9. Mid-Atlantic Bight Region Acidification Research

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Abstract

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

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

Acidification in the Mid-Atlantic Bight Region

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

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

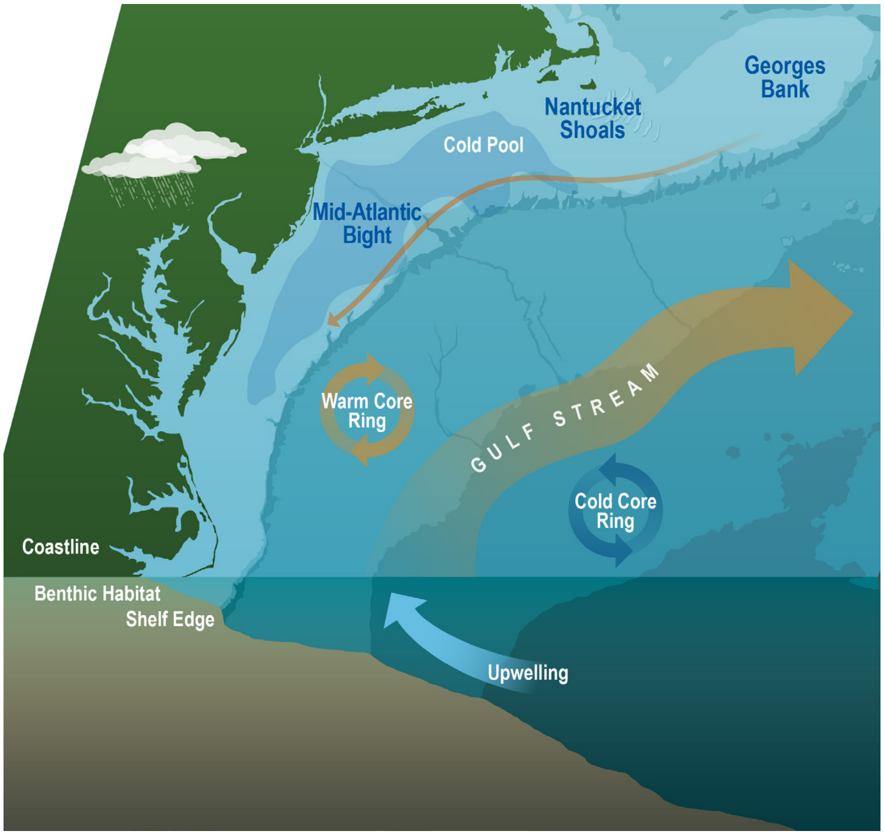

Figure 9.1. The Mid-Atlantic Bight region with depth, from Southern Massachusetts to Cape Hatteras, NC. Water from the Gulf Stream comes in from the south, while the Shelf Break Jet brings water from the North. Warm and cold core rings can be found along the Gulf Stream. Credit: NOAA

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

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

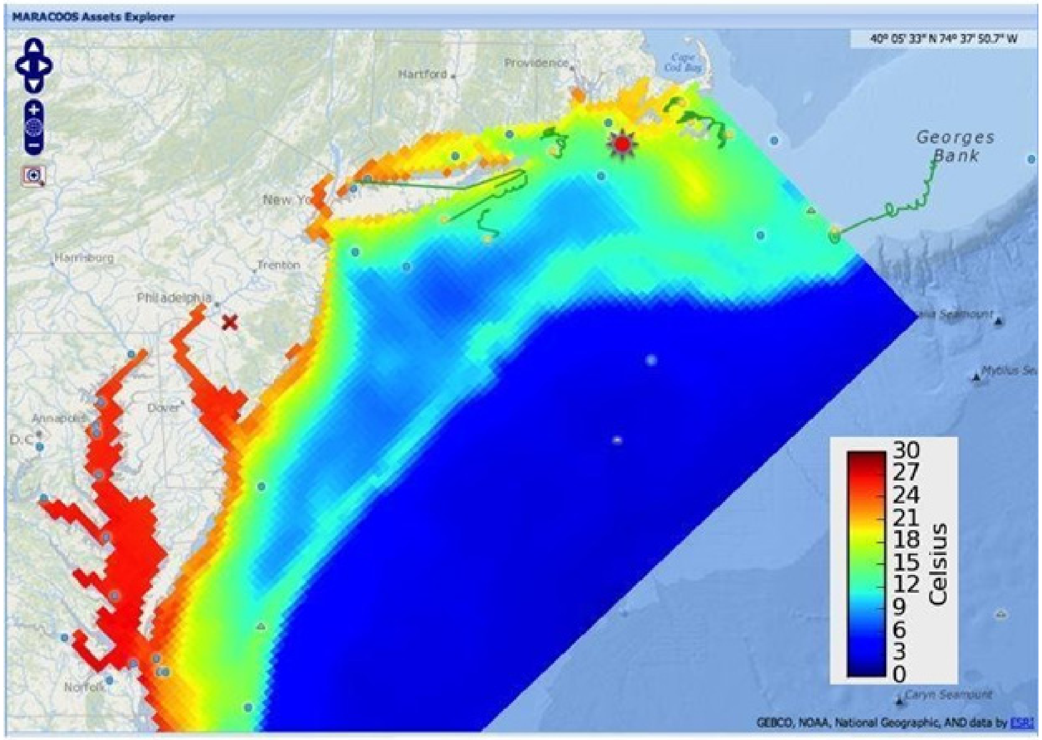

Figure 9.2. Bottom temperatures for part of the Mid-Atlantic region, showing the Cold Pool. Courtesy of: MARACOOS/Rutgers University

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

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

Environmental Change in the Mid-Atlantic Bight Region

Surveys of surface carbonate chemistry in the MAB conducted by NOAA and other research institutions have shown large natural variability on decadal timescales (Boehme et al., 1998; Wang et al., 2017, 2013). Regional satellite-derived surface pCO_2 algorithms depict strong seasonal variability with lower pCO_2 values in winter and spring and higher pCO_2 values during the summer and fall primarily driven by seasonal temperature dynamics. Repeated shipboard campaigns have shown relatively low pH, Ω_{arag}, and buffering capacity of waters of the northeastern U.S. shelves, which indicates elevated risk to continued acidification compared to southern counterparts (**Figure 9.3**; Wang et al., 2013). Limited MAB bottom water CO2SYS surveys have shown enhanced seasonal stratification relative to surface conditions, as respiratory DIC production, and lower temperature and salinity conditions brought in from the north as Labrador Sea slope water. The complexity of the surface and bottom MAB waters demands simultaneous observations of physical, biological, and chemical parameters within the region to better inform OA forecasts and projections.

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

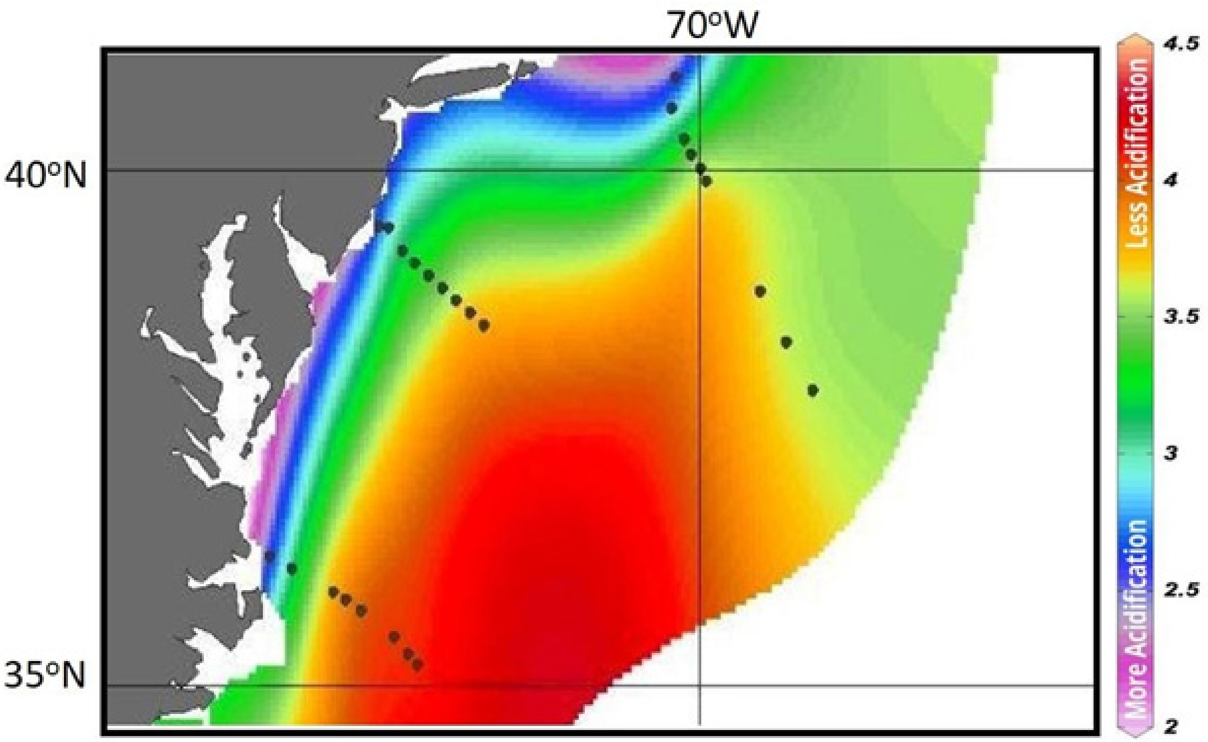

Figure 9.3. Aragonite saturation state of surface water in the MAB. Dots represent transects where data are collected. Source: http://www.aoml.noaa.gov/ocd/ocdweb/occ_oa.html

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Biological Sensitivity in the Mid-Atlantic Bight Region

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Human Dimensions in the Mid-Atlantic Bight Region

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

10. New England Region Acidification Research

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Abstract

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

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

Acidification in the New England Region

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

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

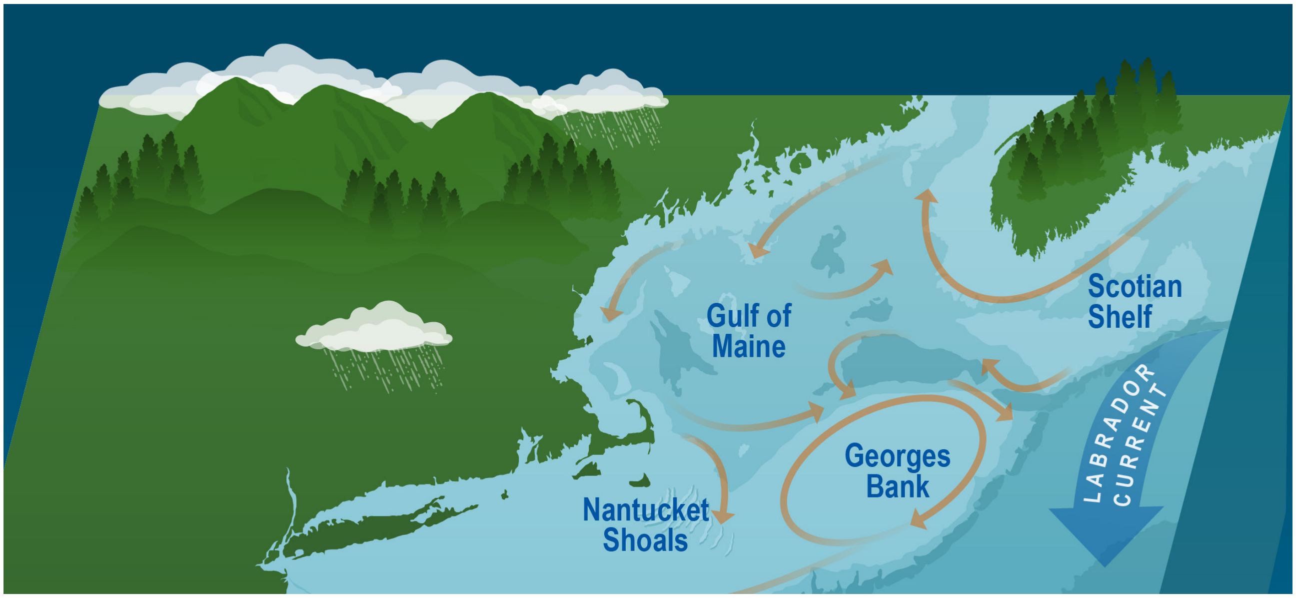


Figure 10.1. The watershed for the New England Region, which includes the Gulf of Maine, Georges Bank, and Scotian Shelf. Credit: NOAA

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

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

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

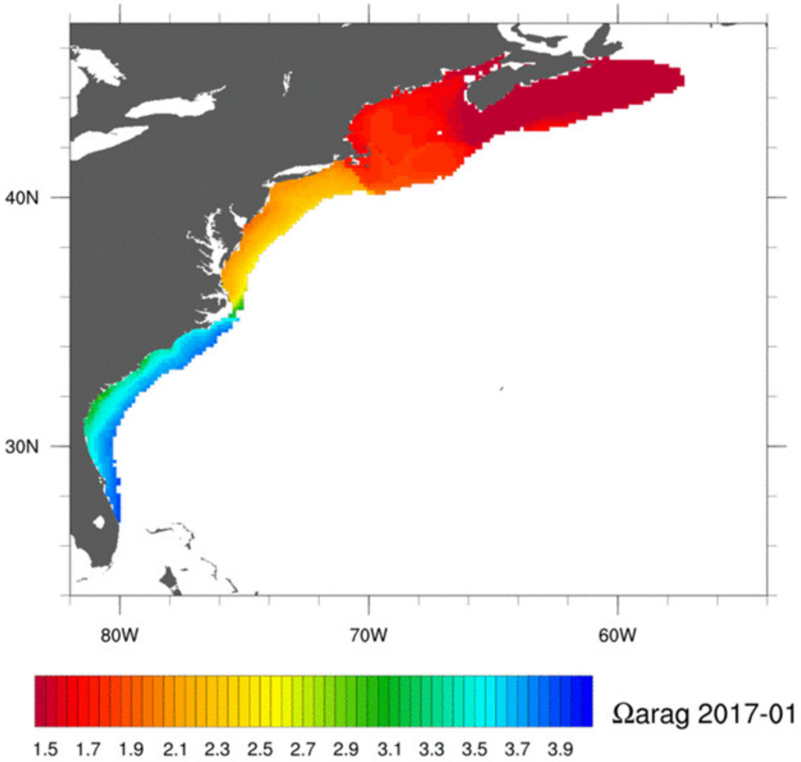


Figure 10.2. Aragonite saturation levels in 2017 for the northeast United States in January. The NE region has the lowest Ωarag on the East Coast with levels below 2.0. Image courtesy of Ruben van Hooidonk NOAA/AOML/CIMAS. The levels for the month of January is shown, with other months being represented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

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

Environmental Change in the New England Region

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

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

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

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

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

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

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

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

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

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

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

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

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

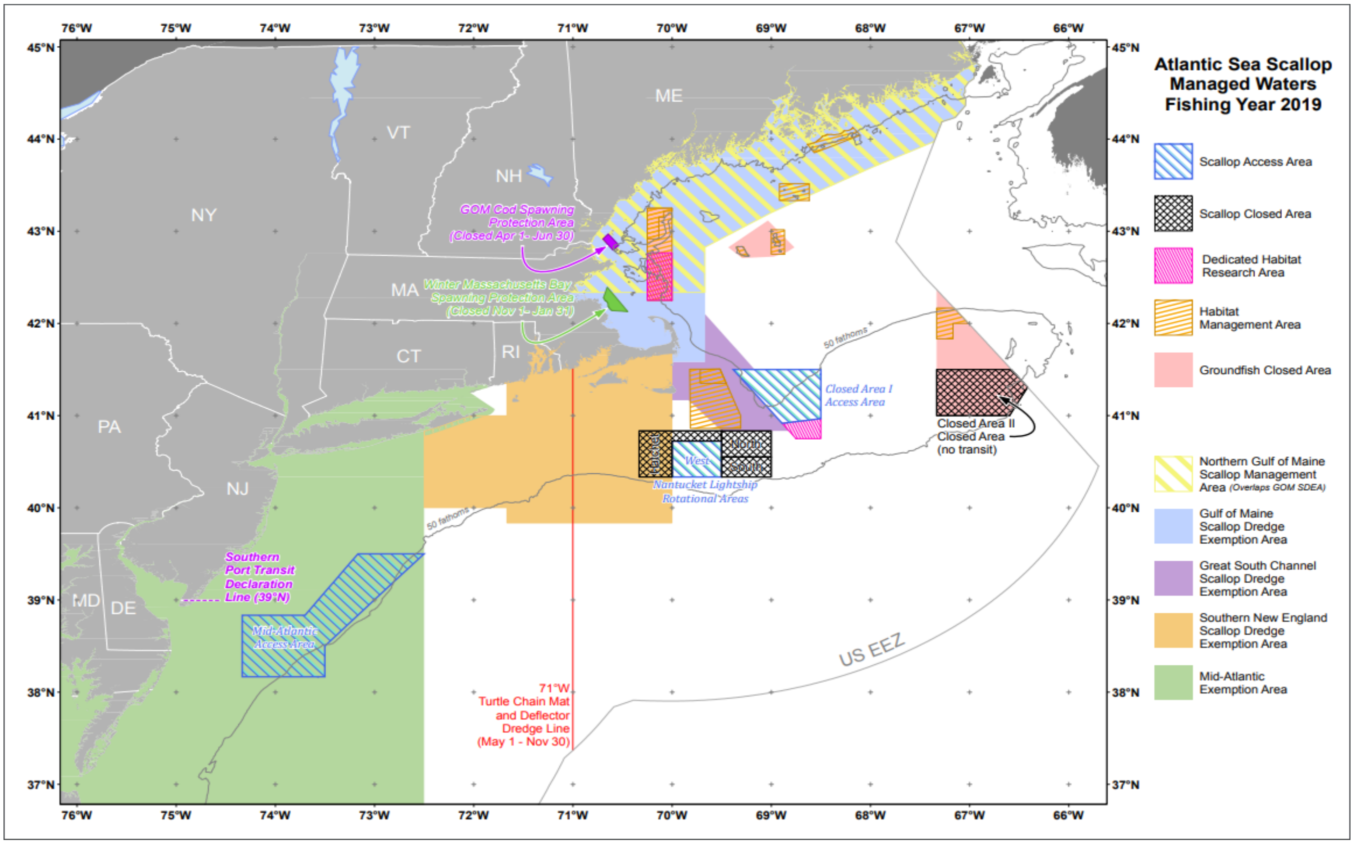


Figure 10.3. Atlantic sea scallop managed waters for fishing year 2019 (April 1–March 30). Source: https://www.fisheries.noaa.gov/resource/map/atlantic-sea-scallop-managed-waters-fishing-year-2019

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

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

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

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

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

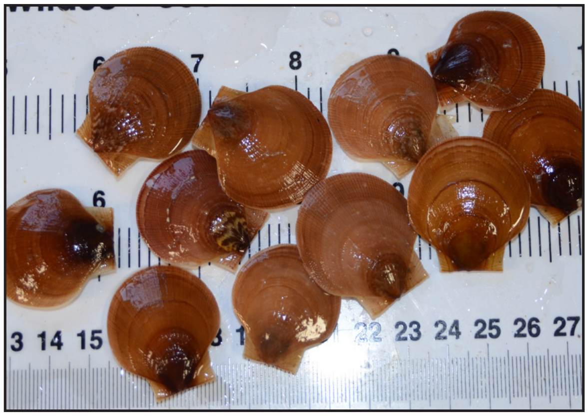
As identified through numerous regional stakeholder and industry engagement forums including those initiated via the Northeast Coastal Acidification Network, there remains a need for predictive capability at timescales not currently well addressed with existing models. These include forecasts of OA conditions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

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

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

Biological Sensitivity in the New England Region

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



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Human Dimensions in the New England Region

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

References

[INTRO] = Introduction;

[NAT] = National Ocean & Great Lakes;

[OO] = Open Ocean Region;

[AK] = Alaska Region;

[ARC] = Arctic Region;

[WC] = West Coast Region;

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

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

[FLC] = Florida Keys and Caribbean Region;

[MAB] = Mid-Atlantic Bight Region;

[NE] = New England Region;

[GL] = Great Lakes Region

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