A MID-DECADE CHECK-IN:

THE NOAA OCEAN, COASTAL, AND GREAT LAKES ACIDIFICATION RESEARCH PLAN 2020-2029

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A Mid-Decade Check-in: The NOAA Ocean, Coastal, and Great Lakes Acidification Research Plan 2020-2029

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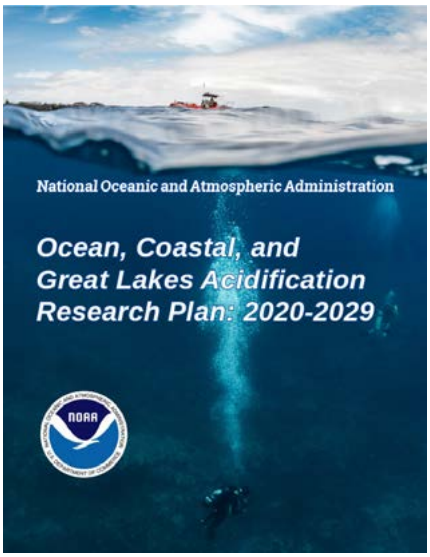
Introduction

Motivation for this Report

Starting in 2020, the National Oceanic and Atmospheric Administration (NOAA) has carried out research guided by the Ocean, Coastal, and Great Lakes Acidification Research Plan: 2020-2029 (the Research Plan). In the ensuing years, NOAA has tracked progress towards implementing the actions in the Research Plan. As we move into the second half of the decade, we would like to take this opportunity to take stock of the progress NOAA has made and reflect on the work ahead to continue to advance the research goals.



Report Format

In this Report we mirror the format of the Research Plan by providing insights into the work accomplished under research actions in each of the 11 geographical areas. In each section we highlight the progress made under actions for each thematic area from the Research Plan: 1) document and predict **environmental change** via monitoring, analysis and modeling; 2) characterize and predict **biological sensitivity** of species and ecosystems; and 3) understand **human dimensions** of ocean, coastal and Great Lakes acidification impacts. These three thematic areas, abbreviated throughout the Research Plan and in this report as 1) environmental change, 2) biological sensitivity and 3) human dimensions, are referred to collectively as the trifecta.

We measured progress toward each action by the number of research projects conducted or underway that work toward accomplishing that action. Projects may support one or several actions, likewise they may contribute to work in one or multiple geographic chapters. The number of actions has then been used to determine if there is a) **overall good progress** being made towards implementing an action, b) **some degree of progress**, or c) **no known progress**. These three categories have been assigned a symbol to represent that progress (see table I.1). Each chapter section of this report also provides some details about the NOAA programs, labs, offices, etc. that are supporting projects to implement research actions.

Table I.1: Symbols representing each of the three designations of progress made towards a research action. Actions with four or more implementing projects are defined as making “overall good progress” and represented by a green circle. Actions with one to three implementing projects are defined as making “some degree of progress” and represented by a yellow triangle. Actions with no known implementing projects are defined as making “no known progress” and are represented by a red diamond.

Degree of Progress Towards Implementation	# of Projects Completed or Underway	Designation (Words)	Designation (Symbol)
Overall good progress	4+	Green Circle	●
Some degree of progress	1-3	Yellow Triangle	▲
No known progress	0	Red Diamond	◆

The report also reflects on emerging topics and high level guidance documents that were not part of the conversation when the Research Plan was released in 2020, but which have generated additional research priorities in which NOAA invests. For example, marine carbon dioxide removal (mCDR) and its potential to mitigate ocean and coastal acidification, was not included in the Research Plan. However, since 2020, it has become a more robust topic requiring research to ensure that the mCDR methods actually achieve what they propose while avoiding harm to ecosystems and communities. Additionally, five new high-level guidance documents provide different frameworks for and opportunities to address acidification research through emerging lenses. This report reflects on these new high level guiding documents as they relate to acidification research.

Crew deploy an ocean chemistry sensing array on the second East Coast Ocean Acidification research mission (ECOA-2)

A Guide for the Remaining Decade

Ultimately, this Report is meant to highlight key research gaps that may be prime for investment and resources in the second half of the decade. It is meant to reveal where additional resources may be needed to advance a research priority. This provides NOAA offices investing in acidification research an opportunity to reflect on the research gaps and needs that may be prioritized in the remaining half of the decade. It also offers research project applicants a chance to see where proposed projects can address key research gaps.

That said, an important point of clarification is that actions in the Research Plan that are currently defined as making "overall good progress" towards implementation should not be misinterpreted to mean those actions no longer need investment. In fact, in many cases those priorities require continuous investment to ensure ongoing long term observations or the sustained research needs required to fully implement an action in this decade. Thus, while this report reveals key opportunities for increased investment, it does not indicate actions that we may be able to stop infusing investments and resources.

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CHAPTER 1

NATIONAL OCEAN, COASTAL, AND GREAT LAKES ACIDIFICATION RESEARCH

Chapter 1 of the National Oceanic and Atmospheric Administration Ocean, Coastal, and Great Lakes Acidification Research Plan: 2020-2029 (the Research Plan) is titled, "National Ocean, Coastal, and Great Lakes Acidification Research" (the National Chapter). This chapter includes research objectives relevant across the open ocean, the continental shelves and coastal zones of the U.S, its territories and the Great Lakes region. There are a total of three research objectives, one pertaining to each of three thematic areas (e.g. environmental change, biological sensitivity and human dimensions). There are a total of 23 actions across the three research objectives: 22 of which are making good progress towards implementation, one of which has limited progress towards implementation and no actions with no known progress made (Table 1.1).

Table 1.1: The National Chapter has a total of 23 actions: Twenty two actions have made good progress toward implementation (Green Circle Actions), one action has made limited progress toward implementation (Yellow Triangle Actions), and there are no actions that have made no known progress toward implementation (Red Diamond Actions).

Chapter Title	**Number of Actions**	●	▲	◆
Chapter 1: National Ocean, Coastal, and Great Lakes Acidification Research	23	22	1	0

Across the National Chapter, there are a total of nine environmental change actions, seven biological sensitivity actions and seven human dimensions actions. Figure 1.1 summarizes the progress made towards each of these actions under the three thematic areas.

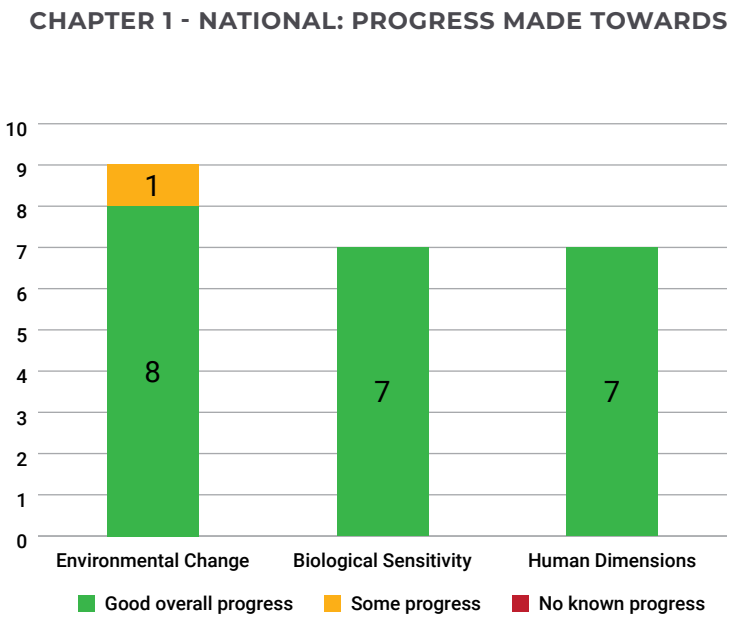


Fig. 1.1: The National Chapter includes a total of 9 environmental change actions, seven biological sensitivity actions and seven human dimensions actions. Of the nine environmental change actions, good progress is being made towards implementing eight actions and limited progress has been made on one action. Good progress is being made towards implementing all seven of the biological sensitivity related actions as well as all seven of the human dimensions actions. There are no actions in the National chapter where no progress has been made towards implementation.

Environmental Change

Under the Environmental Change theme in the National Chapter, there is one objective:

1. The National Environmental Change Research Objective 1.1: Expand and advance OA observing systems and technologies to improve the understanding and predictive capability of OA trends and processes

Table 1.2 summarizes the implementation of each action under this research objective.

Table 1.2: A summary of the actions under the environmental change theme objective in the National Chapter and their implementation status, number of projects implementing the action and NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The National Environmental Change Research Objective 1.1				
1.1.1	Sustain, improve and adopt robust physical, chemical and biological analytical systems, sensors and autonomous technologies to observe the full water column and benthic environments and transition R&D technologies to serve as operational elements	38		AOML, GLERL, GML, GOMO, GOMO BIL, IOOS, OAP, PMEL, SG, with additional NOPP and IRA support
1.1.2	Increase sampling of nearshore waters in sensitive and economically important areas and improve observing connectivity between coastal and open ocean to explicitly characterize the anthropogenic carbon content present in these environments	34		CRP, GLERL, IOOS, NMS, OAP, PMEL, SG, with additional NOPP and IRA support
1.1.3	Sustain long-term acidification in situ time-series to monitor the progression of acidification and determine the impact and importance of regional and climate-related processes	28		GLERL, OAP

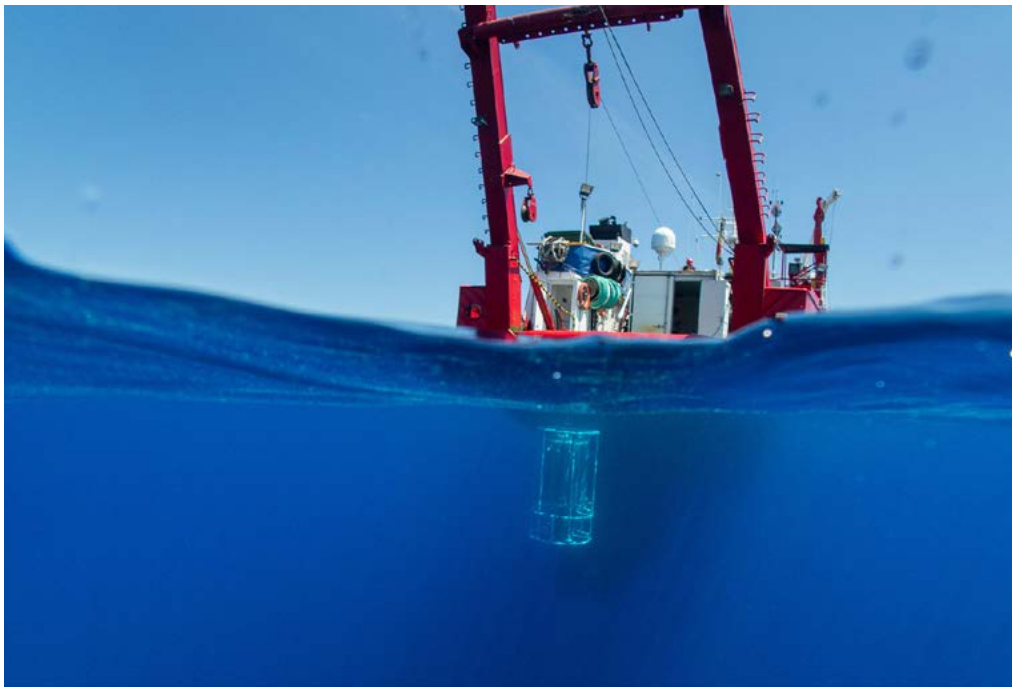
Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
1.1.4	Improve the use of satellite and other remote sensing tools and applications to observe and characterize the open ocean, coastal and estuarine environments	2	▲	GLERL, OAP
1.1.5	Conduct observational and numerical simulation experiments to inform strategic deployment of NOAA OA Network observing assets for optimal spatial and temporal coverage	9	●	GOMO BIL funds, OAP and with additional NOPP and IRA support
1.1.6	Develop and expand coverage of regionally linked biogeochemical-ecosystem models, with a focus on timescales of days to decades, capable of resolving conditions most relevant to local living marine and Great Lakes resources and dependent communities	25	●	AOML, CRP, GFDL, GLERL, IOOS, OAP, PMEL, SG, with additional NOPP and IRA support
1.1.7	Continue leadership of and support for the enhancement of the GOA-ON	10	●	OAP, PMEL
1.1.8	Ensure all data collected by observing systems comply with FAIR data principle	37	●	AOML, GML, GOMO, GOMO BIL funds, NCEI, OAP, PMEL, with additional NOPP and IRA support
1.1.9	Support synthesis activities to ensure environmental data are transitioned to useful products for modelers and other audiences	32	●	AOML, CPO, CRP, GFDL, GML, GOMO, NCEI, OAP, PMEL, SG, with additional NOPP and IRA support

Image credit: Marisa Gedney

FEATURED PROJECT

ANCHORS AWEIGH FOR CUTTING EDGE COASTAL OCEAN ACIDIFICATION RESEARCH CRUISES

NOAA's Ocean Acidification Program supports coastal and ocean acidification research cruises along the major U.S. coastlines. These essential cruises supply the highest quality information on ocean conditions coastwide. More recent 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 four-year cycle for each coastline, help us track long-term ocean change and evaluate our monitoring network of buoys, gliders and other tools. Recent cruises occurred on the East Coast in 2022, the Gulf of America (formerly known as the Gulf of Mexico) in 2021 and the West Coast in 2021.



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FEATURED PROJECT

FILLING GAPS WITH OCEAN CARBON MONITORING

NOAA's Global Ocean Monitoring and Observing Program currently invests $2.1 million per year for three years (FY24-FY26) to expand the global ocean carbon observing network and deploy new carbon dioxide (CO_2) sensors in critical regions, helping to fill important data gaps in undersampled regions. Monitoring and observing surface ocean carbon will help experts track impacts on international ocean health — such as ocean acidification — and can inform ecosystem and fisheries management.

Funds from the Bipartisan Infrastructure Law will support automated measurements of atmospheric and surface ocean CO_2 concentrations as part of the Surface Ocean CO_2 Reference Observing Network (SOCONET), whose overarching goal is to improve the ability to track carbon emissions and uptakes. As part of this investment, a new generation of carbon sensors with improved accuracy will be installed on a variety of novel platforms, such as cargo vessels, passenger cruise lines and research vessels, including NOAA Ship *Ronald H. Brown* and Saildrone autonomous surface vehicles.

The measurements from ships and uncrewed surface vehicles will be recorded annually in the Surface Ocean CO_2 Atlas (SOCAT), a global database with over 100 international contributors. The measurements will be synthesized and used to estimate the amount of atmospheric CO_2 that is absorbed by the ocean. The SOCAT data submissions tools will be modernized to expedite the release of the SOCAT data sets.

Biological Sensitivity

Under the Biological Sensitivity theme in the National Chapter, there is one objective:

1. The National Biological Sensitivity Research Objective 1.2: Understand and predict ecosystem response and adaptive capacity of ecologically and economically important species to OA and co-stressors

Table 1.3 summarizes the implementation of each action under this research objective.

Table 1.3: A summary of the actions under the biological sensitivity theme objective in the National Chapter and their implementation status, number of projects implementing the action and NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The National Biological Sensitivity Research Objective 1.2				
1.2.1	Assess OA and multi-stressor sensitivity among species, particularly ecologically and economically important species, to build understanding, provide important information to ecosystem modeling efforts and inform management decisions	37		CRP, GOMO BIL funds, NWFSC, OAP, SG, with additional NOPP and IRA support
1.2.2	Collect, integrate and synthesize co-located physical, chemical, biological and ecological data to study species and ecosystem response to OA and multi-stressor environments	37		AOML, CRP, GFDL, NEFSC, OAP, OMAO, PMEL, SG, with additional NOPP and IRA support
1.2.3	Promote the full characterization of the marine carbonate system to facilitate attribution of species physiological response and resulting community and ecosystem responses	34		AOML, CRP, GFDL, OAP, with additional NOPP and IRA support
1.2.4	Foster new research to study emerging and unanticipated ecosystem changes, including but not limited to multi-stressor interactions and harmful algal blooms (HABs)	20		AOML, CRP, GFDL, OAP, with additional NOPP and IRA support

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
1.2.5	Use new knowledge to further refine existing ecosystem models that can be linked to biogeochemical models and inform scenarios of future acidification and environmental change	15		CRP, GFDL, OAP, PMEL, SG, with additional NOPP and IRA support
1.2.6	Assess sensitivity within species and populations to evaluate potential for biological capacity to adapt and acclimate to OA and multi-stressor environments	25		CRP, AFSC, OAP, SG, with additional NOPP and IRA support
1.2.7	Explore feasibility and benefits of identifying genetic resistance and resilience to OA and environmental change within species in order to apply active mitigation strategies, foster resilient marine communities, improve habitat conditions and restoration success	16		CRP, AFSC, OAP, NCCOS, SG, with additional NOPP and IRA support

Image Credit: NASA Earth Observatory

FEATURED PROJECT

HEALTH AND HARMFUL ALGAL BLOOMS: UNDERSTANDING THE ROLE OF OCEAN ACIDIFICATION

NOAA's Ocean Acidification Program and National Centers for Coastal Ocean Science invested in five projects to promote understanding of harmful algal blooms (HABs) and ocean acidification (OA) interactions. Recent studies indicate that increased carbon dioxide concentrations support higher phytoplankton densities and that OA parameters such as pCO_2 and pH have variable effects on growth rate and cellular toxin production in different HAB species and strains. OA and HABs can impact the same coastal resources including aquaculture, wild fisheries and tourism in different ways with cascading impacts to coastal ecosystems, communities and economies to inform management decisions. These investments help to understand what synergistic or antagonistic effects may exist between the two stressors so that managers, industries and communities can prepare.

Human Dimensions

Under the Human Dimensions theme in the National Chapter, there is one objective:

1. The National Human Dimensions Research Objective 1.3: Identify and engage stakeholders and partners, assess needs and generate products and tools that support management, adaptation and resilience to OA

Table 1.4 below summarizes the implementation of each action under this research objective.

Table 1.4: A summary of the actions under the human dimensions theme objective in the National Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The National Human Dimensions Research Objective 1.3				
1.3.1	Identify and build relationships with vulnerable communities, stakeholders and partners to identify needs and concerns, exchange knowledge and understand how OA fits within their decision making contexts	22	●	CRP, GLERL, GOMO, IOOS, OAP, SG, with additional NOPP and IRA support
1.3.2	Develop a strategy for engaging indigenous governments and communities to exchange knowledge and integrate indigenous and scientific knowledge sources	6	●	CRP, OAP, SG, with additional NOPP support
1.3.3	Model economic, cultural and social impacts to evaluate intervention actions and explore adaptive strategies that build resilience, empower communities and inform policy-making	8	●	CRP, IOOS, OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
1.3.4	Encourage research partnerships and two-way dialogues with stakeholders to ensure that science is aligned with local to regional level priorities, by supporting networks that are engaging in OA outreach, communication and research, such as the OA Information Exchange	26		CRP, GLERL, GOMO, IOOS, OAP, SG, with additional NOPP and IRA support
1.3.5	Develop and operationalize data synthesis, visualization tools and communication products with robust stakeholder and partner input to ensure products are responsive to needs	25		CRP, IOOS, NCEI, OAP, PMEL, SG, with additional NOPP and IRA support
1.3.6	Create education and outreach resources in partnership with researchers, educators and community partners based on regional needs and real data products to promote understanding and awareness of OA and possible adaptation, mitigation and resilience strategies	18		CRP, GLERL, IOOS, OAP, SG, with additional NOPP and IRA support
1.3.7	Monitor trends in community awareness and perceptions of OA impacts and participation in stewardship activities across diverse stakeholders	7		CRP, IOOS, OAP

Image Credit:Captain Albert E. Theberge, NOAA Corps (ret.)

FEATURED PROJECT

CROWDSOURCING SCIENCE THROUGH ENGAGEMENT AND TRAINING

To foster understanding and enable the pursuit of sustainability, MIT Sea Grant provides hands-on experiences to constituents that manage and depend on coastal resources challenged by warming and increased acidification. They work with key partners in Massachusetts and the New England region, including water quality monitoring organizations, aquaculture operations, federal and state agencies and the Northeast Coastal Acidification Network. In 2018, MIT Sea Grant supported three in-person workshops in Connecticut, Maine and Massachusetts focused on best practices for measuring coastal acidification. More than 60 organizations were trained in methods for water collection and data gathering. In 2019, these workshops led to Shell Day, an ocean acidification monitoring effort during which participants collected 435 seawater samples in a single day from 87 sites along the coast from Long Island Sound to Downeast Maine. Since 2021, MIT Sea Grant has also provided a laboratory to analyze pH and alkalinity for a participatory science project across Massachusetts monitoring acidity of brooks, ponds and rivers in coastal watersheds. For the past two years, this project focused on leveraging resources of water quality monitoring groups to incorporate coastal acidification parameters and collecting water samples to be analyzed for total alkalinity in the laboratory. With this, they aim to increase coastal monitoring assets and build capacity to characterize acidification drivers and adaptation strategies.

LOOKING FORWARD

NOAA has made fairly comprehensive investments to actions across all thematic areas in the National Chapter. However, many of these objectives require continued or sustained investments to monitor and evaluate long-term trends of OA and impacts to species and communities.

Only one action in this chapter received limited investment and may prove to be an important gap to fill in the second half of this decade: Action 1.1.4 promotes the use of satellite and other remote sensing tools in observing. As these technologies allow for improved temporal and spatial coverage, they will be important for modeling and algorithm development for forecasting and beyond.

Credit: Officers and Crew of NOAA Ship PISCES

CHAPTER 2

OPEN OCEAN REGION ACIDIFICATION RESEARCH

Chapter 2 of the Research Plan is titled, “Open Ocean Region Acidification Research” (the Open Ocean Chapter). This chapter includes research objectives aimed at evaluating the vulnerability of open ocean regions in deep waters beyond the continental shelf to future ocean acidification caused by natural variability and anthropogenic changes. There are seven research objectives across the trifecta themes, with four under environmental change, two under biological sensitivity and one under human dimensions. There are a total of 18 actions across the seven research objectives: 10 of which are making good progress, five of which have limited progress toward implementation and three with no known progress made (Table 2.1).

Table 2.1: The Open Ocean Chapter has a total of 18 actions: Ten actions have made good progress toward implementation (Green Circle Actions), five actions have made limited progress toward implementation (Yellow Triangle Actions) and three actions have made no known progress toward implementation (Red Diamond Actions).

Chapter Title	**Number of Actions**	●	▲	◆
Chapter 2: Open Ocean Region Acidification Research	18	10	5	3

Across the Open Ocean Chapter, there are a total of 11 environmental change actions, four biological sensitivity actions and three human dimensions actions. Figure 2.1 summarizes the progress made toward each of these actions under the three thematic areas.

CHAPTER 2 - OPEN OCEAN: PROGRESS MADE TOWARDS IMPLEMENTING ACTIONS ACROSS THEMATIC AREAS

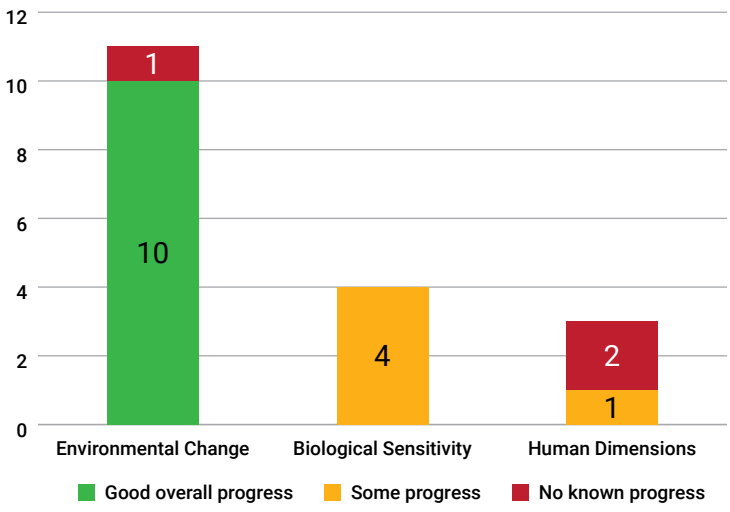


Fig. 2.1: The Open Ocean Chapter includes a total of 11 environmental change actions, four biological sensitivity actions and three human dimensions actions. Of the 11 environmental change actions, good progress has been made toward implementing 10 actions and no known progress has been made on one action. Limited progress has been made on implementing all four of the biological sensitivity actions. Limited progress has been made on one human dimensions action and no known progress has been made on two human dimensions actions.

Environmental Change

Under the Environmental Change theme in the Open Ocean Chapter, there are four objectives:

1. Open Ocean Environmental Change Research Objective 2.1: Continue leadership and support for GOA-ON
2. Open Ocean Environmental Change Research Objective 2.2: Separate natural and anthropogenic CO2 signal and elucidate feedbacks on seasonal to decadal scales
3. Open Ocean Environmental Change Research Objective 2.3: Observe the evolution of marine chemistry and biology to provide model initial conditions and validation
4. Open Ocean Environmental Change Research Objective 2.4: Derive global statistical or quasi-mechanistic algorithms to infer surface ocean carbonate dynamics and underlying biological processes to be acquired from remotely sensed data

Table 2.2 below summarizes the implementation of each action under these research objectives.

Table 2.2: A summary of the actions under the environmental change theme objective in the Open Ocean Chapter and their implementation status, the number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Open Ocean Acidification Research Objective 2.1				
2.1.1	Build upon the existing NOAA-supported GOA-ON activities and expand the global network with new sensors and observing platforms that provide important information on the changing physical, chemical and biological conditions in open ocean environments	8	●	GOMO, OAP, PMEL
2.1.2	Ensure OA relevant measurements are included on all ships of SOOP and SOCONET ships of opportunity	7	●	AOML, GML, GOMO, GOMO BIL funds, OAP, PMEL
2.1.3	Enable the development of globally accessible high-quality data and data synthesis products, including assessments of OA status and trends, which facilitate research and new knowledge on OA, communicate the status of OA and biological response and enable forecasting of OA conditions	17	●	AOML, GML, GOMO, OAP, NCEI, PMEL, with additional NOPP support

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Open Ocean Acidification Research Objective 2.2				
2.2.1	Link open ocean and coastal cruises for tracking the distribution and trends of anthropogenic carbon increases in the ocean	12	●	AOML, GFDL, GML, GOMO, GOMO BIL funds, OAP, PMEL
2.2.2	Expand time-series observations in open ocean and coastal waters (see Chapters 3–11) to characterize rates of ocean carbon change over time, which is necessary to reduce uncertainties in future projections of OA	10	●	AOML, GOMO, GOMO BIL funds, OAP, PMEL
2.2.3	Continue the development of sensors on autonomous platforms that can measure carbon parameters, nutrients and other biogeochemical EOVs, especially those meeting climate- quality standards of GOA-ON	11	●	AOML, GFDL, GOMO, OAP, PMEL, with additional NOPP support
Open Ocean Acidification Research Objective 2.3				
2.3.1	Develop synthesis products including maps and sections of key chemical and biological parameters to quantify the buildup of anthropogenic CO_2, rates of change in global ocean OA conditions and impacts of OA on key species	15	●	AOML, GFDL, GML, GOMO, GOMO BIL funds, OAP, PMEL
2.3.2	Continue the development of data management and quality control systems for autonomous sensors on autonomous surface vehicles and biogeochemical (BGC) Argo profiling floats in order to incorporate these new observations in data products and to validate models	8	●	AOML, GOMO, GOMO BIL funds, OAP, PMEL

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
2.3.3	Continued development of regional-to-global scale prediction BGC models focused on acidification extremes spanning timescales from seasonal to interannual to decadal	9	●	AOML, GFDL, GOMO, OAP, PMEL, with additional NOPP support
Open Ocean Acidification Research Objective 2.4				
2.4.1	Derive seascape-specific multivariate algorithms for predicting global surface ocean pCO_2 at suitable spatiotemporal scales (e.g., monthly, 0.5 degree)	4	●	AOML, GOMO, OAP, PMEL, with additional NOPP support
2.4.2	Incorporate measurements supporting satellite algorithm development and determination of net biological productivity into on-going OA surveys	0	◆	n/a

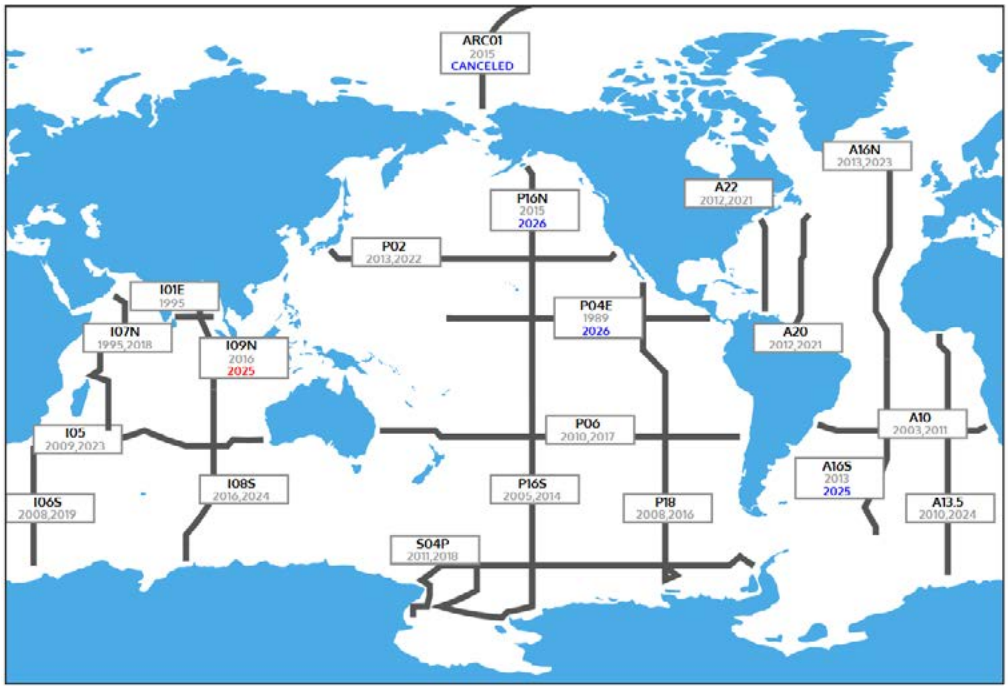


Image Credit: GO-SHIP

FEATURED PROJECT

COVERING THE GLOBE WITH GO-SHIP

The Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) network consists of 55 sustained hydrographic sections that provide global open ocean measurements of the highest accuracy. These hydrographic cruises span ocean basins from coast to coast and sea surface to seafloor to monitor changes in inventories of heat, freshwater, carbon, oxygen, nutrients and transient tracers on decadal timescales. The scientific efforts on GO-SHIP cruises produce carbon system studies, data for model calibration and validation, and calibration and deployment of autonomous sensing equipment such as Argo floats and surface drifters, among other contributions. Between 2021-2024, U.S. GO-SHIP completed or have funded cruises A20, A22, P02, A16N, I05, A13.5, I08S, ARC01 and A16S, that collectively sailed in the Atlantic, Pacific, Indian and Arctic Oceans. With support from NOAA, the National Science Foundation and international partners, GO-SHIP cruises contribute significantly to our understanding of open ocean acidification.

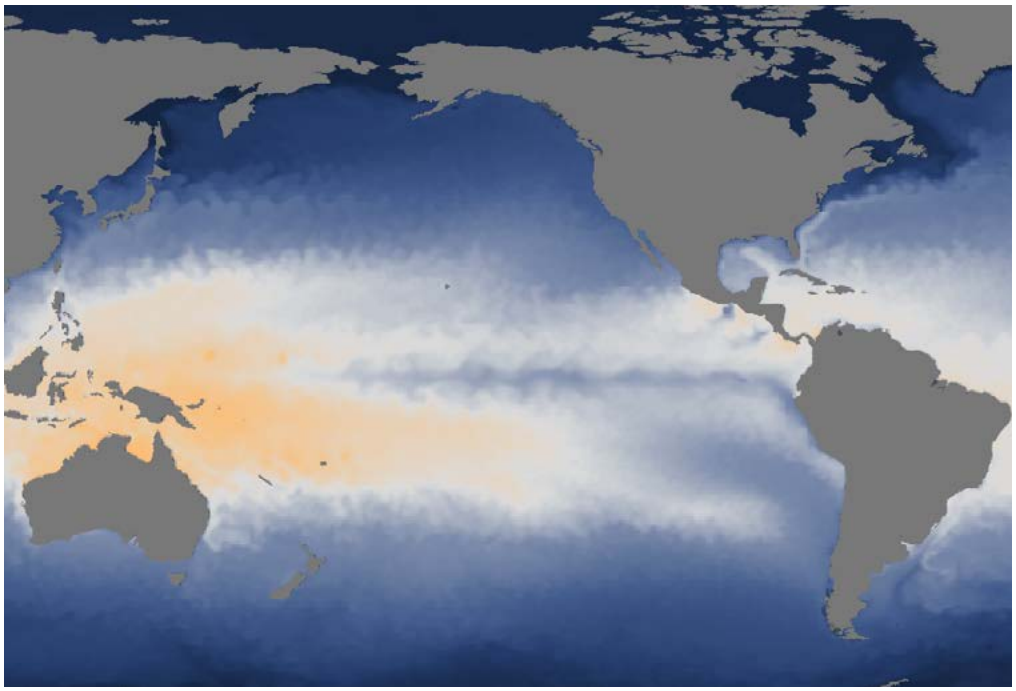


Image Credit: NOAA Climate Program Office

FEATURED PROJECT

IMPORTANCE OF EXTREMES TO U.S. WATERS

Multiple stressors increasingly impact the world's oceans and marine ecosystems. Extremes in these stressors have the potential to exacerbate ecosystem effects, particularly in coastal regions where changes can be magnified. Using a fully-coupled Earth System Model, GFDL-ESM4.1, run under a range of scenarios developed for the 6th phase of the Coupled Model Intercomparison Model (CMIP6), this project quantified the relationship between oceanic long term changes and extremes in individual and compound stressors with particular focus on U.S. territorial waters and Marine Protected Areas. Comparing model historical simulations with available time series observations in these areas helped identify the required observations for detecting and attributing these stressors. While the results of this study highlighted areas of improvement for model-observation agreement, they also showed that monthly 1-degree global model output (publicly available from CMIP6) can be useful in the context of extreme event analysis. This work was funded by OAP in cooperation GFDL and the GOMO.

Biological Sensitivity

Under the Biological Sensitivity theme in the Open Ocean Chapter, there are two objectives:

1. Open Ocean Biological Sensitivity Research Objective 2.5: Research impacts on lower trophic levels in oligotrophic waters
2. Open Ocean Biological Sensitivity Research Objective 2.6: Research impact of OA on highly migratory species

Table 2.3 below summarizes the implementation of each action under this research objective.

Table 2.3: A summary of the actions under the biological sensitivity theme objective in the Open Ocean Chapter and their implementation status, the number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Open Ocean Acidification Research Objective 2.5				
2.5.1	Utilize Bongo and Continuous Plankton Recorder tows during OA cruises to determine the biological impacts of OA and other stressors on planktonic communities	3	▲	OAP, PMEL
2.5.2	Develop statistical tools for assessing the impacts of OA and other stressors on marine organisms	1	▲	NOPP and IRA support
2.5.3	Develop biogeochemical and phylogenetic tools for assessing impacts of OA and other stressors on marine organisms	3	▲	GOMO, OAP, OER
Open Ocean Acidification Research Objective 2.6				
2.6.1	Develop biogeochemical tools for assessing the impacts of OA and other stressors on higher-level taxonomic groups	2	▲	GOMO, OER

Image Credit: NOAA's Fisheries Collection

FEATURED PROJECT

BIOTIC CALCIFICATION IMPACTS ON MARINE CARBON DIOXIDE REMOVAL ADDITIONALITY

The global ocean is a large natural sink for carbon, having absorbed approximately 30% of carbon dioxide over the last few centuries. This fact has inspired research on the feasibility of various marine carbon dioxide removal (mCDR) approaches that aim to enhance natural uptake, leading to changing ocean chemistry impacting marine life and people who depend on healthy ecosystems. One scientific uncertainty regarding certain mCDR techniques is the potential increase in precipitation and export of calcium carbonate minerals by calcifying organisms in response to increases in carbonate mineral saturation states induced by the approaches. This in turn could decrease the efficiency of these techniques. This project led by researchers at the University of Washington aims to quantify the magnitude and uncertainty of this feedback on mCDR additionality through the use of a small model ensemble driven by industry-informed mCDR scenarios. The results will inform the growing mCDR market.

Human Dimensions

Under the Human Dimensions theme in the Open Ocean Chapter, there is one objective:

1. Open Ocean Human Dimensions Research Objective 2.7: Assess direct and indirect effects of OA on communities

Table 2.4, below, summarizes the implementation of each action under this research objective.

Table 2.4: A summary of the actions under the human dimensions theme objective in the Open Ocean Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Open Ocean Acidification Research Objective 2.7				
2.7.1	Identify relationships among key social, cultural and economic drivers to biophysical, fishery and ecosystem parameters along the open ocean to coastal continuum to predict potential responses from future OA scenarios	1	▲	OAP
2.7.2	Create regional economic impact and behavioral models for marine resource-reliant industries that include open ocean forcing to inform consideration of benefits and costs of alternative management strategies to mitigate impacts from OA	0	◆	n/a
2.7.3	Develop management objectives related to human-use sectors, ecosystem services and well-being and derive indicators to monitor effectiveness of management strategies	0	◆	n/a

LOOKING FORWARD

There are a number of actions in the Open Ocean Chapter with limited or no known progress that could warrant additional resources in the second half of the decade. In particular, three of the four biological sensitivity actions, focused on developing statistical, biogeochemical and phylogenetic tools to assess the impact of OA on marine organisms, have received minimal investment. Furthermore, the three actions pertaining to human dimensions research have received minimal or no investment. Implementation is needed across all actions under the human dimensions theme in the Open Ocean chapter, including identifying economic impacts and developing management objectives that help people adapt to changing ocean chemistry impacts.

Image Credit: David Sinson, NOAA, Office of Coast Survey

CHAPTER 3

ALASKA REGION ACIDIFICATION RESEARCH

Chapter 3 of the Research Plan is titled, “Alaska Region Acidification Research” (the Alaska Chapter). This chapter sets research objectives relevant to the Alaska region, including the waters of the Gulf of Alaska, Eastern Bering Sea and surrounding the Aleutian Islands. There are a total of eight research objectives, with three under environmental change, three under biological sensitivity and two under human dimensions. There are a total of 25 actions across the eight research objectives: 14 of which are making good progress toward implementation and seven of which have limited progress toward implementation and four actions with no progress made toward implementation (Table 3.1).

Table 3.1: The Alaska Chapter has a total of 25 actions: Fourteen actions have made good progress toward implementation (Green Circle Actions), seven actions have made limited progress toward implementation (Yellow Triangle Actions) and four actions have made no progress toward implementation (Red Diamond Actions).

Chapter Title	**Number of Actions**	●	▲	◆
Chapter 3: Alaska Region Acidification Research	25	14	7	4

Across the Alaska Chapter, there are a total of eight environmental change actions,10 biological sensitivity actions and seven human dimensions actions. Figure 3.1 summarizes the progress made toward each of the actions under the three thematic areas.

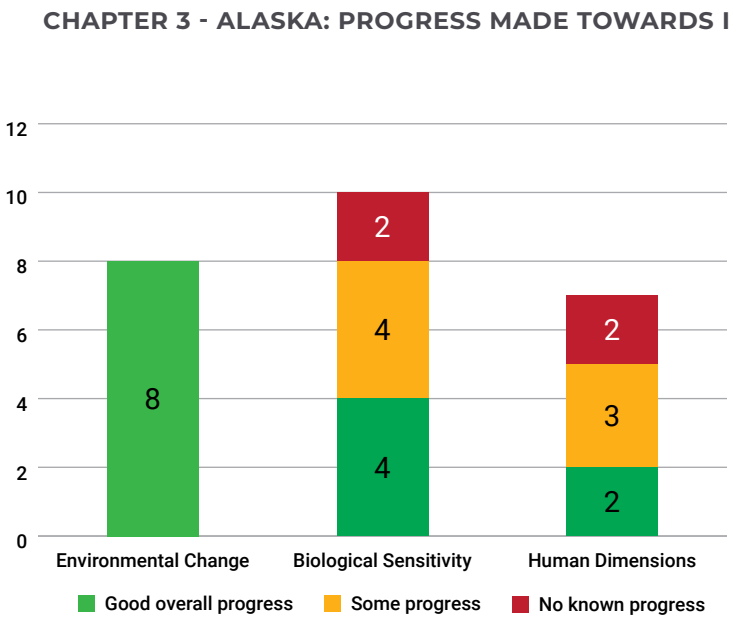


Fig. 3.1: The Alaska Chapter includes a total of eight environmental change actions, 10 biological sensitivity actions and seven human dimensions actions. Good progress is being made toward implementing all environmental change actions. Of the 10 biological sensitivity actions, good progress is being made toward implementing four actions, limited progress has been made on implementing four actions and no progress has been made on two actions. Of the seven human dimensions actions, good progress is being made toward implementing two actions, limited progress has been made on implementing three actions and no progress has been made on two actions.

Environmental Change

Under the Environmental Change theme in the Alaska Chapter, there are three objectives:

1. The Alaska Environmental Change Research Objective 3.1: Characterize seasonal cycles of OA and regional vulnerabilities
2. The Alaska Environmental Change Research Objective 3.2: Characterize future OA trajectories at local to regional spatial scales
3. The Alaska Environmental Change Research Objective 3.3: Develop a distributed, community-level coastal monitoring network

Table 3.2 below summarizes the implementation of each action under its respective research objective.

Table 3.2: A summary of the actions under the environmental change theme objectives in the Alaska Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Alaska Environmental Change Research Objective 3.1				
3.1.1	Maintain fixed-site moored observation network including existing moorings such as M2 and GAK	5	●	GOMO, IOOS, OAP
3.1.2	Conduct ship-based surveys that identify spatial and regional variability in carbonate parameters across important fisheries habitats	9	●	AFSC, GOMO, IOOS, OAP, PMEL
3.1.3	Conduct ship-based process studies to improve fundamental understanding of OA drivers including impacts of advective transport, riverine discharge, seasonal ice melt, pulses of primary productivity, benthic respiration and biological responses	5	●	GOMO, OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Alaska Environmental Change Research Objective 3.2				
3.2.1	Support and validate existing regional ocean models for short and long-term forecasting	7	●	OAP, PMEL
3.2.2	Develop OA indicators that link ecosystem exposure to OA and fisheries population dynamics	7	●	OAP, PMEL
The Alaska Environmental Change Research Objective 3.3				
3.3.1	Develop information networks and data management procedures to ensure accurate and timely reporting of OA conditions	5	●	OAP, PMEL
3.3.2	Work with local communities and shellfish growers to identify local monitoring needs. Provide training and technical expertise to sustain and further develop Alaska's coastal OA monitoring network through establishment of additional OA monitoring sites	4	●	AFSC, IOOS, OAP, SG
3.3.3	Provide high spatial and temporal resolution data from this network to meet real-time monitoring needs of local communities and to improve our understanding and forecasting of coastal acidification throughout Alaska	10	●	IOOS, OAP, PMEL, SG

Image Credit: Michael Theberge, Coastal Nomad

FEATURED PROJECT

FORECASTS FOR ALASKA FISHERIES

Understanding seasonal changes in ocean acidification in Alaskan waters and the potential impacts to the multi-billion-dollar fishery sector is a main priority. Through work funded by NOAA's Ocean Acidification Program, the Pacific Marine Environmental Laboratory developed a model capable of depicting past ocean chemistry conditions for the Bering Sea and is now testing the ability of this model to forecast future conditions. This model is being used to develop an ocean acidification indicator provided to fisheries managers in the annual NOAA Eastern Bering Sea Ecosystem Status Report.

Biological Sensitivity

Under the Biological Sensitivity theme in the Alaska Chapter, there are three objectives:

1. The Alaska Biological Sensitivity Research Objective 3.4: Characterize sensitivity and adaptive potential of critical resource species to OA and other stressors
2. The Alaska Biological Sensitivity Research Objective 3.5: Examine sensitivity of critical lower trophic level "bottleneck" species to OA
3. The Alaska Biological Sensitivity Research Objective 3.6: Identify the ecosystem-wide impacts of OA

Table 3.3 below summarizes the implementation of each action under its respective research objective.

Table 3.3: A summary of the actions under the biological sensitivity theme objectives in the Alaska Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Alaska Biological Sensitivity Research Objective 3.4				
3.4.1	Conduct experiments to understand the range of life-stage responses to OA and associated environmental stressors	8	●	AFSC, OAP
3.4.2	Conduct experiments on potential for organismal acclimation and transgenerational adaptation to future environments	6	●	AFSC, OAP
3.4.3	Expand research to include under-studied species including Alaska salmon and bivalves that have commercial and subsistence value	3	▲	OAP
3.4.4	Expand experimental system capabilities to incorporate time-varying environmental conditions and expand capacity for multi-stressor experiments	4	●	AFSC, OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Alaska Biological Sensitivity Research Objective 3.5				
3.5.1	Conduct OA sensitivity studies on regionally important ecosystem drivers such as krill, bivalves, echinoderms, copepods, pteropods and shrimps	1	▲	NWFSC, OAP, SWFSC
3.5.2	Apply phylogenetic and trait-based analyses to identify sensitive species that have broad impact on the food web	0	◆	n/a
3.5.3	Use these analyses to help identify species that may serve as bio-indicators of OA impacts in the region	0	◆	n/a
The Alaska Biological Sensitivity Research Objective 3.6				
3.6.1	Conduct laboratory experimental studies to quantify the effects of OA and in situ field observations to validate and parameterize OA impacts to biological couplings (predator-prey interactions) in food web and climate-enhanced models	1	▲	IOOS
3.6.2	Improve understanding of responses to OA by incorporating consideration of environmental and ecosystem variability including episodic warming, harmful algal blooms and mass mortality events	8	●	AFSC, IOOS, OAP, PMEL
3.6.3	Develop integrated climate-biological-socioeconomic models that link the physiology, growth, behavior and distribution of species to spatial and temporal patterns of corrosive water exposure which will allow for evaluation of direct and cascading effects of OA on the social-ecological system	3	▲	AFSC, IOOS, OAP

Image Credit: David Csepp, NMFS AKFSC ABL

FEATURED PROJECT

EFFECTS OF OCEAN ACIDIFICATION AND TEMPERATURE ON ALASKAN CRABS

Long-term declines of red king crab in Bristol Bay, Alaska may be partially attributed to ocean acidification conditions. These impacts may be partially responsible for the fishery closures during the 2021–2022 and 2022–2023 seasons. Researchers found that ocean acidification negatively impacts Alaskan crabs generally by changing physiological processes, decreasing growth, increasing death rates and reducing shell thickness. Funded by the Ocean Acidification Program, scientists at the Alaska Fisheries Science Center continue to investigate the responses of early life history stages and study the potential of various Alaska crabs to acclimate to changing conditions. Results will inform models that will use the parameters studied to predict the effects of future ocean acidification on the populations of red king crab in Bristol Bay as well as on the fisheries that depend on them. Fishery managers will better be able to anticipate and manage stocks if changing ocean chemistry affects stock productivity and thus the maximum sustainable yield.

More about this work

Human Dimensions

Under the Human Dimensions theme in the Alaska Chapter, there are two objectives:

1. The Alaska Human Dimensions Research Objective 3.7: Improve assessment of socioeconomic impacts of OA on fisheries-dependent communities
2. The Alaska Human Dimensions Research Objective 3.8: Assess community sensitivity and resiliency to OA impacts on critical nutritional and cultural resources

Table 3.4 below summarizes the implementation of each action under its respective research objective.

Table 3.4: A summary of the actions under the human dimensions theme objectives in the Alaska Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Alaska Human Dimensions Research Objective 3.7				
3.7.1	Use food web models to account for direct and indirect OA effects on multiple species and incorporate these effects in spatial bioeconomic models that represent biological and technical interactions among species and stocks	0	◆	n/a
3.7.2	Analyze direct and indirect effects of OA and develop and apply a new framework for biological and bioeconomic reference points with multiple species that includes aggregate maximum sustainable yield (MSY) and multispecies maximum economic yield (MEY)	0	◆	n/a
3.7.3	Consider OA ontogenetic effects on growth and survival of animals in order to assess tradeoffs and potential co-benefits of various management interventions that target different life-history stages and population productivity bottlenecks	2	▲	OAP
3.7.4	Use integrated assessment models to inform stock assessment status and recovery plans	3	▲	OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Alaska Human Dimensions Research Objective 3.8				
3.8.1	Work with local communities including indigenous peoples to identify locally-important species for additional OA sensitivity analyses and work with community leaders to disseminate the findings of these analyses	4	●	AFSC, OAP, SG
3.8.2	Analyze the economic and sociological effects of OA-induced food web alterations that may impact the harvest of nutritionally and culturally important species including large marine mammals	3	▲	AFSC, OAP, SG
3.8.3	Support community awareness of OA impacts and work with local stakeholders to identify economic and sociological sensitivities and evaluate and implement adaptive responses	9	●	IOOS, OAP, SG

Image Credit: Allen Shimada, NOAA/NMFS/OST/AMD

FEATURED PROJECT

BIOECONOMIC MODELING TO INFORM ALASKA FISHERIES MANAGEMENT

Bioeconomic models are a multidisciplinary tool that use oceanography, fisheries science and social science to assess socioeconomic impacts. Funded by the Ocean Acidification Program, researchers at the Alaska Fisheries Science Center use a bioeconomic model to study the impacts of ocean acidification on Eastern Bering Sea crab, northern rock sole and Alaska cod. The goal is to predict how ocean acidification will affect abundance yields and income generated by the fisheries. This work informs the potential economic impacts of ocean acidification and future decision making and research planning.

More about this work

LOOKING FORWARD

While substantial progress has been made toward implementing the actions under Environmental Change, a number of the actions under Biological Sensitivity and Human Dimensions have no or limited progress made toward their implementation. Under the theme of biological sensitivity, no investment has yet been made in identifying sensitive species that may have broad impacts on the food web or identifying species to serve as bioindicators for the region. Regarding human dimensions, the most investment is needed toward actions related to assessing the socioeconomic impacts of OA to fishing-dependent communities.

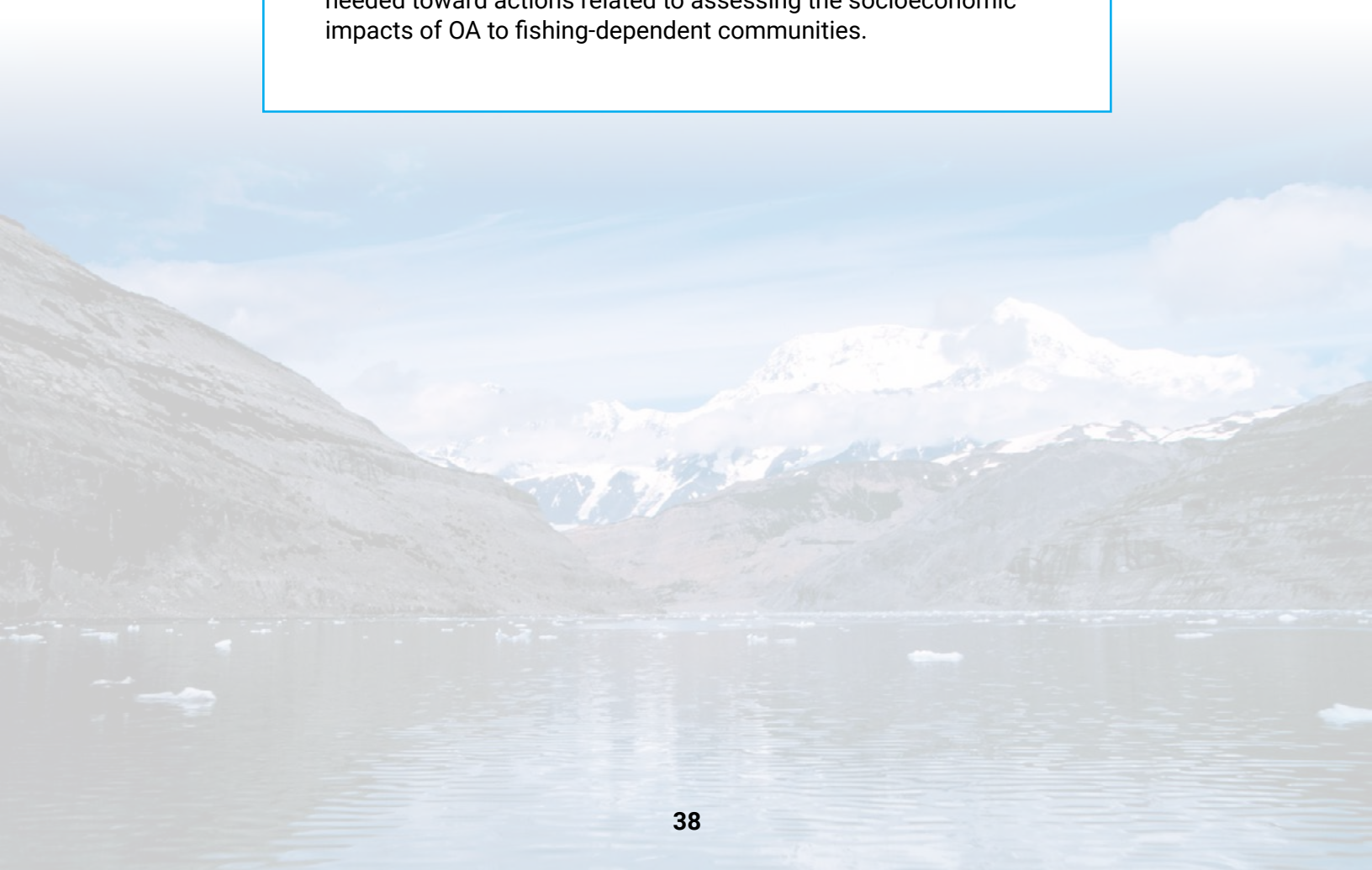


Image Credit: Dr. Pablo Clemente-Colon, National Ice Center

CHAPTER 4

ARCTIC REGION ACIDIFICATION RESEARCH

Chapter 4 of the Research Plan is titled, “Arctic Region Acidification Research” (the Arctic Chapter). This chapter includes research objectives relevant to the Arctic Region, which includes the broad continental shelf areas surrounding northern Alaska, the Northern Bering, Chukchi and Beaufort Seas. There are seven research objectives in this chapter, two focused on environmental change, four focused on biological sensitivity and one focused on human dimensions. There are seventeen actions across the seven research objectives: one of which is making good progress toward implementation,10 are making some progress toward implementation and six have no known progress (Table 4.1).

Table 4.1: The Arctic Chapter has a total of seventeen actions: One action has made good progress toward implementation (Green Circle Actions), 10 actions have made some progress made toward implementation (Yellow Triangle Actions) and six actions have made no known progress toward implementation (Red Diamond Actions).

Chapter Title	**Number of Actions**	●	▲	◆
Chapter 4: Arctic Region Acidification Research	17	1	10	6

Across the Arctic Chapter there are a total of six environmental change actions, nine biological sensitivity actions and two human dimensions actions. Figure 4.1 summarizes the progress made toward each of these actions under the three thematic areas.

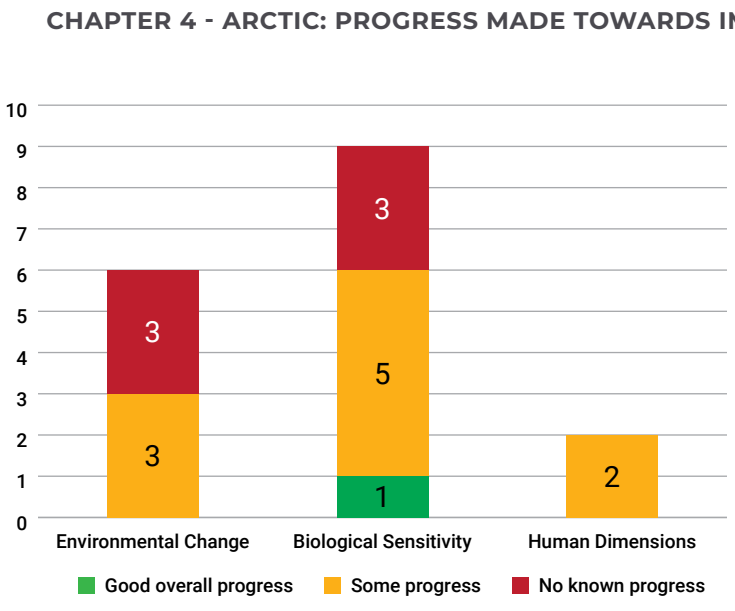


Figure 4.1: The Arctic Chapter includes a total of six environmental change actions, nine biological sensitivity actions and two human dimension actions. Of the six environmental change actions limited progress is being made toward implementing three actions and no progress has been made on three actions. For the biological sensitivity actions good progress has been made toward one, some progress is being made toward implementing five and no known progress has been made on three actions. Some progress has been made on both of the human dimensions actions.

Environmental Change

Under the Environmental change theme in the Arctic Chapter, there are two objectives.

1. The Arctic Chapter Environmental Change Research Objective 4.1: Targeted observations and process studies to increase understanding of OA dynamics and impacts
2. The Arctic Chapter Environmental Change Research Objective 4.2: Build high resolution regional models able to simulate fine-scale OA processes

Table 4.2 below summarizes the implementation of each action under these research objectives.

Table 4.2: A summary of the actions under the environmental change theme objective in the Arctic Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Arctic Environmental Change Research Objective 4.1				
4.1.1	Quantify anthropogenic CO_2 concentrations through coastal and open ocean cruises in order to constrain rates of anthropogenic coastal acidification versus contributions from other processes such as advective transport, changing river inputs, upwelling rates, source water advection, or locally enhanced air-sea exchange	0	◆	n/a
4.1.2	Sustain long-term monitoring of carbonate chemistry observations linked to biological sampling, which will increase our understanding of ecosystem impacts of OA	2	▲	IOOS, AFSC
4.1.3	Design process studies to help the scientific community target key uncertainties in carbonate cycling, such as wintertime cycles and seasonal respiration rates	0	◆	n/a

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Arctic Environmental Change Research Objective 4.2				
4.2.1	Use process studies to generate new observations that can be used to validate regional models and test their predictive capability	1	▲	OAP
4.2.2	Use validated models to project OA trends on multi-year to multi-decadal time frames and develop historical hindcasts of OA variables that can be used to provide context to existing decadal scale ecological time series, such as those that underpin the DBO	1	▲	AFSC
4.2.3	Use validated models to pursue short-term seasonal forecasts of corrosive water conditions and other decision support products for NOAAs stakeholders in the Arctic region	0	◆	n/a

Image Credit: NOAA Pacific Marine Environmental Laboratory

FEATURED PROJECT

ICE-COVERED WATERS: CONNECTING SEA ICE WITH OCEAN CARBON SYSTEMS

Models are an important tool for understanding ocean acidification in the Arctic, where it is difficult to collect observations. However, more research is needed to evaluate the best way to incorporate the relationship between the ice and ocean carbon systems into models. In a collaborative project funded by NOAA's Ocean Acidification Program and Fisheries and Oceans Canada, researchers compare two models with different settings to assess impacts in modeling the carbon system in the Bering Sea. The project also evaluates the model using observations collected by Saildrones, autonomous vehicles that provide high spatiotemporal coverage. This project will improve ocean acidification models for the Sub-Arctic and Arctic, enhancing capacity for ocean acidification projections in ice-covered waters.

Biological Sensitivity

Under the Biological Sensitivity theme in the Arctic Chapter, there are four objectives:

1. The Arctic Biological Sensitivity Research Objective 4.3: Conduct laboratory studies of OA impacts in economically and ecologically important species
2. The Arctic Biological Sensitivity Research Objective 4.4: Conduct ecosystem-level studies to evaluate OA impacts
3. The Arctic Biological Sensitivity Research Objective 4.5: Biological projection and forecast development
4. The Arctic Biological Sensitivity Research Objective 4.6: Support NOAA's contributions to U.S. Arctic fisheries management

Table 4.3 below summarizes the implementation of each action under these research objectives.

Table 4.3: A summary of the actions under the biological sensitivity theme objective in the Arctic Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Arctic Biological Sensitivity - Research Objective 4.3				
4.3.1	Conduct laboratory studies on high-priority species such as potential fisheries species (snow crab, *Chionoecetes opilio*; Arctic cod, *Boreogadus saida*; and saffron cod, *Eleginus gracilis*), species important in the food web such as *Hyas coarctatus* and *Ophiura sarsi* and species that are important food resources for protected species	5	●	OAP, AFSC
4.3.2	Examine OA and temperature interactions in laboratory and field experiments to quantify potential synergistic responses to these co-stressors	3	▲	OAP, AFSC
4.3.3	Conduct laboratory experiments on effects of OA and concurrent stressors, such as salinity and food quality/quantity, using species likely to encounter these environmental conditions, which exhibit potential vulnerabilities to such conditions and meet qualifications listed in Action 4.3.1	1	▲	OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
4.3.4	Use gene expression, metabolomic and proteomic measurements to understand the physiological pathways affected by OA, particularly for species identified in initial response experiments as vulnerable to OA	2	▲	OAP, AFSC
Arctic Biological Sensitivity - Research Objective 4.4				
4.4.1	Establish reference conditions for Arctic ecosystems and invest in sustained ecosystem monitoring of important Arctic species and zooplankton	1	▲	IOOS
4.4.2	Perform targeted process studies to quantify important ecosystem pathways	1	▲	OAP
Arctic Biological Sensitivity - Research Objective 4.5				
4.5.1	Use appropriate modeling techniques, including single-species, ecosystem and qualitative models, to understand the likely effects of OA in the Arctic	0	◆	n/a
Arctic Biological Sensitivity - Research Objective 4.3				
4.6.1	Design targeted carbonate chemistry products that support the U.S. Arctic Fisheries Management Plan and the FiSCAO Science Plan	0	◆	n/a
4.6.2	Include OA risk information when designing fisheries management strategies for the U.S. Arctic region	0	◆	n/a

Image Credit: NOAA Office of Ocean Exploration

FEATURED PROJECT

SENSITIVITY OF ARCTIC COD TO OCEAN ACIDIFICATION

Arctic cod is a keystone species throughout Arctic ecosystems. Productivity could be negatively affected by ocean acidification. Scientists at the Alaska Fisheries Science Center study the effects of ocean acidification on Arctic cod reproduction and offspring viability. Understanding the influence on reproduction is a first step in identifying the potential of Arctic cod and other fish to acclimate and adapt, which can inform forecasts of population level effects of ocean acidification.

More about this work funded by the Ocean Acidification Program and Alaska Fisheries Science Center

Human Dimensions:

Under the Human Dimensions theme in the Arctic Chapter, there is one objective:

1. The Arctic Human Dimensions Research Objective 4.7: Assess regional adaptation strategies to OA coupled with environmental change

Table 4.4 below summarizes the implementation of each action under this research objective.

Table 4.4: A summary of the actions under the human dimensions theme objective in the Arctic Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Arctic Human Dimensions - Research Objective 4.7				
4.7.1	Survey commercial, local and indigenous communities to better understand stakeholder and decision maker needs for OA information and integrate traditional knowledge and perspectives into decision support products	1	▲	IOOS
4.7.2	Work with organizations that have links to communities, including the Arctic Waterways Safety Committee, Adapt Alaska and the Alaska Ocean Observing System's (AOOS) Alaska OA Network (AK-OAN) to develop and to transition decision support products	2	▲	IOOS

Image Credit: Mandy Lindeberg, NOAA/NMFS/AKFSC

FEATURED PROJECT

ALASKAN TRIBAL COMMUNITIES INCREASE OCEAN ACIDIFICATION MONITORING CAPACITY

A community sampling program is filling critical gaps in ocean acidification monitoring in Alaska waters. About 20 communities across the state collect weekly water samples in areas of community importance. This work, coordinated and implemented by Tribes in the region, provide baseline data in areas important for harvesting shellfish and other species of subsistence and cultural value. The Alaska Ocean Acidification Network leads a Tribal Monitoring Working Group to help with coordination, technical assistance and data interpretation. NOAA Integrated Ocean Observing System (IOOS) and NOAA's Ocean Acidification Program support these efforts, in addition to the Environmental Protection Agency, Bureau of Indian Affairs and other funding partners beyond NOAA.

LOOKING FORWARD

NOAA began to make progress toward the biological sensitivity actions in the Arctic region, though additional work is needed to provide ocean acidification for fisheries management to address gaps. Limited investment toward environmental change and human dimensions actions leave opportunity for future investment in the latter half of the decade. Six actions have received no investment and these may be important gaps to address, including quantifying anthropogenic CO_2 concentrations through coastal and open ocean cruises to best understand processes, process studies to target uncertainties, short-term forecasts and continued studies and modeling and forecasts for fisheries management.

Image Credit: NOAA West Coast Fisheries

CHAPTER 5

WEST COAST REGION ACIDIFICATION RESEARCH

Chapter 5 is titled, “West Coast Region Acidification Research” (the West Coast Chapter). This chapter includes the waters, inland seas and continental shelf of Washington, Oregon and California. There are a total of seven research objectives: three pertaining to environmental change, three to biological sensitivity and two to human dimensions. The West Coast Chapter includes 25 actions across the seven research objectives: 19 of which are making good progress toward implementation and six that have limited progress toward implementation (Table 5.1).

Table 5.1: The West Coast Chapter has a total of 25 actions: Nineteen actions have made good progress toward implementation (Green Circle Actions), six have made limited progress toward implementation (Yellow Triangle Actions) and none have made no known progress toward implementation (Red Diamond Actions).

Chapter Title	**Number of Actions**	●	▲	◆
Chapter 5: West Coast Region Acidification Research	25	19	6	0

The West Coast Chapter includes a total of nine environmental change actions, nine biological sensitivity actions and seven human dimensions actions. Figure 5.1 summarizes the progress made toward each of these actions under the three thematic areas.

CHAPTER 5 - WEST COAST: PROGRESS MADE TOWARDS IMPLEMENTING ACTIONS ACROSS THEMATIC AREAS

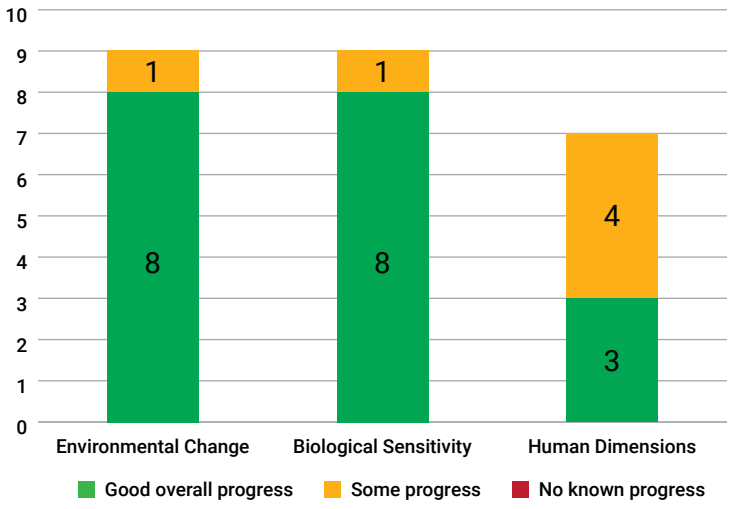


Fig. 5.1: The West Coast Chapter includes a total of nine environmental change actions, nine biological sensitivity actions and seven human dimensions actions. Of the nine environmental change actions, good progress is being made toward implementing eight actions and limited progress has been made on one action. Biological sensitivity related actions exhibit the same progress. Under the human dimensions theme, good progress is being made toward three of the actions and limited progress has been made toward implementing four actions. There are no actions for any of the objectives that have made no known progress.

Environmental Change

Under the Environmental Change theme in the West Coast Chapter, there are three objectives:

1. The West Coast Environmental Change Research Objective 5.1: Improve characterization of OA parameters in subsurface environments that are critical habitats to commercially and ecologically important species
2. The West Coast Environmental Change Research Objective 5.2: Enhance understanding of the relationships between biological systems and chemical conditions, including effective indicators of change for various habitats
3. The West Coast Environmental Change Research Objective 5.3: Advance analytical tools that can better describe ocean conditions in the past, present and future

Table 5.2 summarizes the implementation of each action under these research objectives.

Table 5.2: A summary of the actions under the environmental change theme objective in the West Coast Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The West Coast Environmental Change - Research Objective 5.1				
5.1.1	Ensure that conditions and rates of environmental change of OA and interacting stressors—particularly temperature, carbon chemistry, oxygen, nutrients and HABs—are assessed via co-located observations in critical habitats for key species at vulnerable life stages, as well as for their food resources	28	●	CRP, IOOS, OAP, PMEL, SG with additional NOPP and IRA support
5.1.2	Enhance moorings and profiling platforms to include additional chemical and biological sensors for subsurface waters to delineate rates of change of critical parameters	5	●	IOOS and OAP
5.1.3	Continue to quantify anthropogenic CO_2 concentrations through coastal and open ocean cruises, which collect the data needed to attribute carbonate chemistry change to anthropogenic acidification versus contributions from other processes	9	●	IOOS, OAP, PMEL

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
5.1.4	Provide measured and calculated OA products necessary for validation of underlying physical and biogeochemical processes in coupled physical-biogeochemical coastal models of acidification and model output	16		IOOS, NMS, OAP, PMEL with additional NOPP and IRA support
The West Coast Environmental Change - Research Objective 5.2				
5.2.1	Incorporate biological observations into physical and chemical time-series (e.g., research cruises, long-term monitoring at sentinel sites such as National Marine Sanctuaries, shellfish hatcheries, underway sampling on ships, autonomous platforms)	11		CRP, IOOS, NMS, OAP PMEL
5.2.2	Develop procedures to utilize pteropods and other species as West Coast-specific indicators of species and ecosystem status and change across different habitats	6		CRP, OAP, PMEL
The West Coast Environmental Change - Research Objective 5.3				
5.3.1	Develop models that can be validated, parameterized and evaluated by observational data (e.g., moored time-series, nearshore stations) and that include chemical and biological rates key for understanding the progression of OA	13		CRP, IOOS, OAP, PMEL, SG with additional NOPP and IRA support
5.3.2	Develop short-term and seasonal forecasts and synthesis products that can support annual industry, tribal and management decision points and decadal predictions that support planning, policy and adaptation among West Coast states, tribes and stakeholders	11		CRP, IOOS, OAP, PMEL, Sea Grant with additional NOPP and IRA support

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
5.3.3	Better utilize West Coast satellite observations and satellite-derived products to complement and provide independent estimates of spatially resolved current and upcoming ocean conditions from surface to benthic habitats	3	▲	OAP, PMEL

Image Credit: Olympic Coast National Marine Sanctuary

FEATURED PROJECT

INTEGRATED MULTISTRESSOR OBSERVATIONS, MODELING AND EXPERIMENTS TO INFORM MANAGEMENT IN THE NORTHERN CALIFORNIA CURRENT

Ocean acidification, hypoxia, marine heatwaves and harmful algal blooms are leading environmental stressors in the northern California Current Ecosystem, impacting ecosystems, fisheries, aquaculture and human communities. This project constructs a comprehensive synthesis of multi-stressor exposure using the region's extensive ocean observing assets to characterize real-world conditions. Modeling will then characterize future dynamics for these multi-stressors. Finally, this project integrates information on the response of Dungeness crab and krill to these multi-stressors to help fisheries, state and Tribal resource managers prepare for changing ocean conditions.

More about this project, supported by CPO, IOOS, NCCOS, NMS, NOAA and OAP

Biological Sensitivity

Under the Biological Sensitivity theme in the West Coast Chapter, there are three objectives:

1. The West Coast Region Biological Sensitivity Research Objective 5.4: Understand species sensitivity to OA and characterize underlying mechanisms
2. The West Coast Region Biological Sensitivity Research Objective 5.5: Investigate the potential for species to acclimate and/or adapt to OA
3. The West Coast Region Biological Sensitivity Research Objective 5.6: Enable the detection and attribution of direct and indirect impacts of OA on managed species and ecosystems

Table 5.3 summarizes the implementation of each action under these research objectives.

Table 5.3: A summary of the actions under the biological sensitivity theme objective in the West Coast Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The West Coast Region Biological Sensitivity - Research Objective 5.4				
5.4.1	Conduct laboratory sensitivity studies on species harvested in federal, state and tribal fisheries along the West Coast and the prey species that support them	14	●	CRP, NWFSC, OAP, SG, SWFSC
5.4.2	Develop and implement methods to generate data on the mechanisms driving species sensitivity, including acid-base balance, 'omics approaches and neural and behavioral functioning to elucidate sub-lethal effects of OA conditions and possible adaptation	12	●	NWFSC, OAP, SG with additional NOPP support
5.4.3	Assess how knowledge of sensitivity based on laboratory studies translates to expressions of sensitivity to different carbonate chemistry conditions and multiple stressors in the field	15	●	CRP, NWFSC, OAP, SG, SWFSC with additional NOPP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The West Coast Region Biological Sensitivity - Research Objective 5.5				
5.5.1	Conduct multi-generational, complete life-cycle laboratory studies to characterize sensitivity to OA	1	▲	SG
5.5.2	Assess how OA sensitivity varies within and among individuals, strains and populations of a species in field and aquaculture studies to improve understanding of intra- and inter-specific variance, which has enormous implications for understanding how to manage marine resources for OA	16	●	CRP, NWFSC, OAP, PMEL, SG, with additional NOPP support
5.5.3	Employ molecular techniques to better understand the influence of OA on individuals and populations	16	●	NWFSC, OAP, PMEL, SG
The West Coast Region Biological Sensitivity - Research Objective 5.6				
5.6.1	Develop Habitat Suitability Indices, which provide depth- and time-integrated metrics of species exposure to challenging environmental conditions and can be integrated into forecasts and predictions	7	●	OAP, PMEL, SG
5.6.2	Model species, food web and ecosystem responses to OA to understand the consequences of OA and the success of management strategies for sustainable harvests and conservation. Intensive numerical models can join data and tools from various scientific disciplines in ways that conceptual models cannot	11	●	CRP, NWFSC, OAP, PMEL, SWFSC with additional NOPP support
5.6.3	Conduct biological monitoring and data analysis at robust enough levels to detect species or ecosystem change attributable to OA and specifically to anthropogenic carbon uptake	7	●	CRP, NMS, OAP, PMEL

Image Credit: Austin Triggs, ONMFS / NMFS

FEATURED PROJECT

ASSESSING OCEAN ACIDIFICATION IMPACTS TO DUNGENESS CRAB

The Dungeness crab fishery is the most valuable on the U.S. West Coast. With demonstrated sensitivity to ocean acidification at early life stages, this ecologically and economically important crab and the communities that depend on the fishery may be at risk. This project further investigates the physical and developmental effects of ocean acidification and compares individuals from different populations. Findings helped assess differences in vulnerabilities in the region and build knowledge of the underlying variability necessary to craft an adaptive response to ocean acidification.

More about this project supported by NOAA's Northwest Fisheries Science Center and the Ocean Acidification Program.

Human Dimensions

Under the Human Dimensions theme in the West Coast Chapter, there are two objectives:

1. The West Coast Region Human Dimensions Research Objective 5.7: Improve understanding of the risks to social, cultural and economic well-being of fishing and coastal communities that are dependent on OA-sensitive species and the associated social and economic drivers of OA vulnerability
2. The West Coast Region Human Dimensions Research Objective 5.8: Improve understanding and communication of adaptation strategies of fishing and coastal communities

Table 5.4 summarizes the implementation of each action under these research objectives.

Table 5.4: A summary of the actions under the human dimensions theme objective in the West Coast Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The West Coast Region Human Dimensions - Research Objective 5.7				
5.7.1	Collect new information (e.g., through the use of surveys and interviews) and synthesize existing information (e.g., commercial and recreational fisheries data, fishing community profiles and traditional and local knowledge) to better characterize the interactions of humans and environments and the importance of OA-sensitive species and ecosystems to people across scales	5	●	CRP, IOOS, OAP, NMS
5.7.2	Develop new OA-relevant social-ecological conceptual models and use these coupled models to estimate the risks to humans and community well-being (e.g., cultural, livelihood and health) and the distribution of risks across sectors and social and demographic factors	1	▲	OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
5.7.3	Improve models to 1) provide necessary decision support for estimating income and employment impacts of OA on commercial fisheries, aquaculture and coastal tourism and 2) relate the economic value of recreational crab and other shellfish harvesting to estimated changes in biomass	2	▲	CRP, OAP
5.7.4	Examine the synergistic, antagonistic and cascading effects of multiple and cumulative stressors on human vulnerability to address critical gaps in our knowledge of how OA-impacts interact with other environmental and socioeconomic stressors that communities must contend with	4	●	CRP, NMS, OAP with additional NOPP support
The West Coast Region Human Dimensions - Research Objective 5.8				
5.8.1	Develop information about adaptive capacity and specifically evaluate institutional structures and policy contexts that either help or hinder fisheries and communities in the face of change	4	▲	CRP, NMS, NWFSC, OAP
5.8.2	Identify alternative management actions to improve resilience of communities and ecosystems under OA conditions, for example by identifying resource management actions that generate indirect and co-benefit flows to communities, reflect community priorities and reduce potential negative consequences from management decisions to communities	4	▲	CRP, NMS, OAP, OofA
5.8.3	Provide decision-relevant information to managers and industry, including developing technical tools for simulating scenarios and evaluating the socioeconomic tradeoffs of potential management actions related to OA	12	●	CRP, IOOS, NMS, OAP, OofA, SG with additional NOPP and IRA support

Image Credit: Crew and Officers of NOAA Ship FAIRWEATHER

FEATURED PROJECT

OCEAN ACIDIFICATION SENTINEL SITE ON THE OLYMPIC COAST

NOAA's Office of National Marine Sanctuaries established the Ocean Acidification Sentinel Site (OASeS) off the Olympic coast in Washington in 2019 after extensive coordination with tribal and state representatives, the Olympic Coast Sanctuary Advisory Council and scientists working in the region. OASeS focuses research, monitoring, outreach and public engagement related to ocean acidification and related issues, such as hypoxia and their impacts to natural resources, ecosystems, cultures, communities and economies of the area. It aims to inform Indigenous and other coastal communities that have high dependence on healthy ocean ecosystems and helps them prepare and adapt to ocean change.

Learn more about the Sentinel Site, supported by NOAA's National Marine Sanctuaries.

LOOKING FORWARD

There are a number of actions in the West Coast Chapter with limited progress that could warrant additional resources in the next five years. For monitoring and modeling the environment, additional focus could improve utilizing West Coast satellite observations and satellite-derived products to complement and provide independent estimates of spatially resolved current and predicted ocean conditions. One area with limited progress for understanding the biological response to OA is continued investigation into multi-generational, complete life cycle laboratory studies. The Human Dimensions objectives saw the least progress of the categories and would benefit from continued implementation from information collection to modeling and product delivery.

Image Credit: Dr. Jean Kenyon, NOAA/NMFS/PIFSC

CHAPTER 6

PACIFIC ISLANDS REGION ACIDIFICATION RESEARCH

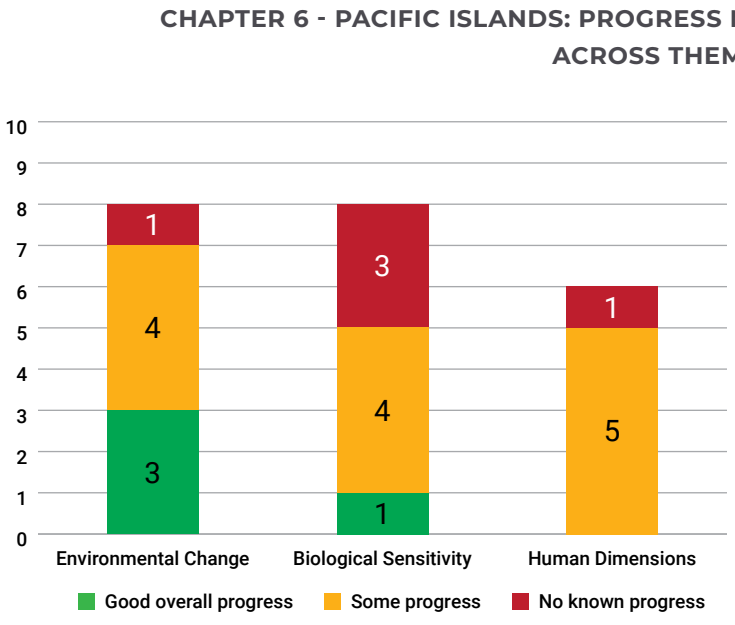
Chapter 6 is titled, “Pacific Islands Region Acidification Research” (the Pacific Islands Chapter). This chapter sets research objectives for understanding OA in the waters of the State of Hawai‘i, the Territories of American Samoa and Guam, the Commonwealth of the Northern Marianas Islands and the U.S. Pacific Remote Island Areas. There are a total of nine research objectives, three pertaining to each of the trifecta themes. There are a total of 22 actions across the nine research objectives: four of which are making good progress toward implementation, 13 of which have limited progress toward implementation and five with no known progress made (Table 6.1).

Table 6.1: The Pacific Islands Chapter has a total of 22 actions: Four actions are making good progress toward implementation (Green Circle Actions), 13 actions made have limited progress toward implementation (Yellow Triangle Actions) and five actions have made no known progress toward implementation (Red Diamond Actions).

Chapter Title	**Number of Actions**	●	▲	◆
Chapter 6: U.S. Pacific Islands Region Acidification Research	22	4	13	5

Across the Pacific Islands Chapter, there are a total of eight environmental change actions, eight biological sensitivity actions and six human dimensions actions. Figure 6.1 summarizes the progress made toward each of these actions under the three thematic areas.

Fig. 6.1: The Pacific Islands Chapter includes a total of eight environmental change actions, eight biological sensitivity



actions and six human dimensions actions. Of the eight environmental change actions, good progress is being made toward implementing three actions, limited progress has been made on four actions and no known progress has been made on one action. Of the eight biological sensitivity actions, good progress is being made toward implementing one action, limited progress has been made on four actions and no known progress has been made on three actions. Of the six human dimensions actions, limited progress has been made on five actions and no known progress has been made on one action.

Environmental Change

Under the Environmental Change theme in the

Pacific Islands Chapter, there are three objectives:

1. The Pacific Islands Region Environmental Change Research Objective 6.1: Continue monitoring and assessment of OA in coral reef ecosystems.
2. The Pacific Islands Region Environmental Change Research Objective 6.2: Expand regional OA observing system to include pelagic and deep-sea environments.
3. The Pacific Islands Region Environmental Change Research Objective 6.3: Create real-time and forecast OA spatial products.

Table 6.2 below summarizes the implementation of each action under this research objective.

Table 6.2: A summary of the actions under the environmental change theme objectives in the Pacific Islands Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Pacific Islands Environmental Change Research Objective 6.1				
6.1.1	Maintain carbonate chemistry water sampling in shallow coral reef environments and expand nearshore OA monitoring in collaboration with local partners to describe spatial patterns and longer-term temporal trends in OA across Pacific insular areas	9	●	NMS, OAP, OCM
6.1.2	Conduct short-term, high-resolution instrument deployments to measure carbonate chemistry and other physical and biogeochemical parameters (e.g., temperature, salinity, water flow, light and dissolved oxygen) and contextualize lower frequency observations (Action 6.1.1)	8	●	OAP, OCM, SG

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
6.1.3	Maintain and expand moored autonomous buoy deployments at representative coral reef sites and offshore reference stations and increase coordination and collaboration with other international moored observing networks in the region to document high-resolution temporal variability in carbonate chemistry and capture multi-decadal OA trends	9	●	NMS, OAP, OCM
The Pacific Islands Environmental Change Research Objective 6.2				
6.2.1	Maintain and expand shipboard underway pCO_2, dissolved inorganic carbon (DIC), total alkalinity (TA) and/or pH analyzers on NOAA ships to measure the two or more pelagic surface carbonate chemistry parameters needed to constrain full carbonate system chemistry along cruise tracks	0	◆	n/a
6.2.2	Deploy autonomous data collectors (e.g., Saildrones, gliders, biogeochemical-ARGO floats) equipped to measure at least two carbon parameters (pCO_2, pH, TA, DIC) and temperature, salinity and other physical and biogeochemical parameters at the ocean surface and along vertical depth profiles to augment or replace shipboard collections	2	▲	OAP
6.2.3	Collect subsurface oceanographic data and carbonate chemistry samples along vertical depth profiles to establish baseline carbonate chemistry levels and monitor OA in mesophotic, subphotic and deep-sea ecosystems	1	▲	OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Pacific Islands Environmental Change Research Objective 6.3				
6.3.1	Construct time-varying insular and pelagic maps of Pacific carbonate chemistry parameters (pCO_2, pH, Ωarag) using remote-sensing data, assimilative models and *in situ* sample data to provide regional-scale perspective on spatial patterns and temporal variability in OA	1	▲	OAP
6.3.2	Couple hydrodynamic and biogeochemical models with climate models to improve understanding of carbonate chemistry dynamics and OA prediction in both pelagic and coastal environments and identify hotspots and refugia	1	▲	OAP

Image Credit: Julie Bedford, NOAA

FEATURED PROJECT

LONG-TERM ASSESSMENT OF OCEAN ACIDIFICATION AND CORAL REEF HEALTH

The Office for Coastal Management's National Coral Reef Monitoring Program (NCRMP) provides consistent, sustained and long-term measurement of key indicators that gauge the status and trends of U.S. coral reef health. In the Pacific Islands, monitoring of climate change and ocean acidification indicators is led by the Pacific Islands Fisheries Science Center and supported by the Ocean Acidification Program. NCRMP monitoring in the region consists of diel carbonate chemistry sampling at fixed sites and discrete carbonate chemistry sampling at fixed and random sites. NCRMP also conducts ocean acidification ecological response monitoring, which include coral growth and calcification, net carbonate accretion and bioerosion rates. Coral reefs provide many ecosystem services like protection from storms and sea level rise and support fisheries and tourism that help safeguard coastal communities and economies.

Biological Sensitivity

Under the Biological Sensitivity theme in the Pacific Islands Chapter, there are three objectives:

1. The Pacific Islands Region Biological Sensitivity Research Objective 6.4: Assess direct OA impacts on key Pacific coral reef and pelagic species
2. The Pacific Islands Region Biological Sensitivity Research Objective 6.5: Evaluate indirect effects of OA on fisheries and protected species
3. The Pacific Islands Region Biological Sensitivity Research Objective 6.6: Determine ecosystem-scale OA impacts

Table 6.3 below summarizes the implementation of each action under this research objective.

Table 6.3: A summary of the actions under the biological sensitivity theme objectives in the Pacific Islands Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Pacific Islands Biological Sensitivity Research Objective 6.4				
6.4.1	Assess calcium carbonate accretion and dissolution on coral reefs and deep-sea coral habitats across latitudinal and depth gradients, paired with long-term monitoring of benthic and fish communities, to document the impacts of OA and other stressors on coral reef communities, describe resilience potential and identify priority areas for management or restoration efforts	4	●	OAP, SG, with additional NOPP support
6.4.2	Complete literature reviews and synthesis of OA impacts to growth, fecundity and mortality of key Pacific species to inform the development of sensitivity scalars of those organisms to decreased pH	1	▲	OAP
6.4.3	Conduct field assays, laboratory experiments and multi-stressor studies to measure OA sensitivity for focal taxa (e.g., calcareous plankton, larval fish, shallow and deep-sea corals, mollusks, coralline algae, seagrass and bioeroders), build OA response curves and assess effects on trophic and food web interactions	1	▲	NOPP support

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Pacific Islands Biological Sensitivity Research Objective 6.5				
6.5.1	Integrate plankton and trawl surveys, fish diet studies, fisheries data, stock assessments and laboratory experiments to assess OA-driven changes to the structure and energy flow of insular and pelagic food webs	0	◆	n/a
6.5.2	Assess effects of OA on abundance and distribution of seagrass beds and determine associated impacts on sea turtle grazing behavior and habitat availability	0	◆	n/a
6.5.3	Build carbonate sand budgets for beaches that serve as pupping and nesting grounds for monk seals and sea turtles to help assess the expected magnitude of changes in sand production related to reductions in coral, crustose coralline algae and calcareous macroalgae calcification rates	0	◆	n/a
The Pacific Islands Biological Sensitivity Research Objective 6.6				
6.6.1	Improve ecosystem model parameterizations by synthesizing carbonate chemistry observations, species-specific OA sensitivity data and response curves (Action 6.4.2)	3	▲	OAP, with additional NOPP support
6.6.2	Refine trophic interaction ecosystem models to include OA drivers and taxa responses in order to provide decision-support tools for fisheries and coastal resource management	2	▲	OAP, with additional NOPP support

Image Credit: K. Bahr

FEATURED PROJECT

ASSESSING ALKALINITY ENHANCEMENT ON CORAL REEF CALCIFIERS

Coral reefs are important ecosystems for marine biodiversity and human communities that can be impacted by ocean acidification. In a project supported through the National Oceanographic Partnership Program with funding from the Department of Energy, scientists are investigating how ocean alkalinity enhancement may help counteract the effects of ocean acidification. The goal of the research is to understand how Pacific tropical and subtropical corals and crustose coralline algae respond to immediate alkalinity additions and to determine the effects of chronic and acute exposure to ocean alkalinity enhancement. Laboratory and mesocosm experiments will test the mechanisms of calcification under different scenarios, with the goal of informing future coral restoration and ocean alkalinity enhancement activities.

More about this work

Human Dimensions

Under the Human Dimensions theme in the Pacific Islands Chapter, there are three objectives:

1. The Pacific Islands Human Dimensions Research Objective 6.7: Assess direct and indirect impacts of OA on Pacific communities
2. The Pacific Islands Human Dimensions Research Objective 6.8: Characterize community awareness and resilience to OA
3. The Pacific Islands Human Dimensions Research Objective 6.9: Develop innovative OA science communication products for diverse stakeholders

Table 6.4 below summarizes the implementation of each action under this research objective.

Table 6.4: A summary of the actions under the human dimensions theme objectives in the Pacific Islands Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Pacific Islands Human Dimensions Research Objective 6.7				
6.7.1	Identify the relationships of key social, cultural and economic drivers to biophysical, fishery and ecosystem parameters to predict potential responses from future OA scenarios	2	▲	OAP, SG
6.7.2	Create regional economic impact and behavioral models for marine resource-reliant industries to inform consideration of benefits and costs of alternative management strategies to mitigate impacts from OA	2	▲	OAP, SG
6.7.3	Develop management objectives related to human-use sectors, non-use values, ecosystem services and well-being and derive indicators to monitor effectiveness	1	▲	SG

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Pacific Islands Human Dimensions Research Objective 6.8				
6.8.1	Monitor trends in community awareness and perceptions of OA impacts and participation in stewardship activities across diverse stakeholders and make efforts to link with environmental (Research Objective 6.2) and biological sensitivity (Research Objective 6.3) trends to understand areas of coherence	0	◆	n/a
6.8.2	Couple analyses of biological sensitivity (Research Objective 6.4) with social vulnerability and adaptive capacity frameworks to inform local community mitigation planning and management	2	▲	OAP, with additional NOPP support
The Pacific Islands Human Dimensions Research Objective 6.9				
6.9.1	Pursue efforts to create visualization products and education and outreach resources targeting diverse stakeholders to communicate scientific findings and promote understanding and awareness of OA processes and potential impacts	3	▲	OAP, SG

Image Credit: Maria Haws, University of Hawaii

FEATURED PROJECT

AQUACULTURE RESEARCH AND OUTREACH ASSESSING OCEAN ACIDIFICATION MITIGATION

The Hilo Bay Research and Training Farm was established in 2011 by researchers to develop shellfish farming in collaboration with non-profit, educational and private sector partners to enhance community benefits. A new project is undertaking research, training and demonstration activities to develop a feasible model for a near-shore integrated multi-trophic aquaculture system that tests the use of four bivalves and *limu* (native seaweed) for water quality improvement, including ocean acidification mitigation. The project will focus on outreach on key coastal issues, such as water quality and sustainable economic development, and the results will be widely disseminated to interested groups and people throughout Hawai'i.

More about this work supported by Hawai'i Sea Grant

LOOKING FORWARD

While significant investment has been made in monitoring coral reef ecosystems, other actions under the Environmental Change theme related to monitoring pelagic and deep-sea environments and creating real-time and forecast spatial products need more investment. One action that has received no investment is maintaining underway systems to measure carbonate parameters on NOAA ships. Many actions under Biological Sensitivity are in need of additional investment. Specifically, three actions related to evaluating the indirect effects of OA on fisheries and protected species have not received any investment. No actions under Human Dimensions are classified as making good progress toward implementation. Opportunities for future investment include monitoring trends in community awareness of OA and developing management objectives.

Image Credit: Erik Zobrist, NOAA Restoration Center

CHAPTER 7

SOUTHEAST ATLANTIC AND GULF REGION ACIDIFICATION RESEARCH

The Southeast Atlantic and Gulf Region Acidification Research Chapter refers to the chapter in the Ocean, Coastal, and Great Lakes Acidification Research Plan: 2020-2029 titled, "Southeast Atlantic and Gulf of Mexico Region Acidification Research." This document will refer to that Research Plan chapter title as "Southeast Atlantic and Gulf Region Acidification Research" (the SE and Gulf Chapter). Furthermore, herein the region, Gulf of America, refers to the formerly known Gulf of Mexico, including the U.S. Exclusive Economic Zone and other waters referred to as Gulf of Mexico. This chapter includes research objectives that encompass continental shelf waters extending from the North Carolina to Florida coasts on the Atlantic seaboard and the marginal sea bounded by the U.S. Gulf Coast. While these two regions experience different stress factors with regards to ocean acidification (OA), they share similar needs such as local community engagement or lack thereof, active research and data availability. There are a total of eight research objectives, including four related to environmental change, three to biological sensitivity and one to human dimensions. Across the eight research objectives are 28 total actions; 10 actions are making good progress toward implementation, 12 that are making some progress toward implementation and six where no known progress has been made (Table 7.1).

Table 7.1: The SE and Gulf Chapter has a total of 28 actions: Ten actions have made good progress toward implementation (Green Circle Actions), 12 actions have made limited progress toward implementation (Yellow Triangle Actions) and six actions have made no known progress toward implementation (Red Diamond Actions).

Chapter Title	**Number of Actions**	●	▲	◆
Chapter 7: Southeast Atlantic and Gulf Region Acidification Research	28	10	12	6

The SE and Gulf Chapter has 13 environmental change actions, twelve biological sensitivity actions and three human dimensions actions. Figure 7.1 summarizes the progress made toward each of these actions under the three thematic areas.

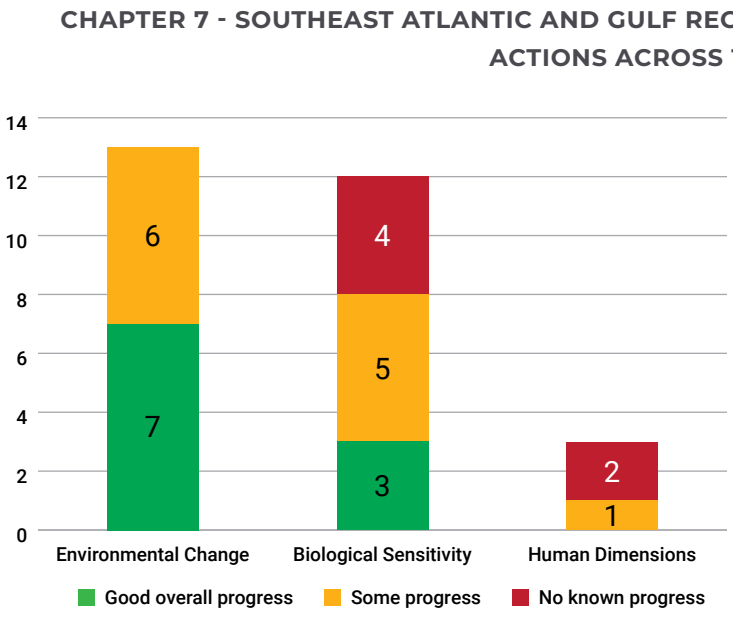


Fig. 7.1: The SE and Gulf Chapter includes a total of 13 environmental change actions, twelve biological sensitivity actions and three human dimensions actions. Of the 13 environmental change actions, good progress is being made toward implementing seven actions and limited progress has been made on six actions. Within biological sensitivity, good progress is being made toward implementing three actions, five actions have made limited progress and four have made no known progress. One of the human dimensions actions has made limited progress and the other two actions in this category have made no known progress.

Environmental Change

Under the Environmental Change theme in the SE and Gulf Chapter, there are four objectives:

1. SE and Gulf Environmental Change Research Objective 7.1: Improve characterization of OA parameters in important economic, cultural and recreational regions
2. SE and Gulf Environmental Change Research Objective 7.2: Improve the characterization of the Open Ocean
3. SE and Gulf Environmental Change Research Objective 7.3: Improve fundamental understanding of regional processes and seasonal trends.
4. SE and Gulf Environmental Change Research Objective 7.4: Improve scaling and predictive capabilities

Table 7.2 below summarizes the implementation of each action under its respective research objective.

Table 7.2: A summary of the actions under the environmental change theme objectives in the SE and Gulf Chapter, their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Southeast Atlantic and Gulf Environmental Change - Research Objective 7.1				
7.1.1	Develop and establish protocols that are complementary to ongoing synoptic cruises to extend regular observations of pertinent OA parameters into the nearshore environment. Focus sampling in Essential Fish Habitats for species predicted to be significantly impacted by OA and in select National Parks and National Marine Sanctuary sites (specifically in the northern Gulf where hypoxia and OA act as co-stressors)	9		OAP, OCM, AOML, OMAO
7.1.2	Explore options, including private and/or industry partnerships, to add an OA buoy or alternative observing platform in the Western Gulf to extend coverage of coastal sites that are presently composed of buoys in the Florida Keys, West Florida Shelf (a non-NOAA asset) and the Mississippi-Atchafalaya area	1		OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
7.1.3	Explore options to add a monitoring site in the SE region within the estuarine environment near to Grays Reef to establish a nearshore-offshore contrasting monitoring site	5	●	OAP, IOOS
7.1.4	Establish OA and water quality monitoring stations at inlets and near commercially and recreationally important estuaries (e.g., oyster bed leases, public clam beds, shellfish hatcheries) to monitor coastal acidification and eutrophication co-stressors in areas where fresh water systems are highly impacted by human activities and strongly influence coastal oceans	4	●	OAP, SG
Southeast Atlantic and Gulf Environmental Change - Research Objective 7.2				
7.2.1	Evaluate capabilities of autonomous sensor(s) for surface to deep water observing (3000m) and observing in the vicinity of cold-water coral communities	3	▲	OAP
7.2.2	Establish plan to deploy BGC-Argo floats in the Gulf region, following the rationale in Chapter 2: Open Ocean Region (Objective 2.3). Leverage GOMECC and other cruises to perform in-situ calibrations and improve quality control procedures for the data, while greatly increasing data availability for the open ocean end-member in the Gulf	3	▲	OAP, AOML

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Southeast Atlantic and Gulf Environmental Change - Research Objective 7.3				
7.3.1	Leverage existing cruises (such as the ones from the state/federal Southeast Area Monitoring and Assessment Program, ecosystem monitoring and restoration, oceanographic) to increase sample collection in between synoptic surveys, particularly in wintertime when observations have historically been particularly limited	4	●	OAP, AOML, CRP, CPO, IOOS
7.3.2	Evaluate methods to measure how upwelling of deep Gulf waters onto shelf affect OA in shelf ecosystems that are also affected by riverine acidification impacts	3	▲	OAP, CRP, CPO, IOOS
7.3.3	Expand the number of observations by increasing frequency of synoptic cruises to sample during other seasons (initially winter) to improve intra-annual sampling and add subsurface sensors to existing buoys, moorings and autonomous platforms	6	●	OAP, CRP, CPO, IOOS

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Southeast Atlantic and Gulf Environmental Change - Research Objective 7.4				
7.4.1	Develop, apply and improve existing models and validate models with direct observations to assess and improve model skill to best project OA within the region	6	●	OAP, AOML, CRP, CPO, IOOS
7.4.2	Incorporate OA and associated biogeochemistry into ecosystem models to help predict OA impacts on valuable components of the marine ecosystem	1	▲	OAP, CRP, CPO, IOOS
7.4.3	Increase utilization of satellite data, tools and products in support of status estimates and now-casts	1	▲	OAP, CRP, CPO, IOOS
7.4.4	Coordinate research with university researchers to build consensus regarding regional OA projections	4	●	OAP

Image credit: Liquid Robotics

FEATURED PROJECT

GLIDING INTO THE FUTURE OF OCEAN ACIDIFICATION MONITORING IN THE GULF

Among the NOAA designated Large Marine Ecosystems, the Gulf of America remains poorly understood in terms of its current ocean acidification conditions, despite its ecological and economic significance. In the northwestern Gulf, decadal acidification has been observed in the shelf-slope region, with metabolic (biological) production of CO_2 contributing to a large yet variable fraction along with the uptake of anthropogenic CO_2. Furthermore, the observed rate of acidification in subsurface waters (10s of meters) is significantly greater than that in other tropical and subtropical areas. Whether the observed ocean acidification in this region represents a short-term phenomenon or a long-term trend is unknown.

Researchers at Texas A&M University- Corpus Christi used wave gliders, *in-situ* sensors, along with underway measurements from research vessels to measure carbonate chemistry in surface and subsurface shallow waters. They aimed to test if increasing atmospheric CO_2, terrestrial nutrient export and enhanced upwelling will cause the continental shelf-slope region in the northwest Gulf to acidify faster than other tropical and subtropical seas. Modeling integrates the chemical signals into the models to hindcast and predict spatial and temporal variation of the ocean acidification signal to develop an optimized monitoring design for the region.

More about this work supported by NOAA OAP

Biological Sensitivity

Under the Biological Sensitivity theme in the SE and Gulf Chapter, there are three objectives:

1. SE and Gulf Biological Sensitivity Research Objective 7.5: Increase understanding of the impacts of OA on ecosystem productivity and food webs
2. SE and Gulf Biological Sensitivity Research Objective 7.6: Identify indicator species for OA in the region
3. SE and Gulf Biological Sensitivity Research Objective 7.7: Characterize sensitivity and adaptive potential of critical resource species to OA and other stressors and improve the understanding of OA impacts to HAB event frequency and duration

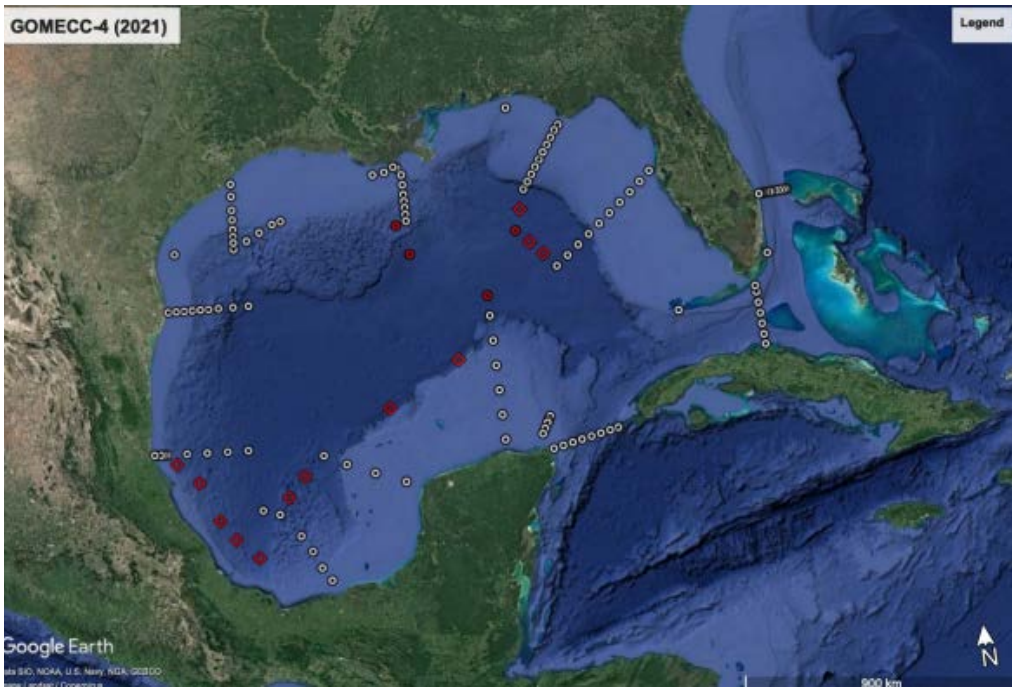
Table 7.3 below summarizes the implementation of each action under its respective research objective.

Table 7.3: A summary of the actions under the biological sensitivity theme objectives in the SE and Gulf Chapter their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Southeast Atlantic and Gulf Biological Sensitivity - Research Objective 7.5				
7.5.1	Characterize plankton communities (from phytoplankton to larval fish) along spatial gradients of eutrophication-driven acidification and hypoxia through regular sampling on GOMECC, ECOA and other cruises to allow for attribution to OA and/or eutrophication stressors rather than seasonal or other episodic drivers (e.g., tropical storms, flood, drought)	5		OAP, CRP, CPO, IOOS
7.5.2	Quantify changes in carbon flow to higher trophic levels (e.g., crustaceans and fish) via modeling studies and shipboard observations during GOMECC and ECOA cruises. Conduct shipboard experiments to determine composition of biological communities during antecedent conditions (not just conditions at the time of sampling) and to understand how rates (e.g., primary productivity, zooplankton grazing) change in response to OA, eutrophication, HABs and hypoxia, which are critical to parameterize ecosystem models	6		OAP, CRP, CPO, IOOS

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
7.5.3	Synthesize existing information from previous cruises and ongoing research and monitoring in the region. Coordinate collection of biological data (e.g., plankton tows, 'omics-approaches and rate measurements) for future GOMECC, ECOA and other cruises. Identify regions where shifts in carbon chemistry are associated with changes in plankton community structure and function	3	▲	OAP
Southeast Atlantic and Gulf Biological Sensitivity - Research Objective 7.6				
7.6.1	Incorporate plankton and neuston net tows and 'omics sampling as part of the standard suite of parameters included in GOMECC/ECOA cruises	5	●	OAP
7.6.2	Incorporate carbon chemistry sampling as part of the standard suite of parameters included in already ongoing SEFSC ecosystem monitoring efforts such as SEAMAP cruises and add DIC/TA/pH water sampling to the suite of samples already being collected	0	◆	n/a
7.6.3	Conduct laboratory studies to examine OA impacts in combination with other co-stressors, such as temperature and nutrients, on potential indicator species identified via field observations	0	◆	n/a

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Southeast Atlantic and Gulf Biological Sensitivity - Research Objective 7.7				
7.7.1	Target species of interest to conduct experimental studies to establish responses to OA and inform species vulnerability assessments	1	▲	OAP
7.7.2	Develop assessments using a multi-stressor framework to include combinations of effects such as eutrophication, river runoff, hypoxia, or increased HABs	2	▲	OAP
7.7.3	Incorporate these results into ecosystem models to drive hypotheses about how changes in indicators species and plankton dynamics will affect commercial and recreational fishery species	1	▲	OAP, CRP, CPO, IOOS
7.7.4	Build monitoring capacity for regionally significant HAB species to be measured during synoptic OA cruises and implement OA sampling in other opportunistic or ongoing cruises organized in relation to HABs already occurring along the Florida coast	3	▲	OAP
7.7.5	Support isolation and cultivation-based laboratory experimentation of local HAB species to examine species-specific and community responses to carbonate chemistry conditions	0	◆	n/a
7.7.6	Quantify socioeconomic impacts from predicted changes in HABs and their toxicity due to OA	0	◆	n/a



GOMECC-4 Cruise Track

FEATURED PROJECT

USING ENVIRONMENTAL DNA TO UNDERSTAND OCEAN FOOD WEB RESPONSES TO OCEAN ACIDIFICATION

NOAA's Ocean Acidification Program and Atlantic Oceanographic and Meteorological Laboratory partnered to support an effort in collaboration with NOAA 'Omics researchers at Northern Gulf Institute, Mississippi State University to conduct eDNA sampling on the Gulf of Mexico Ecosystem and Carbon Cruise in 2021 (GOMECC-4) in an effort to understand how marine microbes and plankton in the ocean food web respond to ocean acidification and other stressors. Researchers identified taxa that are indicative of high dissolved inorganic carbon and pH and thus indicator taxa of ocean acidification in the Gulf of America.

Human Dimensions

Under the Human Dimensions theme in the SE and Gulf Chapter, there is one objective:

1. SE and Gulf Human Dimensions Research Objective 7.8: Improve assessment of socioeconomic impacts of OA on local tourism, recreational fishing, commercial fishing and aquaculture (shellfish, fisheries) industries

Table 7.4 below summarizes the implementation of each action under this research objective.

Table 7.4: A summary of the actions under the human dimensions theme objective in the SE and Gulf Chapter, their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
Southeast Atlantic and Gulf Human Dimensions - Research Objective 7.8				
7.8.1	Evaluate the socioeconomic impacts from key species being impacted by OA either directly or through food web interactions (Research Objective 7.7)	0	◆	n/a
7.8.2	Conduct socioeconomic research to quantify the impacts of OA for specific fisheries, including direct (fishermen/aquaculture) and indirect (related service industries) impacts	0	◆	n/a
7.8.3	Based on outcome from the above, involve local stakeholders and raise awareness about OA to increase community resilience and proactively develop OA mitigation plans for affected ecosystems, industries and economies	1	▲	OAP

FEATURED PROJECT

COASTAL ACIDIFICATION NETWORKS INCREASE REGIONAL CAPACITY

The Gulf of America Coastal Acidification Network (GCAN) and the Southeast Ocean and Coastal Acidification Network (SOCAN) have increased regional capacity by working across the five Gulf coastal states (TX, AL, LA, MS and western FL) and four southeast coastal states (eastern FL, GA, SC and NC) to develop collaborative relationships that build awareness and understanding of acidification; impacts on ecosystems and species; and potential socioeconomic risks and vulnerabilities. GCAN and SOCAN have provided leadership and coordination in the synthesis of regional scientific information, development of collaborative proposals, outreach and communication to communities and interested groups and people and identification of regional needs and priorities. GCAN and SOCAN are coordinated by the regional IOOS associations (GCOOS and SECOORA, respectively) with support from NOAA's Ocean Acidification Program.

LOOKING FORWARD

Over the past five years great progress has been made in this region. Areas with little or no investment include biological laboratory studies with multiple stressors, synthesis of data from cruises and other work, and the relationship between OA and Harmful Algal Blooms and socioeconomic impacts. The Human Dimensions focus area in particular is one in which additional investment over the next five years will be critical.

Image Credit: William B. Folsom, NOAA / NMFS

CHAPTER 8

FLORIDA KEYS AND CARIBBEAN REGION ACIDIFICATION RESEARCH

Chapter 8 is titled, “Florida Keys and Caribbean Region Acidification Research” (the Florida Keys and Caribbean Chapter). This chapter addresses OA research objectives for the Florida Keys and coastal waters of south Florida, as well as Puerto Rico, the U.S. Virgin Islands and the surrounding areas between the Gulf of America and Atlantic Ocean. There are a total of 11 research objectives, four under environmental change, five under biological sensitivity and two under human dimensions. There are a total of 25 actions across the 11 research objectives: three of which are making good progress toward implementation and 14 of which have limited progress toward implementation and eight actions with no known progress made toward implementation (Table 8.1).

Table 8.1: The Florida Keys and Caribbean Chapter has a total of 25 actions: Three actions have made good progress toward implementation (Green Circle Actions), 14 actions have made limited progress toward implementation (Yellow Triangle Actions) and eight actions have made no known progress toward implementation (Red Diamond Actions).

Chapter Title	**Number of Actions**	●	▲	◆
Chapter 8: Florida Keys and Caribbean Region Acidification Research	25	3	14	8

Across the Florida Keys and Caribbean Chapter, there are a total of 11 environmental change actions, ten biological sensitivity actions and four human dimensions actions. Figure 8.1 summarizes the progress made toward each of these actions under the three thematic areas.

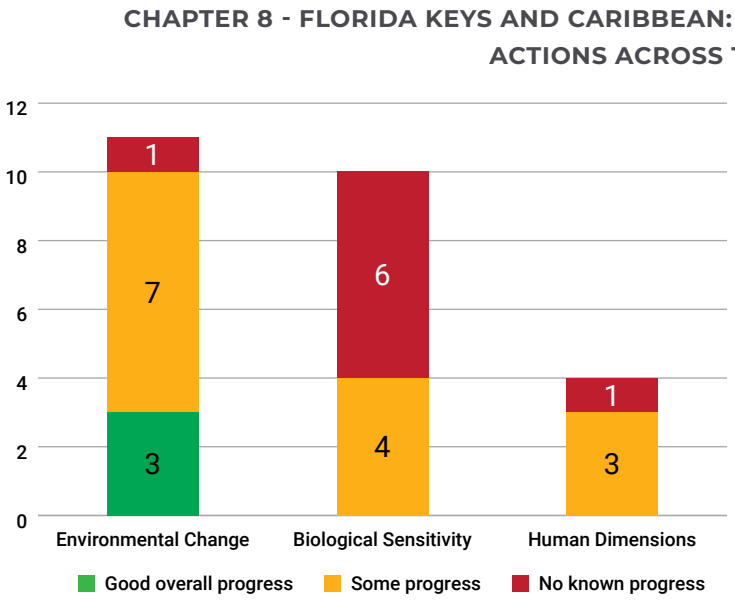


Fig. 8.1: The Florida Keys and Caribbean Chapter includes a total of 11 environmental change actions, 10 biological sensitivity actions and four human dimensions actions. Of the 11 environmental change actions, good progress is being made toward implementing three actions, limited progress has been made on seven actions and no known progress has been made on one action. Of the ten biological sensitivity actions, limited progress has been made on four actions and no known progress has been made on six actions.Of the four human dimensions actions, limited progress has been made on three actions and no known progress has been made on one action.

Environmental Change

Under the Environmental Change theme in the Florida Keys and Caribbean Chapter, there are four objectives:

1. The Florida Keys and Caribbean Environmental Change Research Objective 8.1: Characterize spatial carbonate chemistry patterns
2. The Florida Keys and Caribbean Environmental Change Research Objective 8.2: Characterize temporal carbonate chemistry patterns
3. The Florida Keys and Caribbean Environmental Change Research Objective 8.3: Better understand ecosystems response to OA through paired monitoring of carbonate (and ancillary) chemistry and biological/community-scale metrics
4. The Florida Keys and Caribbean Environmental Change Research Objective 8.4: Ecosystem modeling that integrates multiple functional groups

Table 8.2 below summarizes the implementation of each action under this research objective.

Table 8.2: A summary of the actions under the environmental change theme objectives in the Florida Keys and Caribbean Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Florida Keys and Caribbean Environmental Change Research Objective 8.1				
8.1.1	Improve the spatial resolution of existing carbonate chemistry monitoring in order to better detect regional and local patterns	4	●	OAP
8.1.2	Improve upon the deficiency in measurements taken at depth on coral reefs	3	▲	OAP, OCM
8.1.3	Initiate routine sampling in understudied ecosystems (e.g., seagrass beds, mesophotic coral reefs, mangroves and soft-bottom communities)	5	●	IOOS, OAP and with additional NOPP support
8.1.4	Expand Ship of Opportunity (SOOP) coverage into the Caribbean	1	▲	OAP
8.1.5	Explore the use of advanced autonomous systems (e.g., carbon Waveglider, Saildrone, glider) to achieve improved constraint of OA conditions	2	▲	OAP and with additional NOPP support

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Florida Keys and Caribbean Environmental Change Research Objective 8.2				
8.2.1	Improve the frequency of carbonate chemistry measurements to better understand diel and seasonal oscillations, as well as capture episodic events	6		IOOS, OAP
The Florida Keys and Caribbean Environmental Change Research Objective 8.3				
8.3.1	Monitor individual responses of species with documented sensitivities, especially those that have ramifications for ecosystem health (e.g., calcifying and bioeroding species)	1		OAP
8.3.2	Evaluate the importance of biogeochemistry within sediment pore waters (e.g., dissolution, Cyronak et al., 2013; Eyre et al., 2014, 2018) and improve understanding of how this relates to ecosystem function and services, particularly for coral reefs	0		n/a
8.3.3	Cross-validate, standardize and establish best-practices for techniques to quantify net community calcification (NCC) and net community productivity (NCP) and integrate them into monitoring programs (Cyronak et al., 2018)	1		OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Florida Keys and Caribbean Environmental Change Research Objective 8.4				
8.4.1	Develop a habitat persistence (e.g., carbonate budget) model that incorporates the species-specific sensitivities of key calcifying and bioeroding taxa to forecast reef habitat permanence under OA scenarios (Perry et al., 2012; Kennedy et al., 2013)	3	▲	CPO, CRP, IOOS, OAP, OCM
8.4.2	Apply spatiotemporal patterns in carbonate chemistry to OA-sensitive carbonate budget models to identify hotspots and refugia	2	▲	CPO, CRP, IOOS, OAP

Image Credit: NOAA

FEATURED PROJECT

SUSTAINED MONITORING OF FLORIDA WATERS

The Office for Coastal Management's National Coral Reef Monitoring Program (NCRMP) provides consistent, sustained and long-term measurement of key indicators that gauge the status and trends of U.S. coral reef health. Through NCRMP and sustained NOAA Ocean Acidification Program support, the Atlantic Oceanographic and Meteorological Laboratory leads ocean acidification monitoring in coral reefs ecosystems for the Atlantic Ocean. NCRMP monitoring in the region includes a high-resolution time series of carbonate chemistry and biweekly water sampling collected at the Cheeca Rocks buoy in Florida, diel carbonate chemistry sampling at fixed sites and discrete carbonate chemistry sampling at random sites.

Biological Sensitivity

Under the Biological Sensitivity theme in the Florida Keys and Caribbean Chapter, there are five objectives:

1. The Florida Keys and Caribbean Biological Sensitivity Research Objective 8.5: Improve understanding of the responses of bioeroding communities
2. The Florida Keys and Caribbean Biological Sensitivity Research Objective 8.6: Evaluate the influence of carbonate chemistry variability on ecosystem engineering taxa such as bioeroding and calcifying species
3. The Florida Keys and Caribbean Biological Sensitivity Research Objective 8.7: Evaluate differences in OA-sensitivity within coral species and molecular mechanisms associated with OA resilience
4. The Florida Keys and Caribbean Biological Sensitivity Research Objective 8.8: Investigate the direct response of understudied ecosystems, as well as iconic, invasive, endangered and commercially important species to OA
5. The Florida Keys and Caribbean Biological Sensitivity Research Objective 8.9: Identification and investigation of natural high-CO_2 analogs

Table 8.3 below summarizes the implementation of each action under this research objective.

Table 8.3: A summary of the actions under the biological sensitivity theme objectives in the Florida Keys and Caribbean Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Florida Keys and Caribbean Biological Sensitivity Research Objective 8.5				
8.5.1	Conduct experiments to assess the responses of Caribbean bioeroding organisms to OA and co-occurring stressors (e.g., temperature and land-based sources of pollution)	2	▲	CPO, CRP, IOOS, OAP
The Florida Keys and Caribbean Biological Sensitivity Research Objective 8.6				
8.6.1	Conduct laboratory experiments to assess the responses of key Caribbean taxa to fluctuating carbonate chemistry	1	▲	OAP
8.6.2	Compare the biological responses of species living in environments with different carbonate chemistry dynamics	0	◆	n/a

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Florida Keys and Caribbean Biological Sensitivity Research Objective 8.7				
8.7.1	Incorporate genotypes as a factor when designing OA response experiments	2	▲	CPO, CRM, IOOS, OAP
8.7.2	Conduct experiments to assess how the transcriptomes and proteomes of key taxa are influenced by OA, prioritizing comparisons between sensitive and resilient individuals	1	▲	OAP
8.7.3	Examine the genome and gene expression of key taxa living in OA hotspots	0	◆	n/a
The Florida Keys and Caribbean Biological Sensitivity Research Objective 8.8				
8.8.1	Assess the sensitivity of seagrass and mangrove ecosystems to OA using field studies and laboratory experiments	1	▲	CPO, CRM, IOOS, OAP
8.8.2	Assess the sensitivity of key understudied taxa (e.g., Lobster, Conch, Stone crabs, fishes, Sargassum and Diadema) to OA	1	▲	CPO, CRM, IOOS, OAP
The Florida Keys and Caribbean Biological Sensitivity Research Objective 8.9				
8.9.1	Identify and characterize new high-CO_2 analogs within the region	0	◆	n/a
8.9.2	Leverage naturally high-CO_2 ecosystems to better understand and predict real-world responses to OA	0	◆	n/a

Image Credit: NOAA CCMA Biogeography Team

FEATURED PROJECT

FRESCA - FLORIDA REGIONAL ECOSYSTEM STRESSORS COLLABORATIVE ASSESSMENT

FRESCA - Florida Regional Ecosystem Stressors Collaborative Assessment: South Florida's coastal and marine ecosystems provide critical ecosystem services and economic value to coastal communities. A variety of environmental stressors threaten these ecosystems, which can shift the structure and productivity of marine food webs. Led by Dr. Ian Enochs at AOML and Dr. Ana Palacio at University of Miami a team of nine scientists across seven institutions are investigating five interacting stressors: ocean acidification, hypoxia, harmful algal blooms, warming and eutrophication. This work improves our understanding of how these stressors impact ecosystems under present and future climate change scenarios. The project results will inform Everglades and Mission: Iconic Reefs restoration efforts and water quality and fisheries management. This work is funded by the National Centers for Coastal Ocean Science, the NOAA Climate Program Office, the NOAA Ocean Acidification Program and the Integrated Ocean Observing System, in collaboration with the Office of National Marine Sanctuaries.

Human Dimensions

Under the Human Dimensions theme in the Florida Keys and Caribbean Chapter, there are two objectives:

1. The Florida Keys and Caribbean Human Dimensions Research Objective 8.10: Economic assessment of the impact of OA in the region
2. The Florida Keys and Caribbean Human Dimensions Research Objective 8.11: Interdisciplinary and integrated socio-ecological approaches

Table 8.4 below summarizes the implementation of each action under this research objective.

Table 8.4: A summary of the actions under the human dimensions theme objectives in the Florida Keys and Caribbean Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Florida Keys and Caribbean Human Dimensions Research Objective 8.10				
8.10.1	Quantify the economic impact of OA-accelerated reef structure erosion leading to less protected coastal infrastructure and property	0	◆	n/a
8.10.2	Quantify the economic impact of OA on recreational and commercial fisheries through direct physiological and behavioral alteration of fished species, as well as degradation of essential habitat	1	▲	OAP
8.11.1	Develop mapping tools and socioeconomic indicators related to OA	1	▲	OAP
8.11.2	Use indicators to communicate risk and inform management and adaptation	2	▲	OAP and with additional NOPP support

FEATURED PROJECT

Image Credit: NOAA

ASSESSING OA VULNERABILITY AND RESILIENCE IN PUERTO RICO

In Puerto Rico, more than three million inhabitants rely on ocean and coastal resources for food, economic livelihoods and protection, but impacts from ocean acidification to coastal communities have not been assessed. To fill this gap, a regional vulnerability assessment in Puerto Rico assessed socioeconomic vulnerability through community interviews, identifying scientific trends and research gaps and holding a multi-disciplinary workshop to collect social and natural science perspectives and prioritize activities for a future regional vulnerability assessment. This project also created a multi-stakeholder network to form an initial framework for a new Caribbean Coastal Acidification Network, managed by CARICOOS.

More about this work supported by NOAA Ocean Acidification Program

LOOKING FORWARD

Many actions in the Florida Keys and Caribbean region need additional investment, as 22 out of 25 actions have made no or limited progress toward their implementation. For environmental change, large gaps remain in biological and ecosystem monitoring. Future investments could include monitoring individual species with known sensitivities and evaluating the importance of biogeochemistry within sediment pore waters. For understanding biological sensitivity, future needs include comparing the responses of species living in environments with different carbonate chemistry dynamics, examining the gene expression of key taxa living in OA hotspots and leveraging naturally high-CO_2 ecosystems to understand responses to OA. Very little has been accomplished under the human dimensions theme. There are a few projects working to move the needle on these human dimensions actions, but future investments can help quantify the economic impacts of OA and develop socioeconomic indicators.

Image Credit: Dwayne Meadows, NMFS/OPR

CHAPTER 9

MID-ATLANTIC BIGHT REGION ACIDIFICATION RESEARCH

Chapter 9 of the Research Plan is titled, “Mid-Atlantic Bight Region Acidification Research” (the Mid-Atlantic Chapter) and includes the eastern United States continental shelf area extending from Cape Hatteras, NC to Cape Cod, MA. There are a total of seven research objectives, two pertaining to environmental change, two to biological sensitivity and three to human dimensions. The Mid-Atlantic Chapter includes 26 actions across the seven research objectives: ten of which are making good progress toward implementation, nine of which have limited progress toward implementation and seven actions with no known progress made (Table 9.1).

Table 9.1: The Mid-Atlantic Chapter has a total of 26 actions: Ten actions have made good progress toward implementation (Green Circle Actions), nine actions have made limited progress toward implementation (Yellow Triangle Actions) and seven actions have made no progress toward implementation (Red Diamond Actions).

Chapter Title	**Number of Actions**	●	▲	◆
Chapter 9: Mid-Atlantic Bight Region Acidification Research	26	10	9	7

The Mid-Atlantic Chapter includes a total of eight environmental change actions, seven biological sensitivity actions and 11 human dimensions actions. Figure 9.1 summarizes the progress made toward each of these actions under the three thematic areas.

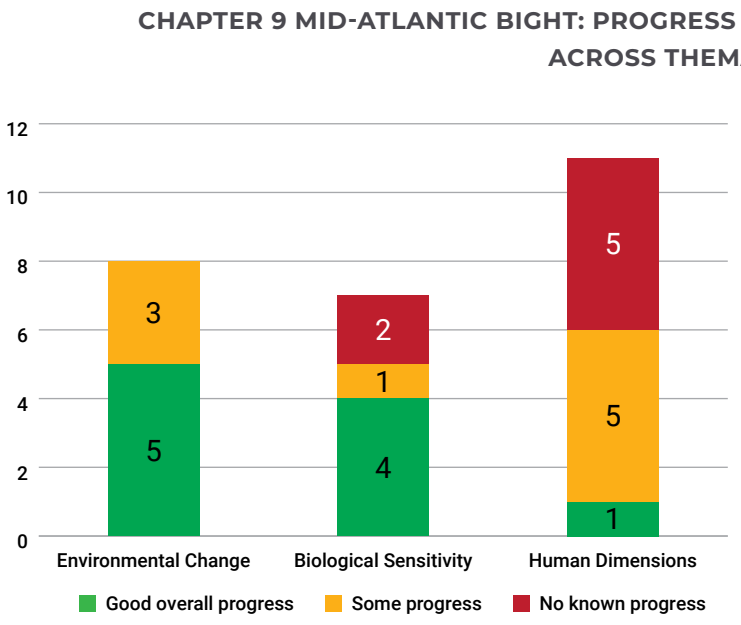


Fig. 9.1: The Mid-Atlantic Chapter includes a total of 8 environmental change actions, seven biological sensitivity actions and 11 human dimensions actions. Of the eight environmental change actions, good progress is being made toward implementing five actions and limited progress has been made on three actions. Good progress is being made toward implementing four biological sensitivity related actions, limited progress has been made toward one and no known progress has been made toward two biological sensitivity related actions. Under the human dimensions theme, good progress has been made toward implementing one action, limited progress has been made toward implementing five actions and no known progress has been made toward five actions.

Environmental Change

Under the Environmental Change theme in the Mid-Atlantic Chapter, there are two objectives:

1. The Mid-Atlantic Bight Environmental Change Research Objective 9.1: Improve OA forecasts on daily to decadal timescales in context with other environmental change
2. The Mid-Atlantic Bight Environmental Change Research Objective 9.2: Simulate full-water column carbonate chemistry dynamics of shelf and primary estuarine systems

Table 9.2 summarizes the implementation of each action under these research objectives.

Table 9.2: A summary of the actions under the environmental change theme objective in the Mid-Atlantic Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Mid-Atlantic Bight Environmental Change - Research Objective 9.1				
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, the benthos, across the shelf and into estuaries	19	●	CRP, NEFSC, OAP, OMAO, with additional NOPP and IRA support
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	6	●	GFDL, OAP, with additional NOPP and IRA support
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	3	▲	OAP
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	5	●	CRP, OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Mid-Atlantic Bight Environmental Change - Research Objective 9.2				
9.2.1	Collate and synthesize existing carbonate chemistry data in the region that can be used for model validation and other studies	5	●	IOOS, NEFSC, OAP, PMEL
9.2.2	Continue development of biogeochemical models to characterize OA conditions and evaluate our understanding of the mechanisms driving environmental conditions	4	●	OAP with additional NOPP and IRA support
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	2	▲	OAP
9.2.4	Conduct studies to inform biogeochemical models to evaluate dynamics at the sediment-water interface with increased OA, eutrophication and hypoxia	1	▲	NEFSC, OAP

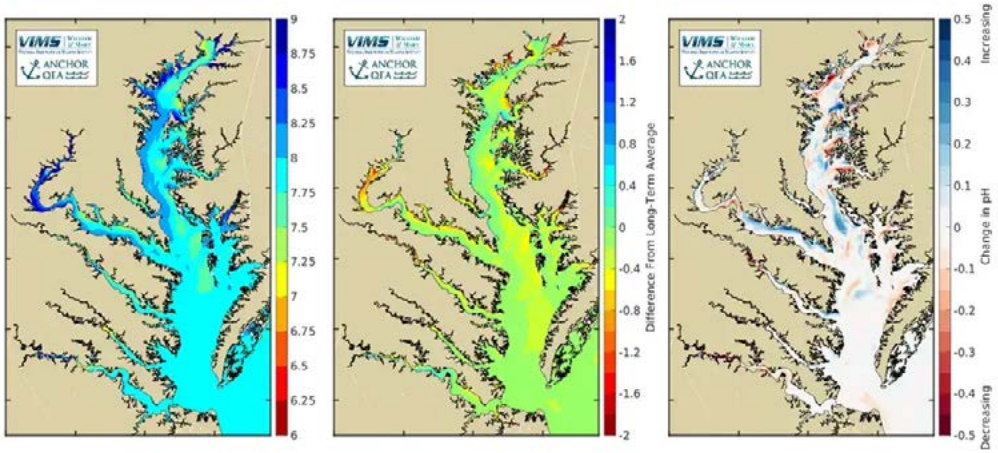


Image Credit: CBEFS

FEATURED PROJECT

NOWCASTS AND FORECASTS FOR CHESAPEAKE BAY

NOAA's Ocean Acidification Program supports the Virginia Institute of Marine Science to maintain the acidification forecasts in the Chesapeake Bay Environmental Forecasting System (CBEFS). CBEFS has been supplying the Chesapeake Bay community with real-time nowcasts and short-term forecasts of environmental conditions since 2017. These forecasts are provided 24 hours a day, 7 days a week. They include coastal and ocean acidification metrics such as pH, alkalinity and aragonite saturation-state, as well as the percent chance of encountering harmful algal blooms and *Vibrio vulnificus*. This information, together with other water quality parameters such as temperature, salinity and water clarity, is regularly used by the general public, aquaculture industry specialists and shellfish restoration managers.

Access CBEFS and other data tools

Biological Sensitivity

Under the Biological Sensitivity theme in the Mid-Atlantic Chapter, there are two objectives:

1. The Mid-Atlantic Bight Biological Sensitivity Research Objective 9.3: Determine how OA and other multi-stressors impact ecologically and/or economically important marine species
2. The Mid-Atlantic Bight Biological Sensitivity 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

Table 9.3 summarizes the implementation of each action under these research objectives.

Table 9.3: A summary of the actions under the biological sensitivity theme objective in the Mid-Atlantic Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Mid-Atlantic Bight Biological Sensitivity - Research Objective 9.3				
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	12		CRP, NCCOS, NEFSC, OAP, SG
9.3.2	Characterize phenotypic plasticity and the genetic potential to understand selective mortality emanating from OA and related stressors	8		CRP, NEFSC, OAP, with additional NOPP and IRA support
9.3.3	Determine the energetic costs of acclimation to OA using experimental mechanistic measure, including physiology	8		CRP, NEFSC, OAP, with additional NOPP and IRA support
9.3.4	Encourage field experiments that use existing platforms (i.e., hatcheries, restored oyster reefs) to monitor physiological and life-stage responses	5		NEFSC, OAP, SG, with additional NOPP and IRA support

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Mid-Atlantic Bight Biological Sensitivity - Research Objective 9.4				
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	0		n/a
9.4.2	Ground truth model predictions with experimental testing of predictions within and beyond the parameterized framework of the model	2		NEFSC, OAP, with additional NOPP and IRA support
9.4.3	Compare and contrast models for sensitivity and robustness in applications within the MAB and the model utility in other regions	0		n/a

Image Credit: Molly Roberts, NOAA NEFSC

FEATURED PROJECT

POPULATION ADAPTATION OF ATLANTIC SURFCLAMS TO OCEAN ACIDIFICATION

The U.S.Atlantic surfclam (*Spisula solidissima*) fishery generates $20-30 million of revenue annually and hundreds of jobs, but research identifies this species as vulnerable to climate change. Atlantic surfclam habitat is a dynamic environment that can experience tidal, seasonal and yearly changes in carbonate chemistry, temperature and food availability. Partnering with NOAA's Ocean Acidification Program, the Northeast Fisheries Science Center combines laboratory and field experiments to characterize the phenotypic plasticity of two genetically distinct Northern surfclam populations. Understanding how each population responds, adapts, or acclimatizes to ocean acidification is important to help maintain a viable Atlantic surfclam fishery.

Human Dimensions

Under the Human Dimensions theme in the Mid-Atlantic Chapter, there are three objectives:

1. The Mid-Atlantic Bight Human Dimensions Research Objective 9.5: Understand how OA will impact fish harvest, aquaculture and communities
2. The Mid-Atlantic Bight Human Dimensions Research Objective 9.6: Evaluate benefits and costs of mitigation and adaptation strategies
3. The Mid-Atlantic Bight Human Dimensions Research Objective 9.7: Integrate OA understanding into regional planning and management

Table 9.4 summarizes the implementation of each action under these research objectives.

Table 9.4: A summary of the actions under the human dimensions theme objective in the Mid-Atlantic Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Mid-Atlantic Bight Human Dimensions - Research Objective 9.5				
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	0	◆	n/a
9.5.2	Expand model capability to use species-specific data to predict economic impacts	0	◆	n/a
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	0	◆	n/a
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)	2	▲	OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Mid-Atlantic Bight Human Dimensions - Research Objective 9.6				
9.6.1	Determine costs of mitigation strategies and fishers relocating to follow species displaced by OA	2	▲	SG
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)	0	◆	n/a
9.6.3	Investigate alternative management options to ensure maximum sustainable fisheries yield and aquaculture production under future conditions	2	▲	CRP, OAP
The Mid-Atlantic Bight Human Dimensions - Research Objective 9.7				
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	2	▲	CRP, OAP, SG
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	0	◆	n/a
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	2	▲	IOOS, OAP
9.7.4	Incorporate OA research findings into existing NOAA products that support management, such as NMFS ecosystem status reports	4	●	OAP, NEFSC

Image Credit: NOAA

FEATURED PROJECT

ASSESSING VULNERABILITY AND RESILIENCE OF THE ATLANTIC SEA SCALLOP FISHERY

The U.S. Atlantic sea scallop fishery generates more than $500 million per year, making it the second highest grossing fishery in the United States and the largest wild scallop fishery in the world. The vulnerability and resilience of fishing communities to the effects of warming and ocean acidification depends on social and species-specific adaptive capacity. The regional contribution of sea scallop to total regional landed value has steadily increased over recent decades, in turn increasing the dependence of fishing communities on it. Research focused on using spatially-explicit regional projections of ocean change to inform Atlantic sea scallop fishery management and increase fishing community resilience. This work, conducted by researchers from the University of Connecticut, Rutgers University, the Commercial Fisheries Research Foundation and NOAA NEFSC, along with key input from community partners, include co-development of management recommendations to assist scallop industry stakeholders with OA- and temperature-driven changes in the fishery.

More about this work supported by NOAA OAP

LOOKING FORWARD

There are a number of actions in the Mid-Atlantic Chapter with limited or no known progress, which could benefit from additional resources in the next five years. Specifically, the three actions under Research Objective 9.4, which focuses on using biological research to develop models to evaluate within- and among-generation consequences of OA, have received minimal investments. Furthermore, there are no actions within all three human dimensions research objectives that have made good progress. Implementation is needed across all actions under the human dimensions research theme in the Mid-Atlantic Chapter.

Image Credit: Captain Albert E. Theberge, NOAA Corps (ret.)

CHAPTER 10

NEW ENGLAND REGION ACIDIFICATION RESEARCH

Chapter 10 of the Research Plan is titled, “New England Region Acidification Research” (the New England Chapter). This chapter includes research objectives relevant to the New England Region which geographically includes the Gulf of Maine, Georges Bank and Scotian Shelf. There are a total of nine research objectives which collectively and equally with three each, span the trifecta themes of environmental change, biological sensitivity and human dimensions. There are a total of 27 actions across the nine research objectives: ten of which are making good progress toward implementation, eleven of which have made limited progress toward implementation and six actions where no known progress has been identified to date (Table 10.1).

Table 10.1: The New England Chapter has a total of 27 actions: Ten actions have made good progress toward implementation (Green Circle Actions), eleven actions have made limited progress toward implementation (Yellow Triangle Actions) and six have made no known progress toward implementation (Red Diamond Actions)t.

Chapter Title	**Number of Actions**	●	▲	◆
Chapter 10: New Englad Region Acidification Research	27	10	11	6

Throughout the New England Chapter, there are a total of eleven environmental change actions, eight biological sensitivity actions and eight human dimensions actions. Figure 10.1 summarizes the progress made toward each of the actions under the three thematic areas.

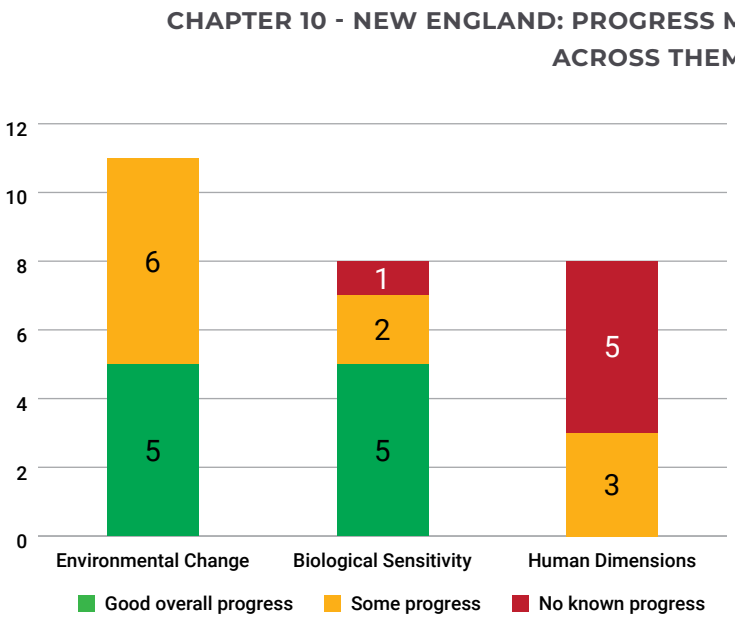


Fig. 10.1: The New England Chapter includes a total of eleven environmental change actions, eight biological sensitivity actions and eight human dimensions actions. Of the eleven environmental change actions, good progress is being made toward implementing five actions and limited progress has been made on six actions. Of the eight biological sensitivity actions, good progress is being made toward five actions, limited progress has been made toward two actions and no known progress has been made thus far on one action. Of the eight human dimensions actions, three have made limited progress and five actions have not yet been addressed.

Environmental Change

Under the Environmental Change theme in the New England Chapter, there are three objectives:

1. The New England Environmental Change Research Objective 10.1: Improve biogeochemical characterization of marine habitats most relevant to economically and/or ecologically important species.
2. The New England Environmental Change 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.
3. The New England Environmental Change Research Objective 10.3: Produce forecasts of changes in OA conditions in dynamic environments on daily, monthly, seasonal and yearly time periods.

Table 10.2 below summarizes the implementation of each action under its respective research objective.

Table 10.2: A summary of the actions under the environmental change theme objective in the New England Chapter and their implementation status, number of projects implementing the action and NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The New England Environmental Change Research Objective 10.1				
10.1.1	Support the development of new autonomous technologies suited for full carbonate chemistry water column profiling and benthic environment observing	4	●	OAP with additional NOPP and IRA support
10.1.2	Conducting data mining of existing benthic carbonate chemistry data, implementing long-term benthic monitoring at targeted locations, synthesizing exercises and improving geochemical models to better capture the processes governing benthic environment	3	▲	NEFSC, OAP, with additional NOPP and IRA support
10.1.3	Conduct analyses to identify data gaps in parameters needed to characterize acidification dynamics within the region (past and present conditions)	1	▲	OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the 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	8	●	IOOS, NEFSC, OAP
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	5	●	OAP with additional NOPP and IRA support
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	1	▲	NEFSC, OAP
The New England Environmental Change Research Objective 10.2				
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 NERACOOS	7	●	IOOS, OAP
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	7	●	NEFSC, OAP, OMAO, with additional NOPP and IRA support
10.2.3	Based on these exercises and analyses, identify new areas that are important for increased monitoring	1	▲	OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The New England Environmental Change Research Objective 10.3				
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, as well as precipitation and nutrient dynamics to more accurately predict variability in the coastal waters	3	▲	NEFSC, OAP, SG, with additional NOPP and IRA support
10.3.2	Configure model results to be fit-for-purpose and interpretable by decision makers to better provide needed guidance for regional planning	2	▲	SG, with additional NOPP and IRA support

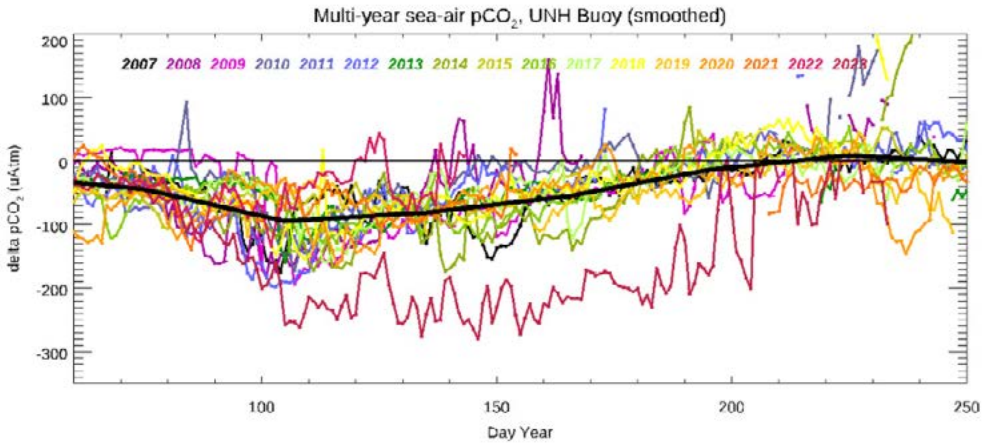


Figure 10.2: Gulf of Maine time-series capturing an unprecedented pCO_2 drawdown levels in early April 2023.

FEATURED PROJECT

OCEAN CHEMISTRY MONITORING IN THE GULF OF MAINE

A buoy moored in the Gulf of Maine monitors changes in the carbonate chemistry. This buoy plays a key role in a regional monitoring portfolio that supports our understanding of local changes to ocean conditions. In 2023, the Gulf of Maine time-series captured an unusual and long-lasting algal bloom event, an event that was first detected in unprecedented pCO_2 drawdown levels in early April 2023 (Fig. 10.2). More information on the buoy and its data are available here. Researchers at NOAA's Pacific Marine Environmental Laboratory and the University of New Hampshire's Coastal Carbon Group coordinate the operation and data collection for this buoy. This work is supported by NOAA's Ocean Acidification Program and the Integrated Ocean Observing System.

Biological Sensitivity

Under the Biological Sensitivity theme in the New England Chapter, there are three objectives:

1. The New England Biological Sensitivity Research Objective 10.4: Identify critical (sensitive, predictive and consequential) responses of selected keystone species to OA and multi-stressor conditions.
2. The New England Biological Sensitivity Research Objective 10.5: Characterize the adaptive capacity of species to OA and investigate potential mitigation patterns.
3. The New England Biological Sensitivity Research Objective 10.6: Incorporate OA and other marine stressors into single species and ecosystem models to improve ecosystem management.

Table 10.3 below summarizes the implementation of each action under its respective research objective.

Table 10.3: A summary of the actions under the biological sensitivity theme objectives in the New England Chapter and their implementation status, number of projects implementing the action and NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The New England Biological Sensitivity Research Objective 10.4				
10.4.1	Develop laboratory and field capability to expand existing single and multi-stressor OA experiments for all life-stages on shellfish and finfish of aquaculture, wild fisheries and ecosystem importance	13	●	CRP, NCCOS, NEFSC, OAP, with additional NOPP and IRA support
10.4.2	Use these expanded frameworks to evaluate the response key bivalves, finfish and forage species in the region for the coming decades	8	●	NCCOS, NEFSC, OAP
The New England Biological Sensitivity Research Objective 10.5				
10.5.1	Conduct experiments on potential for organismal acclimation and transgenerational adaptation to future environments	10	●	NEFSC, OAP, SG, with additional NOPP and IRA support
10.5.2	Conduct experiments to determine if there are different genetic lines within and across populations that respond differently to OA	7	●	CRP, NEFSC, OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
10.5.3	Identify potential mitigation practices that could offset local acidification (i.e., kelp grown around aquaculture beds)	5	●	NEFSC, OAP, with additional NOPP and IRA support
The New England Biological Sensitivity Research Objective 10.6				
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	3	▲	CRP, NEFSC, OAP
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	3	▲	CRP, NEFSC, OAP, with additional NOPP and IRA support
10.6.3	Identify future locations and times where successful recruitment of our Living Marine Resources (LMRs) may no longer be feasible	0	◆	n/a

Oyster hatchery technicians Hannah Colwell and Isaac Reeves (NOAA Fisheries/AIS) cleaning the flow through, high-density larval system to maintain flow and keep oyster larvae healthy. Industrial Plankton photobioreactors in the background are used to grow large quantities of phytoplankton (algae) to feed larvae and juvenile oysters for the Northeast Oyster Breeding Center. Image Credit: NOAA Fisheries/Kristen Jabanoski

FEATURED PROJECT

BREEDING OA AND DISEASE RESISTANT OYSTERS

In June 2024, NOAA NEFSC Milford Laboratory, with support from the NOAA Fisheries Office of Aquaculture, partnered with the U.S. Department of Agriculture's Agricultural Research Service to launch a new, state-of-the-art Northeast Oyster Breeding Center. The Center is an investment that will bolster shellfish farming in the Northeast. Scientists will use advanced selective breeding methods to develop better-performing lines of Eastern oysters to boost production. They aim to breed disease-resistant oysters that are resilient in the face of current and changing environmental conditions in the Northeast's diverse oyster growing areas, including ocean acidification.

More about the launch is available here.

Human Dimensions

Under the Human Dimensions theme in the New England Chapter, there are three objectives:

1. The New England Biological Sensitivity Research Objective 10.7: Understand how OA will impact fish harvest, aquaculture and communities.
2. The New England Biological Sensitivity Research Objective 10.8: Evaluate benefits and costs of mitigation and adaptation strategies.
3. The New England Biological Sensitivity Research Objective 10.9: Integrate OA understanding into regional planning and management.

Table 10.4 below summarizes the implementation of each action under its respective research objective.

Table 10.4: A summary of the actions under the human dimensions theme objective in the New England Chapter and their implementation status, number of projects implementing the action and NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The New England Human Dimensions Research Objective 10.7				
10.7.1	Estimate the time threshold by when changes in the carbonate chemistry will make harvesting or growing shellfish unprofitable	2	▲	OAP
10.7.2	Expand model capability to use species-specific data to predict economic impacts on individual fishery and aquaculture stocks	0	◆	n/a
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	0	◆	n/a
The New England Human Dimensions Research Objective 10.8				
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)	0	◆	n/a

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
10.8.2	Evaluate how the removal of excess nutrients aimed at reducing nearshore eutrophication will influence estuarine carbonate chemistry and acidification	1	▲	NOPP and IRA support
The New England Human Dimensions Research Objective 10.9				
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	2	▲	NEFSC, OAP
10.9.2	Support economic modeling and sociological studies to determine the ability of fishery members to alter fishery practices as harvested populations change (Objective 10.6)	0	◆	n/a
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	0	◆	n/a

Image Credit: NOAA

FEATURED PROJECT

NORTHEASTERN REGIONAL ASSOCIATION OF COASTAL OCEAN OBSERVING SYSTEMS (NERACOOS)

Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS) develops engagement, communication and training programs to increase community and public awareness of ocean acidification research as a scientific frontier from NOAA and affiliate researchers. This effort is coordinated through the Northeast Coastal Acidification Network (NECAN).

LOOKING FORWARD

While substantial progress has been made toward implementing the actions under the Environmental Change and Biological Sensitivity objectives, there is significant opportunity to bolster progress toward the New England Human Dimensions research objectives, including supporting research on economic tipping points needed to better understand the vulnerability of fishing and aquaculture communities and how the industry can adapt.

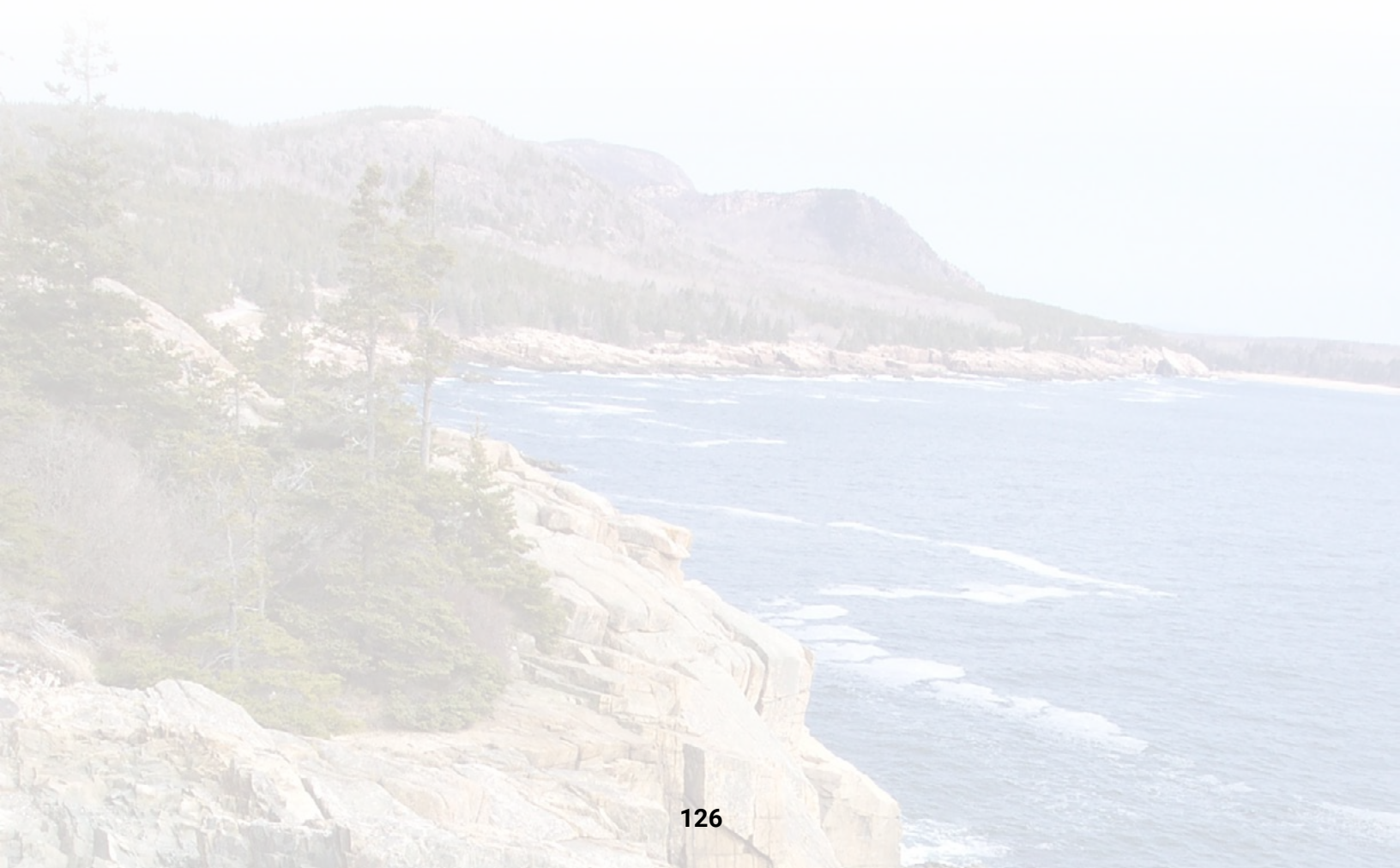


Image Credit: Richard B. Mieremet, NOAA OSDIA

CHAPTER 11

GREAT LAKES REGION ACIDIFICATION RESEARCH

Chapter 11 is titled, “Great Lakes Acidification Research” (the Great Lakes Chapter), which includes Lake Superior, Michigan, Huron, Erie and Ontario. There are a total of six research objectives, one pertaining to environmental change, three to biological sensitivity and two to human dimensions. The Great Lakes Chapter includes 12 actions across the six research objectives: one action is making good progress toward implementation, eight of the actions are making limited progress toward implementation and there are three actions with no known progress made (Table 11.1).

Table 11.1: The Great Lakes Chapter has a total of 12 actions: One action has made good progress toward implementation (Green Circle Actions), eight actions have made limited progress toward implementation (Yellow Triangle Actions) and three have made no known progress toward implementation (Red Diamond Actions).

Chapter Title	**Number of Actions**	●	▲	◆
Chapter 11: Great Lakes Region Acidification Research	12	1	8	3

The Great Lakes Chapter includes a total of two environmental change actions, eight biological sensitivity actions and two human dimensions actions. Figure 11.1 summarizes the progress made toward each of these actions under the three thematic areas.

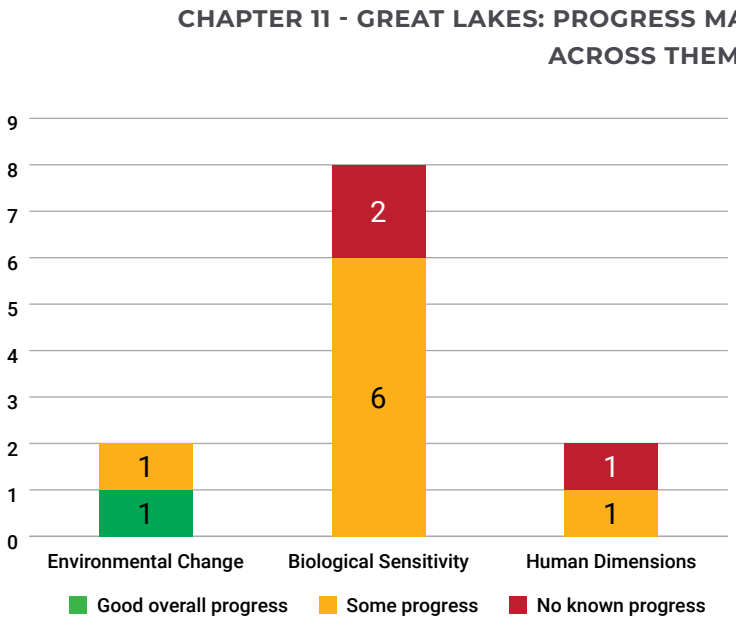


Fig. 11.1: The Great Lakes Chapter includes a total of two environmental change actions, eight biological sensitivity actions and two human dimensions actions. Regarding the two environmental change actions, one action is making good progress and one is making some progress toward implementation. Six of the biological sensitivity actions and one human dimensions action have limited progress. No known progress has been made on two of the biological response actions and one of the human dimensions actions.

Environmental Change

Under the Environmental Change theme in the Great Lakes Chapter, there is one objective:

1. The Great Lakes Environmental Change Research Objective 11.1: Expand NOAA's OA monitoring network to include sampling sites in the Great Lakes Region

Table 11.2 below summarizes the implementation of each action under these research objectives.

Table 11.2: A summary of the actions under the environmental change theme objective in the Great Lakes Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Great Lakes Environmental Change - Research Objective 11.1				
11.1.1	Leverage existing observing networks in the region to build a carbonate chemistry observing network through addition of sensor packages suited to make high quality measurements	3	▲	GLERL, NMS, OAP
11.1.2	Strategically identify priority sampling regions in order to best detect trends (relatively-deep basin and low-productivity environments) that can be compared across lakes	4	●	GLERL, OAP

Image Credit: NOAA GLERL

FEATURED PROJECT

HIGH QUALITY MONITORING IN THE GREAT LAKES

The Great Lakes ecosystem provides over 1.3 million jobs and $82 billion in wages the U.S.Blue Economy. In order to support a healthy, productive and resilient Great Lakes ecosystem the Thunder Bay National Marine Sanctuary (TBNMS), with partners at the Great Lakes Environmental Research Laboratory (GLERL) established the first monitoring network focused on freshwater acidification in theU.S.Great Lakes. Sites established in Lake Huron will provide baseline measurements and start a long-term record for tracking freshwater acidification and climate impacts. While water quality monitoring is extensive and long-term in the Great Lakes, this project fills the gap for carbonate system and carbonate chemistry monitoring that has been largely neglected.

See real-time monitoring data here for this project, supported by GLERL, NMS and OAP.

Biological Sensitivity

Under the Biological Sensitivity theme in the Great Lakes Chapter, there are three objectives:

1. The Great Lakes Biological Sensitivity Research Objective 11.2: Conduct research on harmful algal bloom species and the influence of elevated pCO_2 and temperature on bloom toxicity, concentration and frequency
2. The Great Lakes Biological Sensitivity Research Objective 11.3: Conduct research to understand the sensitivity of dreissenid mussels, plankton, fish and other biota to changes in pH and carbonate saturation states, including early life stages
3. The Great Lakes Biological Sensitivity Research Objective 11.4: Incorporate carbonate chemistry into biophysical and food web models to project the impacts of changing pH and carbonate saturation states on important ecological endpoints

Table 11.3 below summarizes the implementation of each action under these research objectives.

Table 11.3: A summary of the actions under the biological sensitivity theme objectives in the Great Lakes Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Great Lakes Biological Sensitivity - Research Objective 11.2				
11.2.1	Conduct monitoring and experiments to understand the influence of elevated pCO_2 and temperature on bloom toxicity, concentration and frequency	1	▲	CRP, OAP
11.2.2	Incorporate the influence of elevated pCO_2 and temperature into models that can predict HAB occurrence in short-term forecasts and in longer-term scenarios to inform nutrient management decisions	2	▲	CRP, GLERL, OAP

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Great Lakes Biological Sensitivity - Research Objective 11.3				
11.3.1	Given its marginal Ωarag values and gradients in Ωarag, Lake Huron dreissenid distributions may be most sensitive to acidification and could serve as an early indicator of changing trends in pH and Ωarag. Compare and contrast dreissenid distribution over time and with other lakes as a function of Ωarag	1	▲	GLERL
11.3.2	Conduct monitoring and experiments to understand the influence of elevated pCO_2 on Great Lakes plankton community composition	1	▲	CRP, OAP
11.3.3	Conduct monitoring and experiments to evaluate the influence of elevated pCO_2 on early life stages of fish and dreissenid mussels	1	▲	NCCOS
11.3.4	Focus research on nursery habitats for fish early life stages, such as poorly buffered tributaries and wetland habitats that currently experience fluctuating pH levels and will be most at risk to anticipated pH declines	0	◆	n/a
The Great Lakes Biological Sensitivity - Research Objective 11.4				
11.4.1	Develop biophysical models capable of simulating the carbonate system, pH and Ωarag in the Great Lakes	2	▲	GLERL, OAP
11.4.2	As understanding develops regarding the influence of elevated pCO_2 on Great Lakes biota, incorporate these mechanisms into biophysical and food web models	0	◆	n/a

Image Credit: NOAA GLERL

FEATURED PROJECT

POTENTIAL ACIDIFICATION EFFECTS ON GREAT LAKES HARMFUL ALGAL BLOOMS

Acidification, warming and shifts in alkalinity and nutrient availability dramatically alter aquatic systems and lead to changes in phytoplankton. Of particular concern in the Great Lakes are cyanobacteria Harmful Algal Blooms (cHABs), which have had significant impacts in the region over the past five years. Past effort has undersampled and largely ignored acidification and understanding its potential impacts on the ecosystem. This project fills these gaps by determining the effects of acidification, temperature, total alkalinity and nitrogen on cyanobacteria growth, physiology, genetic underpinnings and toxicity. Using genetic and paleolimnology approaches, researchers connect historical trends of phytoplankton and environmental conditions. This project has been supported by OAP and NCCOS.

Human Dimensions

Two research objectives in the Great Lakes Chapter focus on human dimensions research priorities:

1. The Great Lakes Biological Sensitivity Research Objective 11.5: Engage stakeholders and public in the knowledge production process
2. The Great Lakes Biological Sensitivity Research Objective 11.6: Evaluate economic and social impacts of ecological outcomes or mitigation actions

Table 11.4 below summarizes the implementation of each action under these research objectives.

Table 11.4: A summary of the actions under the human dimensions theme objective in the Great Lakes Chapter and their implementation status, number of projects implementing the action and the NOAA offices funding the implementation of the action.

Action Number	Objective/Action Detail	# of Projects Implementing the Action	Implementation Status	NOAA Programs Funding the Action
The Great Lakes Human Dimensions - Research Objective 11.5				
11.5.1	As research activities are undertaken, develop engagement, communication and training programs to increase stakeholder and public awareness of NOAA's acidification research as a scientific frontier. Test hypotheses about best ways to engage stakeholders and public	3	▲	GLERL, OAP
The Great Lakes Human Dimensions - Research Objective 11.6				
11.6.1	As the ecological impacts of Great Lakes acidification are identified, conduct vulnerability assessments to identify sectors of the economy that are vulnerable to Great Lakes acidification and measure economic and social impacts of acidification	0	◆	n/a

Image Credit: Thunder Bay National Marine Sanctuary

FEATURED PROJECT

OCEAN ACIDIFICATION RISKS TO MARITIME HERITAGE RESOURCES

The Great Lakes system is one of the most rapidly changing ecosystems. Maritime heritage resources within sanctuaries may be threatened by increased acidification and changing conditions. The Great Lakes Environmental Research Laboratory (GLERL) and partners at Thunder Bay National Marine Sanctuary (TBNMS) and Wisconsin Shipwreck Coast National Marine Sanctuary (WSCNMS) established and maintain a freshwater acidification monitoring network to inform potential risk to these cultural resources. It addresses critical lack of data concerning acidification in the Great Lakes and impacts to natural and maritime heritage resources within the sanctuary system.The approach and procedures will provide a monitoring framework for the region.This effort is supported by OAP.

LOOKING FORWARD

Investigation into acidification in the Great Lakes began later than ocean and coastal acidification, which may underlie the level of progress toward implementation of the Great Lakes Chapter actions. None of the actions reached overall good progress toward implementation thus far. Overall, the Great Lakes is a region in need of continued investment to further progress toward implementation across research objectives.

Image Credit: NASA

MARINE CARBON DIOXIDE REMOVAL: AN EMERGING TOPIC IN OA RESEARCH

Background

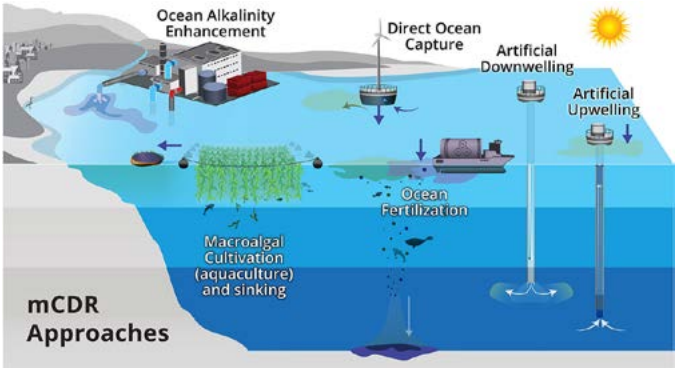
Voluntary carbon markets, and to a lesser extent compliance markets, are increasing in value and there is potential for CDR to become over a trillion dollar industry by 2050. The private sector is already moving forward with carbon dioxide removal pilots in the United States and abroad. NOAA serves as a trusted agency to research and monitor efforts that can de-risk and provide integrity to this emerging market.

Carbon dioxide removal (CDR) aims to remove carbon dioxide from the atmosphere and store that carbon on land, in the ocean, or underground for a long period of time (hundreds to thousands of years). Marine carbon dioxide removal (mCDR) techniques take advantage of the fact that the ocean naturally draws down carbon from the atmosphere through inorganic and biological processes. There are many ocean-based strategies that aim to accelerate the ocean's ability to draw down carbon dioxide from the atmosphere or surface ocean.

NOAA's emphasis on big-picture, long-term monitoring and its existing research capabilities are ideally suited to understand, evaluate and verify public and private entities' exploration of CDR efforts and their potential for success. NOAA's ecological monitoring and research programs can help assess the impact, effectiveness, feasibility and risk of mCDR technologies.

NOAA's mCDR Vision

NOAA's Office of Oceanic and Atmospheric Research, in particular OAP, has been leading the agency's strategic vision of mCDR engagement with the aim of understanding the efficacy and safety of mCDR approaches. NOAA's Office of Oceanic and Atmospheric Research set up a cross line office CDR Task Force in 2020. With support from OAP, in June of 2023 the Task Force published a NOAA CDR Research Strategy. The strategy, which includes contributions from more than 60 NOAA authors, has four main parts: 1) the Federal Motivation to engage in CDR, 2) the State of CDR Science, 3) NOAA's assets that underpin the foundational science needed for CDR and 4) the vision for CDR research at NOAA.



Approaches to Marine Carbon Dioxide Removal
Image Credit: Sarah Battle, NOAA

Existing assets to underpin the scientific basis of mCDR are supported by programs and laboratories across NOAA (highlighted in **bold**). Firstly, NOAA has the largest network of **marine carbon observations** in the country. Observations supported through the NOAA Ocean Acidification Observing Network (NOA-ON), NOAA Coastal Acidification cruises, Surface Ocean CO_2 Reference Observing Network (SOCONET) and the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP) provide critical baseline information to understand the natural carbon variability of U.S. Large Marine Ecosystems and the global ocean. Even still, this network must be expanded, particularly at the regional scale, to ensure robust, sustained and verifiable ocean observations to assess the efficacy of mCDR. Secondly, through current investments (see Research Portfolio), existing **earth systems models** are currently being expanded to assess the impact of carbon dioxide removal on the integrated Earth system, as well as to examine the effects on the ecosystem from scaled mCDR research and deployments. Thirdly, NOAA continues to invest in infrastructure for NOAA Fisheries Science Centers to better understand the impacts of ocean acidification. In many cases, the same infrastructure can be utilized to **assess environmental impacts** of mCDR. This environmental impact work must be considered in conjunction with research into the efficacy of

mCDR approaches. Finally, NOAA's ocean carbon programs (OAP and GOMO) have exemplified how research programs can support NOAA's **decision support tools**, such as data management, data synthesis products and invested community engagement.

The NOAA CDR Research Strategy's vision for research includes three main waves of engagement. The first wave of the strategy is focused on foundational research. Specific items to pursue include conducting laboratory bench studies, designing and growing local to regional ocean carbon observations, developing modeling packages, supporting permitting infrastructure and engaging with invested communities. Some of this work, specifically lab and modeling work, is ongoing. The critical work in Wave 1 of designing and growing local to regional ocean carbon observations is a task that will require increased and sustained funding. The second wave focuses on engaging with field trials and scaling approaches through the year 2030. Actions include synthesizing research results, process studies on ecosystem impacts including higher trophic levels, taking part in large-scale controlled demonstration projects, assessments of risks of approaches and comparing/contrasting cost-benefit analysis studies. NOAA is starting to support work particularly around data synthesis and ecosystem impacts. The third wave involves mature global monitoring of gigaton-scale mCDR. This engagement would support expansion of public-private partnerships and expand NOAA's observations and modeling capabilities to contribute to the verification and validation of this fast-growing industry.

Research Portfolio

In support of the NOAA CDR Research Strategy, OAP has developed a strong portfolio of mCDR research projects. A cornerstone of this portfolio is NOAA's collaboration with the National Oceanographic Partnership Program (NOPP) in Fiscal Years (FYs) 2022 and 2023. This effort represented the first ever large-scale, interagency public funding opportunity for approach agnostic foundational mCDR research.

The projects work toward addressing a variety of knowledge gaps called out in the NOAA CDR Research Strategy's Wave 1 and collectively address all three aspects of the OAP trifecta. Though NOAA served as the lead agency for this NOPP call, the scale and scope of awards was made possible through collaboration and funding support from other U.S. Government agencies, including the National Science Foundation (NSF), Office of Naval Research (ONR) and Department of Energy. Of the 17 awards distributed, 14 are managed through OAP, two through the ONR and one through NSF.

In addition to the NOPP calls in FY22 and FY23, OAP provided funding for mCDR research through its sustained investment portfolio for FY24-26. This research explores the effect of elevated pH and alkalinity - a short-term result of some mCDR approaches - on the survival, growth and physiology of Dungeness crab and Pacific oyster, two of the region's economically, ecologically and culturally important marine species. As species which are geographically likely to intersect with potential future scaling of mCDR activities, this project's findings will support critical scientific understanding of the co-benefits and risks associated with alkalinity-enhancing mCDR approaches. In FY24, OAP developed two targeted Requests for Workplans to engage technical assistance around the topics of mCDR data management and environmental response to mCDR, respectively.

Moving forward, OAP continues to seek opportunities to further expand its mCDR research portfolio in support of the NOAA CDR Research Strategy.

LOOKING FORWARD

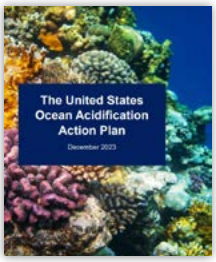
Overall, mCDR research overlaps with, yet has distinct needs from, OA research. The carbonate chemistry and environmental response data the OA research community executes has provided much of the foundational knowledge that underpins mCDR research. This includes coastal carbon observing, ecosystem assessments and community engagement. Moving forward, mCDR field trial research and baseline observations could bolster some of ocean carbon and ecosystem data. Many of the engagement networks that OAP supports, such as the Coastal Acidification Networks and the Global-Ocean Acidification Observing Network, are also engaging in the topic, especially where there is potential to actively mitigate ocean acidification. The close relationship of the OA community and the burgeoning mCDR community is integral to carrying out the most informed and impactful research on timelines relevant to rapidly accelerating private industry projects and the growing CDR market.

New High-Level Guidance Documents

Since the NOAA OA Research Plan was released in 2020, new high-level guidance documents relevant to ocean acidification research have been released. Both the IWG-OA Strategic Plan and the U.S. OA Action Plan were developed with consideration of NOAA's goals as outlined in the Research Plan. NOAA is also responsive to these strategies and priorities when executing actions to understand and address ocean acidification. Much of NOAAs ongoing funded work supports these documents in addition to addressing the Research Plan. When the Research Plan is refreshed for future years, the authors will need to consider how best to appropriately align with these new high-level guidance documents. Likewise research projects in the remaining half of this decade will want to attribute achievements to some of the goals in these documents. As time goes on, trying to ensure research projects ensure that they are covering this span of other high level guidance documents is something that funding offices at NOAA will have to do.

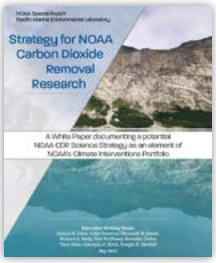
Strategic Plan for Federal Research and Monitoring of Ocean Acidification

Released by the Interagency Working Group on Ocean Acidification in 2023, this strategic research plan guides federal OA research and monitoring investments. The plan contains objectives and research themes organized around seven thematic areas: (1) research; (2) monitoring; (3) modeling; (4) technology development; (5) socioeconomic impacts; (6) education, outreach and engagement strategies; and (7) data management and integration. NOAA is listed as the lead agency for implementing many of the action items. The Federal Ocean Acidification Monitoring and Reserach Act of 2009 (FOARAM) mandated this strategic research plan to direct national efforts toward addressing OA.



United States Ocean Acidification Action Plan

The United States government released the U.S. OA Action Plan in 2023 after joining the OA Alliance, a voluntary coalition that works to build international momentum for actions to address OA. The U.S. OA Action Plan describes federal priorities around OA mitigation, monitoring and research, resilience and adaptation strategies and sub-national and international collaboration. This document aims to be a roadmap for other countries and to encourage them to join the OA Alliance, write action plans and support OA activities within their countries.



Strategy for NOAA Carbon Dioxide Removal Research

NOAA's CDR research strategy outlines what we know about existing technologies and what we need to learn to make the best decisions moving forward to meet climate goals with these approaches. NOAA can contribute to advancing our understanding through coastal observing networks and data assimilation, modeling, scaling and projecting CDR pathways, ecosystem research and assessing impacts and decision support.

Conclusion

Collective Progress to date

Since 2020, NOAA has supported 308 research projects across the U.S. and its territories (Table C.1) guided by the NOAA Ocean, Coastal and Great Lakes Acidification Research Plan. This was made possible through close partnerships across at least 24 NOAA divisions that have financially invested in implementing the Research Plan, as well as a number of NOAA and non-NOAA partners that have conducted the projects.

Table C.1: Summary of the number of projects implementing the actions and objectives in each chapter of the Research Plan. (Note that that number of projects implementing chapters will not add up to the total number of projects, because several projects implement actions under multiple chapters.)

	Number of Projects Supporting Implementation
Chapter 1: National	197
Chapter 2: Open Ocean	48
Chapter 3: Alaska	44
Chapter 4: Arctic	13
Chapter 5: West Coast	76
Chapter 6: Pacific Islands	21
Chapter 7: Southeast Atlantic and Gulf	37
Chapter 8: Florida Keys and the Caribbean	16
Chapter 9: Mid-Atlantic Bight	47
Chapter 10: Northeast	43
Chapter 11: Great Lakes	9
Total	**313**

As a result, 104 (42%) of all actions in the Research Plan have good overall progress toward implementation, 96 (39%) have some progress and 48 (19%) have no known progress (Fig. C.1a).

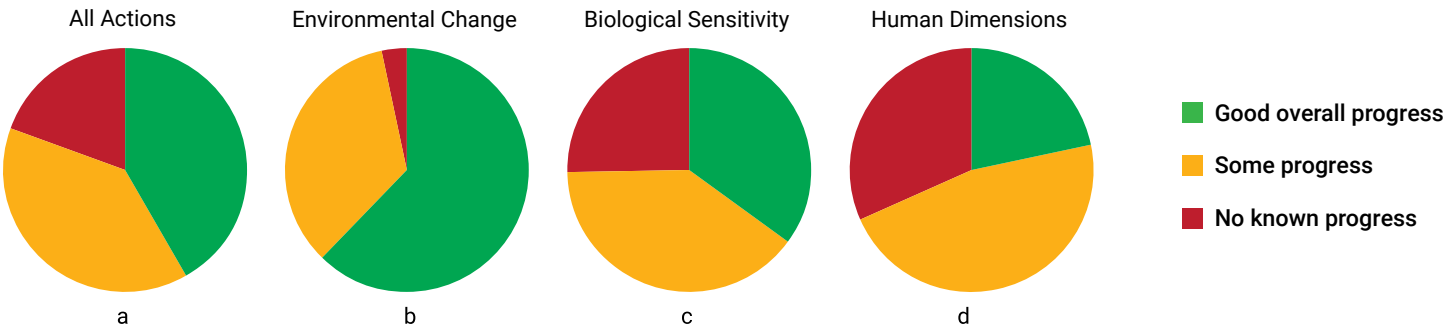


Figure C.1a, b, c, d: Relative progress on actions overall as well as within each thematic area across the Research Plan, 2020-2024.

Despite these successes, certain work areas and certain regions still need more investments to ensure that NOAA research provides a comprehensive, nationwide understanding of how ocean acidification is unfolding and affecting marine ecosystems and the people who depend on them. This report has identified that the human dimensions work area has fewer actions across all chapters (60) than the environmental change (96) and biological sensitivity (92) work areas. Though to some degree, the human dimension actions tend to be broader than other research themes, as this area of research evolves and more specific research actions are identified, this may lead to an increase in the number of human dimension actions overall. Even still, the human dimensions work area also has the smallest proportion of "green circle" (good overall progress) actions (Fig. C.1).

Furthermore, some regions have more limited progress made toward implementing all actions (Fig. C.2) and fewer projects implementing the regional chapter overall (Table C.1). Regions with more limited progress include Chapters 11 (Great Lakes), 4 (Arctic), 8 (Florida Keys and the Caribbean) and 6 (Pacific Islands). An important note here is that in some cases, regional chapters have actions written with such narrow precision that they almost read more as an implementation plan of research objectives. This results in the limited ability of invested projects to move the needle on any actions and can bias the results of action implementation status.

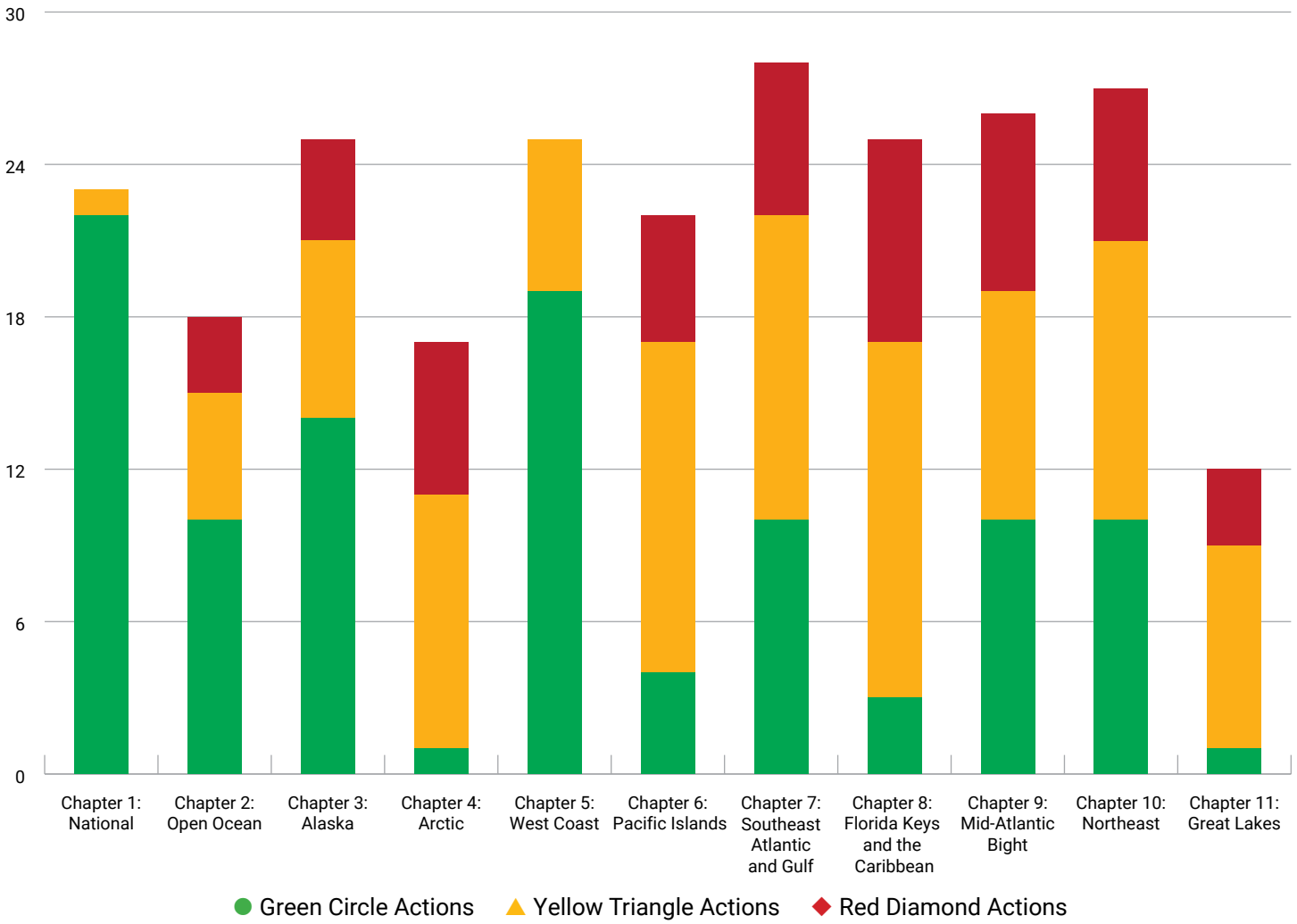


Figure C.2. Implementation status of all actions of each chapter in the Research Plan (red, no known progress; yellow, some progress; green, good overall progress).

CREATIVELY ADDRESSING MULTIPLE PRIORITY AREAS

Researchers who specialize in one priority area of the Research Plan may be concerned they are not equipped to develop research projects that address multiple priority areas. In fact, all types of specialists have led projects that address at least in part priority areas outside of their specialty. And these priority-area-spanning projects do not necessarily require large multidisciplinary teams. Consider the following examples of projects of varying complexities that may primarily address either environmental change or biological sensitivity actions but take it a step further to ensure the works is also implementing human dimensions actions:

- A project pertaining to lab-based species sensitivity research, in which the researcher shares the results to resource managers for the direct translation and inclusion into documents that inform fishery management (e.g. Ecosystem Status Reports)
- A project that conducts a field monitoring mission and the researcher provides the data to regional groups that provide regularly updated ecosystem indicators to the public
- A project focused on species research in which a researcher engages with a fisheries association at the beginning, throughout and at the end of the project to ensure the research speaks to the communities questions and needs
- A project whose primary objective is to maintain a time-series of carbonate chemistry, but the researcher collaborates with an extended network of researchers to relay the data in a format that supports ecosystem-wide decision making

Nonetheless, there are clearly areas (both geographically and thematically) with more limited investment than others that emerge from this mid-decade status check. At the same time, it is important to continue investing in areas making good progress, capitalizing on that good progress, rather than ceasing investment there to build less well-developed areas. One way to start moving the needle on less implemented actions, is to identify more investment funding for ocean acidification in those areas. However, the reality is resources are likely to remain limited into the near future. Thus it's important to consider in the design and selection of future research projects ways in which ocean acidification investments can address multiple related actions across thematic areas.

Many of the projects that support the Research Plan help address one or more thematic areas and increasingly strategic project designs can enable future projects to advance slower-maturing areas by leveraging progress and successes in other areas (See callout box "Creatively addressing multiple priority areas").

Furthermore, it often can be difficult to capture the full breadth of actions a project implements as other benefits or uses of a project's data often come to maturity after the official end date of a project. For example, biological sensitivity information from individual species can later be synthesized and provided to resource managers as part of an ecosystem-scale condition evaluation,

which would have substantial human dimensions impact. Moving into the second half of the decade, it will be important to determine a more effective and formal means of capturing these efforts in tracking implementation of the Research Plan.

Finally, when it comes to regional disparity, in recent years the focus has been on building NOAA funding partnerships and researcher capacity in regions with more limited progress on implementation. These steps have proven to be effective means of advancing work in these regions. Continuing these efforts into the next half of the decade should support implementation in these regions even under resource limited conditions.

Emerging opportunities

In addition to keeping track of the Research Plan needs for OA information around the nation, OAP will continue to scope new research tools and opportunities. Like mCDR (see section "mCDR: An Emerging Topic in OA Research"), new topics overlapping or adjacent to OA will continue to emerge. New opportunities related to infrastructure and technology development will arise and indeed have in the past (e.g. omics techniques, uncrewed systems, etc.). As in the past, to adequately face new developments, NOAA offices must identify efficient means to enable continuous innovation amidst rising overhead costs and flat or modestly growing budgets.

Collaborating at Multiple Scales

Finally, coordinating OA science from local to global scales remains a challenge for everyone. NOAA's legislative charge includes specific international actions, including participation in international research efforts; coordinating US ocean and coastal acidification research and monitoring with other nations and international organizations; and leading educational activities that encourage an interdisciplinary, international approach to exploring ocean and coastal acidification. The Ocean, Coastal and Great Lakes Research Plan encompasses work that has helped lead international capacity building and engagement efforts, such as projects with GOA-ON, nonprofits and U.N. partners. New high-level OA-specific guidance (see section "New High-Level Guidance Documents") in the Strategic Plan for Federal Research and Monitoring of OA and the US-OA Action Plan provide broad goals to help shape a robust OA science-to-action pipeline. Additionally, the 2008 Memorandum of Understanding between NOAA and Environment Canada (now Environment and Climate Change Canada) led to the establishment of a collaborative framework for joint Department of Fisheries and Oceans (DFO)/NOAA ocean acidification research and monitoring (2016). As with the Research Plan actions, individual projects are likely to align with one or more, but not all, aspects of these high level plans and collaborative efforts. To help integrate local to global scale plans and goals, researchers should consider how their own projects help address goals laid out by these recent high-level guidance documents and collaborative efforts.

Resource limitations pose perennial challenges to addressing every goal of every plan. Despite the prior success of NOAA and other partners in sharing OA science and knowledge domestically and internationally to create efficiencies and capitalize on limited resources, there remains a large demand for research advances and a need to train new OA experts to fill those knowledge gaps. NOAA's international collaboration efforts, such as those to coordinate ocean acidification research and education with Canada's DFO, its participation in GOA-ON's planning and information exchange efforts and its leadership of US contributions to Sustainable Development Goal 14.3.1, help fulfill its legislatively mandated international engagement. These activities are helping sustain the capacity development momentum begun by training courses and international network-building led by others. Increasing the leverage of NOAA investments strategically using thoughtfully developed partnerships and creatively designed projects that can satisfy many goals are proven methods that successfully extend the reach of the Research Plan-guided investments toward addressing a variety of high-level goals too.

Appendix A: NOAA program abbreviations table

NOAA OFFICE	ABBREVIATION
Alaska Fisheries Science Center	AFSC
Atlantic Oceanographic and Meteorological Laboratory	AOML
Bipartisan Infrastructure Law	BIL
Climate Program Office	CPO
Coral Reef Conservation Program	CRCP
NCCOS Competitive Research Program	CRP
Geophysical Fluid Dynamics Laboratory	GFDL
Great Lakes Environmental Research Laboratory	GLERL
Global Monitoring Laboratory	GML
Global Ocean Monitoring and Observing	GOMO
Integrated Ocean Observing System	IOOS
National Centers for Coastal Ocean Science	NCCOS
National Centers for Environmental Information	NCEI
Northeast Fisheries Science Center	NEFSC
National Marine Sanctuaries	NMS
National Oceanographic Partnership Program	NOPP
Northeast Fisheries Science Center	NEFSC
Northwest Fisheries Science Center	NWFSC
Ocean Acidification Program	OAP
Office for Coastal Management	OCM
Ocean Exploration	OER
Office of Marine and and Aviation Operations	OMAO
Office of Aquaculture	OofA
Pacific Islands Fisheries Science Center	PIFSC
Pacific Marine Environmental Laboratory	PMEL
Sea Grant	SG
Southwest Fisheries Science Center	SWFSC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