCO_2 or pH is a measurement that can be carried out in the field via deployed instruments or in a lab setting. Carbonate chemistry CRM's exist for both TA and pH_T allowing for easier potential validation.

pCO_2 and pH is by far the most common carbonate system pairing used in deployed instrumentation (shipboard, moored buoys, fixed pier deployments). pCO_2 and pH sensors have been deployed at a number of locations and in different configurations using a variety of manufacturers instruments, although fouling and instrument drift can pose challenges. The pCO_2 pool is labile and is almost always analyzed in the field via deployed or in-situ sensors as pCO_2 samples are not routinely preserved. Carbonate chemistry CRMs are not available for pCO_2, so most researchers use pre-mixed gasses at known concentrations for instrument calibration and validation. pH (pH_T and pH_{NBS}) is most often measured in the field, but preservation of samples for lab analysis (Chou et al. 2016) is possible. TRIS buffers in seawater of known pH_T are available (Certified Reference Materials Laboratory - Andrew Dickson) for validation of pH_T measurements. If using glass electrodes, pH can be measured at the NBS scale or carefully calibrated to the total pH scale; both scales allow later carbonate system calculations (i.e. 2 of 4 parameter calculations to obtain omega). A benefit to the commercial availability of pCO_2 and pH instruments is that calibration can often be accomplished by sending the unit to the manufacturer on a scheduled basis.

In the next paragraphs we included the following options for increasing frequency capabilities in monitoring carbonate parameters: a) investment in existing monitoring programs or assets; b) use of TA-Salinity regional relationships to estimate total alkalinity when measuring already one other carbonate parameter; c) modeling; d) investment at existing facilities; and e) implementation of new sensing technologies.

Investment in Existing Monitoring Programs or Assets. There are various programs currently monitoring two or more carbonate parameters. Typically, these include cruises and other programs that collect discrete samples and measure underway parameters. These cruises might collect high-frequency data on the order of an hour or less, and run for a few months in a year, every year at the most (e.g. ECOA, EcoMon). High-frequency data in the order of a few hours or less, is attainable by in-situ sensors and underway samplings and analysis.

Monitoring Action: Increasing carbonate chemistry instrumentation on buoys is the most direct path to increase the number of high-frequency monitoring assets that measure at least two of four carbon parameters.

The specific assets of each program need to be further inventoried and updated to optimize for increased frequency of parameters, broad spatial distribution, and more cost-effective options. Examples of carbonate chemistry monitoring programs (see this 2020 map of monitoring assets), include:

Buoy/Fixed-Pier Based – Higher Frequency

- NOAA/NERACOOS Coastal Western Gulf of Maine Node: 43.02°N, 70.54°W, (pCO_2, pH) (Buoy D)
- Casco Bay National Estuary Program, (pCO_2, pH) (Rosenau et al. 2021).
- MASS Bays National Estuary Program collaboration with USGS starting in May 2025. Three continuous monitoring systems with pCO_2 and pH capability. (personal communication)

Ship Based – Lower Frequency

- NOAA ECOA Cruises (DIC, TA, pCO_2, pH)
- NOAA Ecosystem Monitoring (ECOMON) cruises (DIC, TA, pH, pCO_2)
- CODAP-NA cruises (TA, DIC, pH)
- EPA's ACESD Narragansett Bay Ecosystem Time Series program (TA, DIC, pH). Eight stations monthly from 2014 to present.

- Long Island Sound Study (pCO_2, pH, DIC, TA)

Use of TA-Salinity Regional Relationships. For sites currently monitoring one parameter (DIC, pCO_2, or pH), a regional seawater-alkalinity model would allow researchers to obtain 2 of 4 parameters by estimating TA from salinity. Various TA-Salinity relationships are available within the region (e.g. Rheuban et al. 2019, Hunt et al. 2021, Pimenta et al. 2023, Champenois et al. in review). Based on available sensors, high-frequency pCO_2 or pH can be paired with the salinity derived TA to obtain the two carbon parameters. Of the pH measurements, using pH_T is preferable because constants used in carbonate system calculations were developed for pH_T, though pH_T instrumentation tends to be more expensive. pH measurements on the NBS scale are prominent among coastal watershed organizations that monitor water quality, and if carefully performed, can serve as one of the parameters used for carbonate chemistry calculations.

Modeling. Increased frequency of carbonate parameters might be achieved by using modeling approaches that use relatively few in-situ measurements in predictions. For the NECAN region, there are already data-driven empirical models that render these estimates (Salisbury and Jönsson 2018, McGarry et al. 2021, Lima et al. 2023, Champenois et al. in review), which have been used to produce regional projections (Siedlecki et al. 2021) and historical reconstructions. These models are likely to get better and easier to implement with improved computing capacities, and the ability to use numerical simulations that capture the complexity of physical and biological processes involved.

Investment at Existing Facilities. Along the coast, there are several marine laboratories and facilities with flowing seawater that are collecting carbonate parameters, monitoring water quality or that have laboratory capacity that might be expanded to measure those parameters. Examples of sites already measuring carbonate parameters include the UNH Coastal Marine Lab and the Downeast Institute.

Monitoring Action: Augment existing facilities with carbonate instrumentation, such as the UMaine Darling Marine Center; the Marine Science Center of Northeastern University, and hatcheries along the coast. The investment in these facilities will be leveraged by resources in place and can directly benefit shellfish hatcheries and growers in the region, as it has been done along the US West Coast (Gouldman et al. 2011).

New Sensing Technologies: High-frequency monitoring is limited by sensing technology that is constantly improving and might guide future directions. In-situ high frequency sensors have been available for pCO_2 and pH for many years, primarily for surface deployments but also for limited deployments at depth. Current technology for TA allows its adaptation for underway determinations (Seelmann et al. 2019) or in-situ measurements (Sonnichsen et al. 2023, Spaulding et al. 2014). DIC autonomous sensors with high-frequency capabilities have also been described (Yan et al. 2020, Ringham et al. 2024, and Battacharya et al. 2024), though it should be noted, these are not systems currently available for purchase.

Monitoring Need D:Increase near real time and rapid response observing capacity to capture episodic events

Rapid Response networks are of growing importance within the NECAN region as the Gulf of Maine is one of the fastest changing coastal systems in the world. While warming temperatures are well-documented in the region and represent a longer-term change (Pershing et al 2021), other changes and events occur over shorter time scales and require a different response than long-term monitoring. One example of this comes from an unusual algal bloom that occurred in the Gulf of Maine in the summer of 2023. The population of a dinoflagellate common in low numbers in the Gulf of Maine (*Tripos muelleri*) exploded, resulting in a bloom which covered the majority of the region and could be seen from space. The presence of the bloom was first noted by researchers at the University of New Hampshire (UNH) who observed anomalously low pCO_2 levels near shore as part of their ongoing, near-real-time monitoring program. An ad-hoc email discussion began, which entrained biological and chemical oceanographers, remote sensing researchers, federal fisheries scientists, and regional regulatory agencies. The bloom event led to cooperative efforts to collect additional samples on cruises of opportunity, and a workshop was later convened to discuss the event. However, all of these responses were assembled informally and funded from researchers' discretionary funds.

As this area continues to change, it is important to have an array of monitoring resources available to deploy in a flexible manner. By their very nature episodic events such as the *Tripos* bloom are unpredictable, and therefore monitoring and studying these events and their effects is difficult to prepare. Flexibility is paramount, and will allow for rapid data collection if an anomalous event occurs, the faster this data can be collected the better understanding that we can have of these increasingly common anomalous events.

Currently, the largest hurdle facing the realization of a rapid response network is the lack of funding available for assets and capacity. One suggested solution to this problem is to coordinate across topic areas to create a supply of monitoring assets for rapid deployment that can monitor carbonate parameters among other oceanographic variables of interest.

By combining the interests of the OCA monitoring community with those of other fields of oceanographic monitoring (i.e. Harmful algal blooms), a "lending library" of monitoring assets could become available for rapid deployment by the wider community. Collaboration could also assist in developing co-located observations during rapid deployment events, further assisting Monitoring Need A.

Other scientific fields of ocean monitoring have started the process of creating a rapid response network already (i.e. harmful algal bloom rapid response). The OCA rapid response network could benefit from the lessons learned by these existing networks. An essential part of creating a rapid response network is the ability of the network to communicate quickly and effectively during a period of deployment. As part of this play book a common communication pathway should be identified for the region that can coordinate the deployment of monitoring assets from the lending library, any additional private assets, and identify ships of opportunity to include more sensors on. Due to the frequent "siloing" of different topic areas in the academic and monitoring communities the development of this single communication pathway would be crucial to properly coordinating multiple topic areas during a rapid response event. This pathway should meet certain criteria to ensure the Northeast observing community will be ready for rapid deployment:

- Accessibility to everyone in the monitoring community to ensure any early warning system
- Act as a public archive to show how efforts were coordinated in past events to further improve the ability of the network to deploy in any future events
- Create an area where monitoring information can be shared to individuals who monitor different oceanographic parameters
- Provide a platform which facilitates the conversations of experts in the monitoring community in the Northeastern US and the Maritime Provinces of Canada

An example of a similar communication pathway that has been successfully implemented in the past is the Ocean Acidification Information Exchange (OAIE). The OAIE was created in response to the Federal Ocean Acidification Research And Monitoring Act (FOARAM) of 2009, which mandated the establishment of an ocean acidification information exchange through which information related to the mitigation and/or adaptation to the impacts of OCA can be accessed by stakeholders through electronic means. The OAIE was established in 2018 and has grown to have 1700+ users first as a federally focused platform and now to facilitate the discussion of the global OCA observing community. When creating an observation communication pathway for the northeastern US, the OAIE could be used as a model community to assist with design and implementation.

Although the OAIE can be used as a model community, the proposed communication pathway would have specific differences that will make it a distinct platform. The communication pathway should have an audience with a wider array of expertise but restricted to the northeastern US. This differs from the more global and open audience of the OAIE.

Pairing a lending library of assets, a rapid response fund, and a streamlined communication pathway, will lead to a better understanding of anomalous events in the region that are tied to ocean acidification. This process can also help move the ocean observing community in the region to continue to break down topic area “silos” to give a more holistic understanding of ocean systems in the northeastern US.

<u>Monitoring Action:</u> *The NECAN region should develop a lending library of monitoring assets to be deployed, conduct regular scenario planning workshops and evaluations with the rapid response community, create a playbook of what steps need to be taken during an event that requires rapid monitoring, create a clear and effective communication pathway for when rapid response events occur, and evaluate how current permanent monitoring assets and remote sensing products can act as an early warning system to allow for the earlier deployment of rapid response assets.*

Monitoring Need E: Better spatial coverage of “climate”-quality observations

Coastal and shelf environments experience significant variations in carbonate chemistry, temperature, and salinity due to freshwater inputs, upwelling, and biological activity. These variations are typically stronger and less predictable than those observed in open ocean systems, where changes in carbonate chemistry are smaller and require very precise measurements. High-quality data allows for tracking of these fluctuations, helping to differentiate between natural variability and trends driven by increasing anthropogenic CO_2 concentrations. Long-term, high-quality ocean and climate observations provide the foundation for detecting changes caused by increasing anthropogenic atmospheric CO_2 over time. These data enable the quantification of decadal trends in ocean carbonate chemistry and help contextualize the progress of acidification in coastal and shelf regions (Jiang et al. 2021, Li et al. 2024a, b). These long term, high quality ocean and climate observations are challenging to maintain on long timescales due the specialization of the equipment used, as well as the infrastructure, ship and personnel required.

Long-term “climate”-quality data also provide tools for developing mitigation and adaptation strategies for policy makers, such as reducing nutrient runoff, protecting sensitive ecosystems, and evaluating potential marine Carbon Dioxide Removal (mCDR) efficacy. Policymakers, managers, and stakeholders rely on this information to make informed decisions about preserving marine resources, such as fisheries and aquaculture, which are directly affected by acidifying waters. “Climate”-quality data also represent a reliable, long-term standard that anchors weather quality measurements collected by different groups using a variety of methods. This “climate”-quality reference enhances the consistency, accuracy, and comparability of regional weather quality data collection.

The Global Ocean Acidification Observing Network has specified uncertainty ranges for the highest quality “climate quality” data for dissolved inorganic carbon, total alkalinity, pCO_2 and pH of ±2 μmol/kg, ±2 μmol/kg, ±0.5% (about ±2-3 μatm for typical pCO_2 values) and ±0.003 pH units, respectively (Newton et al. 2015). These uncertainty ranges require much higher precision than comparable “weather” quality measurements, which call for respective uncertainties of ±10 µmol/kg in TA and DIC, ±2.5% in pCO_2 (about ±6-10 µatm for typical values) and ±0.02 pH units. “Climate”-quality measurements of discrete samples for TA and DIC are achieved by a number of laboratories (i.e. Bockmon et al. 2015), while only a few in-situ sensors or autonomous systems achieve “climate”-quality measurements for pH (i.e. Sunburst SAMI-pH) or pCO_2 (i.e. NOAA PMEL MapCO2 system, General Oceanics underway pCO_2 system). Thus, while “climate”-quality data are achievable, the complexity and expense of measurements and equipment limits their availability.

In the NECAN region there are several current efforts centered on producing “climate”-quality data. The NOAA East Coast Ocean Acidification (ECOA) cruise surveys the region every 3-4 years during the summer, making “climate”-level measurements of all four carbonate parameters at numerous stations and depths. The NOAA Ecosystem Monitoring (EcoMon) cruises and Canadian DFO Atlantic Zone Monitoring Program (AZMP) each seasonally sample a limited number of stations in the region for “climate”-level TA and DIC, as well as “climate”-quality surface underway pCO_2. The sentinel “climate”-quality timeseries site in the NECAN region is a coastal mooring operated cooperatively by NOAA’s PMEL and the University of New Hampshire (Vandemark et al. 2011, Salisbury and Jonsson 2018, Sutton et al. 2016), which is co-located along a seasonally-sampled cross-shelf transect (Gledhill et al. 2015, Siedlecki et al. 2021). While a baseline of “climate”-quality data is already established, the NECAN region is hydrographically and biochemically diverse. Barring any unanticipated technological advances, the clearest route to expanding “climate”-quality monitoring in the region lies in wider adoption of existing technology and enhanced coordination.

Adding Moored Autonomous Partial Pressure of Carbon Dioxide (MAPCO2) “climate”-quality pCO_2 measurements to other existing mooring locations in the region is one technologically-ready approach to expand “climate”-quality monitoring. The locations for expanded MAPCO2 systems should be planned collaboratively by buoy operators, managers, researchers, and modelers to ensure that the data serves as many regional needs as possible, and ECOA, ECOMON and AZMP cruises could add sampling at new MAPCO2 locations for validation measurements.

Coastal and shelf acidification monitoring with “climate”-quality data should emphasize long-term time series that capture seasonal variability and decadal trends. Seasonal changes in river runoff, upwelling, and biological productivity can all affect acidification, so frequent and repeated sampling is essential to understand the full dynamics of coastal acidification. Additionally, the NECAN region experiences dramatic changes in source water inputs and decadal-scale oscillations in biogeochemical conditions imposed from outside the region, which demand long-term monitoring to resolve. However, it is difficult for one researcher or institution to sustain the collection and analysis of the needed data. By enhancing collaboration, coordination, and integration of data collected by different groups working in the region, we can collectively achieve better time series.

Applying the Distributed Biological Observatory (DBO) model used in the Arctic may offer valuable insights and structured approaches for monitoring and understanding regional acidification. The DBO model relies on a series of fixed transects and "hotspot" locations that are revisited by different groups to monitor biological and environmental changes. The DBO model emphasizes collaboration between different scientific disciplines and institutions, allowing for coordinated data collection, standardizing methods and reporting, and sharing. NECAN monitoring networks could similarly benefit from cross-disciplinary collaboration between oceanographers, biologists, policy experts and stakeholders. The DBO can be applied by cooperatively identifying critical locations including areas with significant anthropogenic influence, biological and oceanographic hotspots, or sites where long-term observations exist. Participants can add their own sampling efforts at these locations as part of their ongoing monitoring efforts, and contribute data to the collective distributed dataset, which will enable the detection of trends in pH, alkalinity, DIC, and carbonate chemistry over time and biological responses. Establishing open-access databases will allow for broader data sharing and integration across regions, making it easier to assess coastal acidification trends on larger scales.

Monitoring Action: Support and coordinate outreach and capacity-building needed to both assemble the operators in the region who can contribute to a DBO-type model, and to identify the specific sentinel sites or hotspots of focus. These activities could take the form of conferences, workshops, webinars, or OAIE discussion groups. Data from the Northeast Ocean Data Portal can be used to identify sites ideally suited to collaborative climate-quality monitoring. Once monitoring begins, NERACOOS is the regional entity best suited for hosting recent or real-time data, while NOAA's Ocean Carbon and Acidification Data System (OCADS) is a recognized and available repository for long-term data archival.

Monitoring Need F: Determine fluxes and rates that would help parameterize and constrain regional modeling efforts to understand past conditions and project future trends.

Modeling is necessary to translate OCA monitoring observations into knowledge. It can be used to characterize OCA trends, spatial and temporal variability, and impacts to ecosystems as well as to forecast and project conditions into the future (e.g. Siedlecki et al. 2021). Models can also help identify important regions for monitoring. Examples of uses of model products within the NECAN region have been documented elsewhere (Wright-Fairbanks et al. in review). Observations from monitoring efforts increase the capacity to project future conditions of OCA, or simulate historical conditions to understand past events. Observations are needed to constrain model boundary conditions, feed new data into assimilative models, and to develop parameterizations of important processes. The evaluation of model performance requires independent monitoring data, which is important not only to understand how the model is working, but also to develop trust with the stakeholders expected to act on model findings. Observations are also required to evaluate model performance to ensure simulated feedbacks are well constrained. These activities reduce structural uncertainty in the models that generate forecasts and projections so the uncertainty around the decision point can be focused. Models, in turn, can help monitoring programs by identifying critical locations where significant influence on the region or rapid change is expected and new observations are needed.

Forecasts have their own broad user groups, but most observing data needs to revolve around model initialization and evaluation (Alvarez et al. 2022) . There are few operational models providing short-term forecasts that include the carbonate systems. Examples in North America include operational systems in the Chesapeake Bay (Bever et al. 2021) and on the Washington State shelf (LiveOcean Homepage). Real-time access to observations is the only way to evaluate short-term forecasts in near-real time (on the order of days) and develop trust from the users in the forecast system, and these observations need to be high frequency (hourly to daily). Sub-seasonal to seasonal forecasts, as well as decadal forecasts, are also very useful for fisheries management, planning, permitting, and other ocean use decisions. These activities require data inputs at a less frequent rate to make short-term forecasts on the order of a few days. Such a model is in development for the east coast of North America, including the NECAN region (Ross et al. 2023). Climate projections require long-term, sustained, consistent observations to support evaluation of trends and spatial patterns and these observations can be less frequent (on the order of sub-seasonal to seasonal). These climate projections also require robust parameterizations with the lowest amount of structural uncertainty possible to best resolve the climate signals of OCA (Siedlecki et al. 2021, Lavoie et al. 2020).

Considering the limited amount of flux and rate measurements presently available in the NECAN region, many important biogeochemical processes are not well constrained or parameterized (some at any scale) and as such have been prioritized here. These include air-sea CO_2 fluxes, fluxes at the sediment-water interface, $CaCO_3$ cycling (especially non-conservative changes to $CaCO_3$ such as coccolithophore blooms), TA fluxes and observations (in particular at the land-ocean boundary), and net community production (NCP). Additional TA and DIC observations, together with better-constrained relationships between temperature, salinity and other proxies and TA or DIC is also identified as a priority as these relationships can be used to extend observational records in time and space but often require regional tuning (McGarry et al 2021, Lima et al. 2023). These relationships and observational strategies are currently more feasible in offshore and open ocean regions. In support of additional development and tuning of existing relationships, deployment of subsurface oxygen, nutrient, and $p\mathrm{CO_2}$ sensors is encouraged. The $p\mathrm{CO_2}$ sensors, while depth limited, can be effectively deployed in shallow shelf regions.

Certain areas within the NECAN region have been identified as high priority locations important to monitor (see Monitoring Needs A and B), and include the continued support of the ECOA cruise lines including the extension to benthic fluxes, regional net community production and gross respiration (NCP/GR) measurements, standardized assays, and continued augmentation of ECOMON cruises and long term observing sites such as Buoy D (Coastal Western Gulf of Maine Node: 43.02°N, 70.54°W) and the A1 mooring (Massachusetts Bay: Lat: 42.53 Lon: -70.56).

Monitoring Action: *Additional suggested sites for new, long term deployment of continuous sensors or regular sampling on the shelf in support of model and forecast efforts include Georges Bank, within the Nantucket lightship-shoals region, and the Northwest Channel. Some coastal embayments and estuarine regions of high priority to pair with long term observations include Long Island Sound, Casco Bay, the Plum Island Long Term Ecosystem Research Reserve, Wells National Estuarine Research Reserve, and the Damariscotta estuary region.*

Some gaps in observing technologies to invest in or develop to support modeling needs were identified. These gaps include high-frequency TA observations, NCP+GR assays and incubations, a better understanding on the role of organic matter contributions to TA and its impacts on pH and saturation state estimates. TA or DIC measurements (in combination with pH or pCO_2 sensors) to overconstrain the carbon system, particularly at the land-ocean interface, are important and attainable. Furthermore, pairing TA or DIC measurements with pH or pCO_2 data ensures internal consistency, offering better results compared to pairing pCO_2 and pH sensor data together. Also, mCDR pilot studies are already underway in the NECAN region focused on TA enhancement, lending additional urgency to expanded observations of this parameter. Standardized and refined NCP+GR measures and methods are needed in order to include these rate measurements in regional biogeochemical surveys. We acknowledge that some direct measurements, especially in subsurface waters, are an existing knowledge gap (see Monitoring Need B).

Conclusions

This report outlines six Monitoring Needs for the NECAN region and provides future steps and locations that will allow decision makers to take immediate action to improve the OCA monitoring system. Criteria for how recommended steps and locations were identified for each Monitoring Need are also outlined to provide guidance for future actions. OCA monitoring recommendations will most likely change as technology, infrastructure, and understanding of the needs of the NECAN region evolve. Through the NECAN regional network of experts, we synthesized existing knowledge, identified opportunities, and worked with end users and collaborators to prioritize eight overarching themes that cross-cut many of the Monitoring Needs that were identified in this plan, which we discuss below.

	A	B	C	D	E	F
A complete assessment of ocean acidification, its effects, and future trends requires expanded monitoring efforts beyond water column carbonate chemistry.	✓	✓		✓		✓
Enhance or leverage existing monitoring platforms for a cost-effective and collaborative approach to creating a more complete OA monitoring system in the NECAN region.	✓	✓	✓	✓	✓	✓
Expand the existing NECAN network to included, protected area experts, terrestrial biogeochemists and hydrologists, fisheries experts, social scientists, tribal liaisons, project leads from large assessments, and other important stakeholders, rights holders and decision makers	✓			✓		
Increase funding in the Northeast to both sustain current efforts and grow a more robust ocean acidification monitoring program as proposed here.	✓	✓	✓	✓	✓	✓
Technological and capacity limitations will make the implementation of some recommendations challenging, but pathways for more immediate implementation are identified to pursue while new technologies are developed.	✓		✓	✓		
Synthesize monitoring information to advance the collective understanding of OA in the Northeast.				✓		✓
Deploy monitoring assets strategically, with end-user needs in mind, ensuring that the collected data is accessible, relevant and useful for decision-making.	✓	✓	✓	✓	✓	✓
Share NECAN's experience in developing these recommendations with other regional CANs.	✓	✓	✓	✓	✓	✓

Table 2: The relationship between eight cross cutting themes (left column) and identified monitoring needs (top row). Check marks indicate a section of overlap between activities, (i.e. creating a monitoring asset that fills a gap identified in MN E would also work towards achieving cross cutting themes b), d), g), and h) but not a), c), e), or f).

a) Expand monitoring beyond water column to provide a complete assessment of OCA, its effects, and future trends requires expanded monitoring efforts beyond water column carbonate chemistry

To properly understand OCA at a regional and local-scale, knowledge of interactions with interrelated systems (i.e., ecological, chemical, physical, and social systems) is needed. It is paramount that information silos are broken down to ensure that this holistic understanding of the system is realized. Many organisms that are most susceptible to OCA are infaunal, quasi infaunal, or benthic. Our current poor understanding of the ocean chemistry at the sediment interface, in turn leads to a poor understanding of the impacts OCA will have on organisms that live there. This includes organisms that have significant economic and cultural value to the region, such as Quahog clams and sea scallops. Bringing together an assessment of trends below the water column will better prepare the region to understand how some of its most important and also most vulnerable species will be impacted under increasingly acidic conditions. Key actions needed are outreach, communication, and capacity building with biological monitoring programs and other programs conducting subsurface operations (for example, bottom-deployed acoustic platforms).

b) **Enhance or leverage existing monitoring platforms for a cost-effective and collaborative approach to creating a more complete OCA monitoring system in the NECAN region.**

When assessed across disciplines, the NECAN region has a well-developed set of monitoring platforms and programs. Evaluating ongoing monitoring efforts that do not currently measure any carbonate parameters can help realize cost savings and increased feasibility for developing new projects in the NECAN region such as bottom-water OCA monitoring. Utilizing the existing monitoring programs in the region (i.e. NERRs, NEPs, fishery surveys, see Monitoring Need A) would promote the collection of co-located data, moving the NECAN region one step closer to the goal of understanding the impacts of OCA on important species, ocean chemistry, and the region's ocean economy.

By measuring parameters across disciplines, especially measuring parameters not typically measured together, could lead to not only unforseen scientific discovery, but also an enhanced sharing of resources that could lead to forging connections between monitoring personnel and programs in the region. This familiarity will allow for a more smooth and effective response to any anomalous event which would require a rapid monitoring response. Additionally it may allow these personnel or monitoring programs to pool resources, allowing for more monitoring for a multitude of oceanographic and biological parameters.

c) **Expand the existing NECAN network to included protected area experts, terrestrial biogeochemists and hydrologists, fisheries experts, social scientists, tribal liaisons, project leads from large assessments, and other important stakeholders, rights holders and decision makers**

To properly understand a biogeochemical system and its potential impacts on ecosystems and human culture an understanding must be developed that includes human activities as part of the system. Upstream human activity, such as wastewater treatment and agriculture can have cascading impacts throughout coastal systems, especially due to contaminants carried by freshwater inputs. Without including human dynamics in the system, freshwater inputs, for example, make coastal systems incredibly dynamic and difficult to understand without a deep understanding of processes at a local scale. Adding human activity into the system greatly increases the complexity at the local scale. By better understanding upstream and terrestrial inputs to the coastal systems of the NECAN region we will be able to better understand future OCA conditions of the region.

Although this plan focuses on the importance of monitoring OCA, its impacts are often invisible and only become apparent when other stressors such as invasive species, water temperature fluctuation, or hypoxia events are introduced to the system. Due to many of these stressors coming from, or having drivers generated from, terrestrial or freshwater environments (such as wastewater treatment practices supporting a coastal algal bloom), it is critical to understand coastal systems in a more holistic manner when thinking about OCA.

d) Increase funding in the Northeast to both sustain current efforts and grow a more robust ocean acidification monitoring program.

Current observation efforts must be preserved before attempting to expand the NECAN regional observation network. Diverting resources from current and long-term observations would undermine the ability to generate a baseline for the carbonate system, resulting in poor understanding of any extreme events that occur as well as future trends. It is of paramount importance that the current funding level for these efforts is maintained, before considering addressing the other Monitoring Needs that are outlined in this plan. This plan recognizes that increasing funding for monitoring can be a lengthy process.Through the ranking activity at the Monitoring Priorities in the Northeast Workshop this plan describes pressing needs, as well as areas for immediate action that should be addressed in the NECAN region. Cost-effective immediate actions can be found under the Monitoring Needs that scored best in the Cost category (Table 1).

e) Pursue immediate implementation of proxy approaches or interim strategies for measurements with technological or capacity limitations, while new technologies are being developed

Commercial OCA monitoring technology is not available for all carbonate system parameters (see Monitoring Need C), or for all platforms or environments (see Monitoring Needs B, C, and F). Similarly, laboratory capacity in the NECAN region for analyzing OCA samples, especially to a “climate”-quality level, is limited. However, opportunities do exist to expand OCA observations in the region using present technology while equipment improvements are developed (see Monitoring Needs A and F for example). Support to provide analytical laboratory capacity to monitoring groups in the region will also enhance OCA understanding in the region. Technological advances are also on the horizon (such as in-situ TA and DIC instruments), which should be integrated into the monitoring network when available.

f) Synthesize monitoring information to advance the collective understanding of OCA in the NECAN region.

Monitoring is a vital first step, but synthesis of monitoring information is critical to advance the understanding of OCA trends and impacts in the region. Synthesis reports play an important role in directing decision makers, ocean users, and rights holders to actions they can take to react to OCA. Raw data and data products are not always impactful or useful to those who need to react to changing ocean conditions. Synthesis products and information needed for the region include a regional inventory of monitoring programs and laboratories, a region-wide dataset of OCA and related parameters (see for example the CODAP-NA product, Jiang et al. 2021), and short- and long-term model forecasts of OCA conditions. These synthesis products will in turn inform the placement and design of new monitoring activities in the region.

g) **Deploy monitoring assets strategically, with end-user needs in mind, ensuring that the collected data is accessible, relevant and useful for decision-making.**

It is important to be as intentional when developing a monitoring network. This is especially pertinent when deploying an asset that could produce a long-term data set, as these data will use valuable financial, technical, and personnel-related resources in the region. The inclusion of social scientists into the decision-making process can ensure the data collected is of the most use to the communities, stakeholders, and rights holders in the region.

The ranking of the Monitoring Needs in this plan came about as a result of non-social scientists deciding on the feasibility, cost, and importance of the data collected to user groups. In this ranking all three of these categories were ranked equally to generate an average score relative to the other proposed activities. All of the identified Monitoring Needs are important, which is why they are only ranked relative to one another. When thinking about implementation of this plan it is important to take into consideration the local needs as well as the regional needs for OCA monitoring. Broader outreach and coordination between stakeholders (such as coastal communities, fishermen, resource managers, ect.) and non-social scientists/monitoring operators could be facilitated through meetings, site visits, and further workshops, to encourage a more impactful regional OCA monitoring network.

h) **Share NECAN's experience in developing these recommendations with other regional Coastal Acidification Networks.**

The IWG OA Ocean Acidification Monitoring Prioritization Plan (IWG OA Plan) outlines the need for entities like NECAN to build understanding of Monitoring Needs and prioritization on a regional to local scale. This report acts as documentation of activities taking place over two years to engage with regional experts to create a holistic regional understanding of OCA Monitoring Needs in the NECAN region. The IWG OA Plan, when paired with this report, forms a road map for other regional organizations to collect information that can set monitoring priorities for other regions.

During the process of collecting information over the last two years as part of informing the IWG OA Plan, NECAN OA Workshop, and writing this monitoring plan, the NECAN Steering Committee gained insights into practices that worked well to collect this information and to coordinate regional expertise, as well as techniques that fell short of their goals. One such technique that worked particularly well was the focusing the 2023 NECAN webinar series on the topics to be covered in the Monitoring Priorities in the Northeast Workshop. The summaries of the recommended takeaways from the regional experts that presented in the webinar series were required reading and guided the discussion that occurred at the workshop. By removing the need to have these presentations at the workshop, it allowed time to be efficiently used for synthesizing monitoring priorities for the region, and also acted as a way to archive the information that was gathered by other regional experts.

This report is intended to help guide decision makers in the NECAN region to create a robust, effective, and useful OCA monitoring system in the northeast. We encourage decision makers to consider the recommended locations for monitoring that are put forward in each section of this plan including the criteria to set new monitoring goals in the region.

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Appendix A: Webinar Speakers and Titles (arranged by topic)

Climate

Wiley Evans- Coastal CO2 Monitoring from Volunteer Observing Ships

Xinyu Li- Anthropogenic Carbon Estimation from the US East Coast Ocean Acidification

Brendan Carter- Climate in the Pelagic Ocean with a focus on Anthropogenic Carbon and Marine Carbon Dioxide Removal

Rob Holmburg- Monitoring and Mitigation Sediment Pore Water Acidification on Marine Tidal Mudflats

Current Assessments

Holly Galavotti- Expanding the LISWQMP: Coastal Acidification Monitoring

Katie Clayton- O'Brien- Coastal Acidification Monitoring in the US

Ivy Frignoca- Maine Ocean Climate Collaborative

Tammy Silva- Stellwagen Bank National Marine Sanctuary Ocean Acidification Monitoring

Sarah Gaichas- Ocean Acidification in the Northeast US: State of the Ecosystem Reporting

Jason Goldstein & Jeremey Miller- Monitoring Coastal Acidification: Using Existing Infrastructure and Local Collaboration to Increase our Ability to Accurately Monitor Carbonate Chemistry in Coastal Systems

Indigenous Interests, Concerns, and Perspectives

Sharri Venno- Maliseets & Ocean Acidification

Modeling

Changsheng Chen & Lu Wang- Simulating Ocean Acidification in the Northeast US Region Using a Fully Coupled Three-dimensional Biogeochemistry and Ecosystem Model

Damian Brady & Kate Liberti- What do we Need to Know to Model Ocean Acidification in Estuaries

Sam Siedlecki- Observational needs for regional Oa modeling Biological Impacts

Brittany Jellison- Variability of carbonate chemistry in the nearshore/intertidal environment

Jaoquim Goes- Assessing the Potential Impacts of Ocean Acidification on Phytoplankton Communities in River Influenced Coastal Ecosystems

Hannes Baumann- Untitled

Shannon Messeck- Benthic organisms respond to a changing environment: Laboratory experiments, field experiments, and monitoring?

Justin Ries- Priorities for Ocean Acidification Research

Chris Algar- Monitoring sediment impacts on carbonate chemistry in a coastal estuary

New Tech/Sensors/Methods

Grace Saba- The application of novel, autonomous profiling gliders for high resolution observations of coastal and ocean acidification in the US Northeast Shelf

Luke Thompson- Environmental DNA methods for assessing ecosystem responses of Gulf of Mexico prokaryotic and eukaryotic communities to ocean acidification

Jamie Palter- Autonomous platforms for studying biogeochemistry (for the Northeast Coastal Acidification Network)

Mike Brosnahan- Changing HAB threats in the rapidly warming Gulf of Maine

Adam Subhas- Calcium Carbonate and Alkalinity Cycling in the Gulf of Maine and Beyond

Aleck Wang- Towards high-frequency, low-cost in situ sensing of the seawater carbonate system

Rapid Response

Doug Vandemark- 2023 Gulf of Maine Tripos event Dave Wu- MWRAResponse Monitoring

User Needs/Products

Anne Giblin- Report on the Ocean Acidification Crisis in Massachusetts

Frederic Cyr- Spatiotemporal variability of ocean carbonate parameters on the Canadian Atlantic Continental Shelf

Janet Nye- Ocean acidification and ecosystem monitoring in the New York Bight