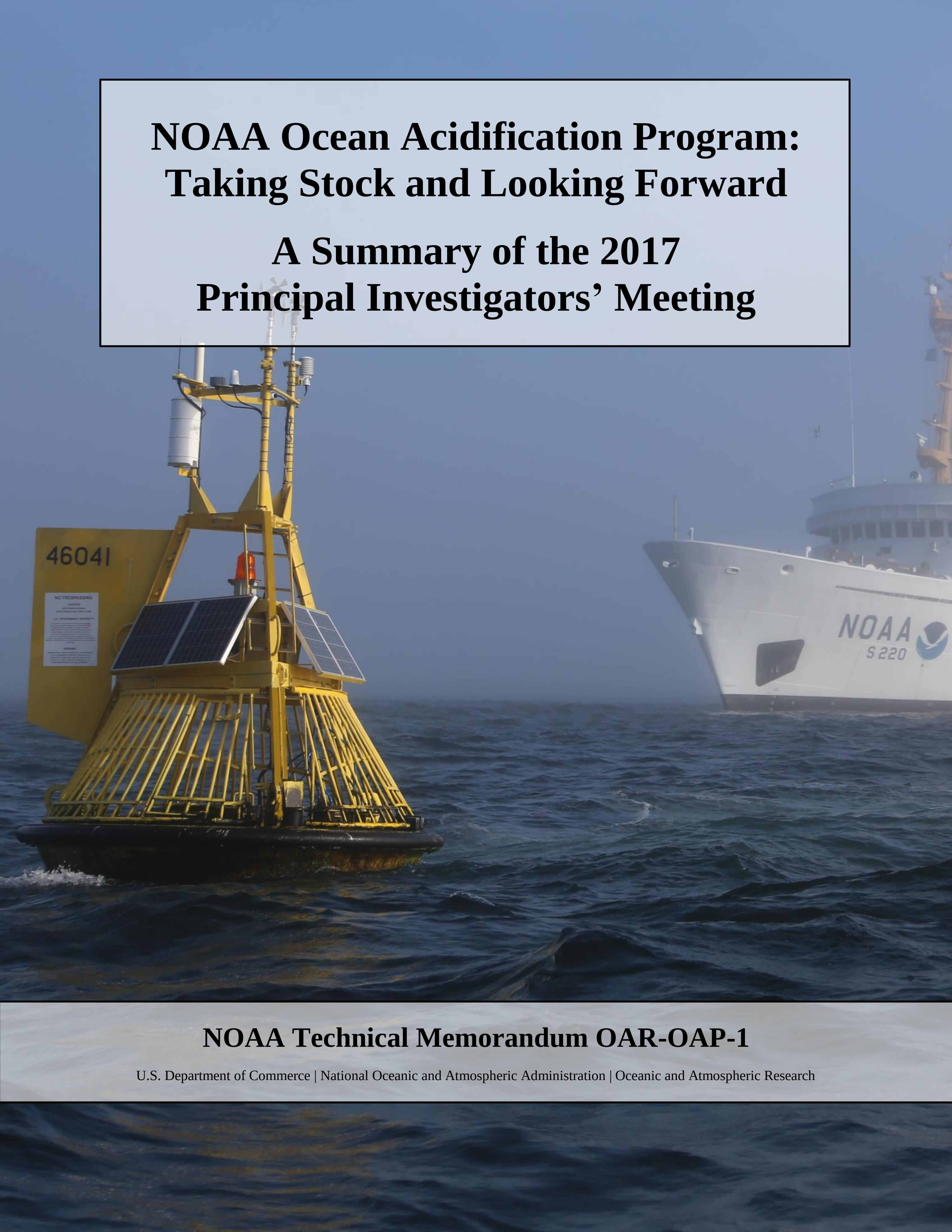
NOAA Ocean Acidification Program: Taking Stock and Looking Forward

A Summary of the 2017 Principal Investigators' Meeting



NOAA Technical Memorandum OAR-OAP-1

U.S. Department of Commerce | National Oceanic and Atmospheric Administration | Oceanic and Atmospheric Research

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Wilbur L. Ross, Jr., Secretary

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Office of Oceanic and Atmospheric Research
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Photo:
NOAA Fairweather ship holds alongside NH10, a buoy which measure CO_2 and pH off Oregon's coast, during the 2013 West Coast Ocean Acidification research cruise. Credit: NOAA

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1. Executive Summary

The NOAA Ocean Acidification Program (OAP) uses a multidisciplinary approach to understand how ocean chemistry is changing in response to ocean acidification (OA), how ecosystems are responding to these changes, and how human communities and economies may be affected. In close partnership with other NOAA programs, labs, and science centers, OAP supports an interdisciplinary range of intramural and extramural science in support of NOAA's mission and communicates OA science to the public and stakeholders. The OAP resides in NOAA's Office of Oceanic and Atmospheric Research (OAR), but is considered a "matrix program" involving multiple NOAA line offices including OAR; National Marine Fisheries Service (NMFS); National Environmental, Satellite, and Data Information Service; National Ocean Service; and Office of Marine and Aviation Operations. Leveraging partnerships with programs and scientists across NOAA and other institutions, the OAP funds work guided by the NOAA Great Lakes and Ocean Acidification Research Plan (NOAA OA Plan), which outlines six themes with national- and regional-scale tasks (Appendix 1).

On January 4-6, 2017, the OAP convened a meeting of its partners and OAP-funded scientists in Seattle, Washington to take stock of its science portfolio and partnerships (Appendices 2, 3). This document summarizes the presentations and conversations that took place at the meeting, and records the advances that NOAA has made in OA science and communications. Meeting attendees expressed interest in OAP expanding its efforts to foster collaboration among scientists and between scientists and stakeholders, investing more in synthesis efforts, better characterizing the ocean environment through enhanced monitoring and high-resolution modeling, further improving our understanding of both the sensitivity and adaptive capacity of species and ecosystems, and promoting additional study of the social and economic implications of OA. OAP partners that attended the meeting provided an important voice in evaluating current work and setting the course for the future.

2. Lessons learned by the OAP

Reflecting on the research taking place in each region (see Section 3), along with what the NOAA community has learned in the last six years, provides an opportunity for the OAP to identify lessons learned.

A hallmark of the OAP is its ability to embrace its role as a matrix program. Emphasizing a collaborative approach among NOAA line offices has allowed the OAP to grow a relatively large and varied portfolio. **Partnerships** have been a key way that the OAP has worked with other organizations inside (Table 1) and outside of NOAA. In developing these partnerships, the OAP has sought out joint activities that fulfill the mission of both the OAP and the partnering group(s). For example, the OAP has partnered with NOAA's National Centers for Coastal Ocean Science, National Sea Grant Program, and U.S. Integrated Ocean Observing System to jointly fund grants of common interest. It has also worked with NMFS (i.e., Alaska, Northwest, and Northeast Fisheries Science Centers), National Ocean Service (i.e., Office of National Marine Sanctuaries, Coral Reef Conservation Program), and others inside of the Office of Oceanic and Atmospheric Research programs (i.e., Pacific Marine Environmental Laboratory, Atlantic Oceanographic and Meteorological Laboratory, and Climate Program Office) to leverage OAP funds to build NOAA's portfolio of OA science. For example, the Climate Program Office's

Ocean Observing and Monitoring Division (OOMD) has funded the foundational observations and baseline understanding of inorganic carbon chemistry globally, and OAP has leveraged these investments. The OAP has also worked with other countries to launch the Global Ocean Acidification Observation Network (GOA-ON), which sets OA monitoring standards and fosters OA science worldwide, especially in countries with low scientific capacity. In addition to fostering collaboration among different organizations, the OAP has fostered a collaborative sentiment within and across traditional scientific “silos.” This has yielded an **integrated, interdisciplinary research portfolio**. By fostering interdisciplinary teams of investigators, the OAP has moved forward on its three-pronged approach to science, simultaneously addressing environmental exposure, species response, and human vulnerability. Such interdisciplinary research efforts are necessary for generating the high-level information requested by stakeholders and policy makers. The OAP’s investments in **nowcasts, forecasts, and projections** are an example of interdisciplinary science that stakeholders are requesting. Finally, the OAP has developed a robust **education and outreach portfolio** that is driven by the 2014 NOAA OA Education Implementation Plan. This portfolio includes a strong presence online through its social media platforms and regular engagement with classroom and experiential educators.

Table 1. NOAA groups that have partnered with the OAP to work on OA.

Line office	Program/Laboratory
National Environmental, Satellite, and Data Information Service	Center for Satellite Applications and Research National Centers for Environmental Information
National Marine Fisheries Service	Office of Science and Technology Alaska Fisheries Science Center Northwest Fisheries Science Center Northeast Fisheries Science Center
National Ocean Service	National Centers for Coastal Ocean Science Office for Coastal Management (includes Coral Reef Conservation Program) Office of National Marine Sanctuaries U.S. Integrated Ocean Observing System Program
Office of Oceanic and Atmospheric Research	Atlantic Oceanographic and Meteorological Laboratory Climate Program Office Pacific Marine Environmental Laboratory National Sea Grant College Program
Office of Marine and Aviation Operations	Ship fleet

NOAA and the OAP are leaders nationally and internationally for information and engagement on OA related issues. For example, the NOAA OAP director, Libby Jewett, chairs the U.S. Interagency Working Group on Ocean Acidification and co-chairs the Global Ocean Acidification Observing Network. OA efforts are really just getting underway, as major investment in the field of science and societal efforts around it are just over a decade old. OA stakeholders need information that is not yet available from scientific pursuits and the **OAP is working to address this need by funding data syntheses and modeling work**, which can help address the “big questions” that the public are asking (i.e., Where are the OA hotspots and refugia? What can we do to protect marine resources from the impacts of OA?). Communicating the limits of our current knowledge requires careful attention, as does explaining why these limits exist. These new data synthesis products are being recognized both nationally and globally as important tools for expanding understanding of OA.

Stakeholders for OA are diversifying; over the past few years, this has resulted in a growing interest and investment in OA science at all levels of government. As new information needs arise, the OAP expects to form new partnerships with which to tackle a diversifying portfolio. Examples of emerging science which will necessitate new partners include: the interaction of OA with hypoxia and harmful algal blooms, development of more robust place-based information, the role of coastal and estuarine processes in the development of OA conditions, how OA will influence wild-capture fisheries and related human systems, and social science and impacts, in general.

Collaborations can advance OAP’s science portfolio by **better capitalizing on existing efforts to address questions** related to OA. For example, much headway could be made to understand the relationship between ocean carbon chemistry and biological communities by adding chemical measurements to existing biology-focused cruises (e.g., fisheries stock assessments) and vice versa. Additionally, summaries of OA could be incorporated into existing ecosystem “report cards” to help stakeholders track OA conditions. In addition, simulations of OA could be incorporated into existing ecosystem and biogeochemical models and earth system models could be updated to better reflect the latest OA science. Adding OA to existing efforts is a cost-effective way to make headway on conducting and delivering OA science and better integrating it with other ecosystem considerations.

As an emerging field of research, the OAP is poised **to take advantage of and, in some cases, develop new technologies** as its portfolio develops. A key challenge is how to bring new technologies into the OAP portfolio while continuing to support the OAP’s core portfolio of sustaining NOAA efforts and extramural awards. Advances in autonomous platforms (i.e., saildrone, carbon prawler, etc.) for observing the ocean’s chemistry and biological communities are rapid, and provide opportunities that have never before been available. These autonomous platforms often take advantage of new sensors, which are rapidly developing in the chemical and biological fields. New sensors are also needed to capitalize on the strong interest in monitoring related to OA by place-based groups and institutions (e.g., parks, marine stations, tribes, local governments), who typically do not have the capacity to become experts in OA science. Low cost instruments are being pushed for both national and international use by the GOA-ON community. The development of molecular techniques, often referred to as *‘omics*, has yielded a powerful toolset for studying OA in the field and laboratory, and can be used to build datasets on presence/abundance, condition, acclimation, and adaptation. Similarly, advances in computer modeling and computing capacity have opened new opportunities for biogeochemical and ecosystem modeling.

3. OAP Portfolio

In an effort to integrate the various priority areas of the NOAA OA Plan, the OAP has adopted a three-pronged approach to assess the vulnerability of marine life, ecosystems, and human communities to OA: (1) document environmental change in response to OA, (2) characterize species and ecosystem sensitivity to that change, and (3) better understand the human dimensions implications of further projected change (Figure 1). The OAP seeks to identify the nation's greatest vulnerabilities to OA which occur at the nexus of where there is significant human dependence on sensitive marine resources which are experiencing the greatest environmental change in response to OA. National monitoring informs modeling efforts that document changes in ocean and coastal carbonate chemistry so as to achieve a more comprehensive understanding of environmental change in response to OA. Laboratory experiments, fieldwork, and ecosystem models are used to determine how sensitive various species and ecosystems are to the identified changes and why they respond in the way that they do. Finally, what this could mean for society is addressed through a human dimensions component which examines the socio-economic impacts of OA, explores possible adaptation strategies, and conducts education and outreach. In order to address questions that are most relevant to human communities, this component of the portfolio works to incorporate stakeholder needs in designing monitoring and research strategies.

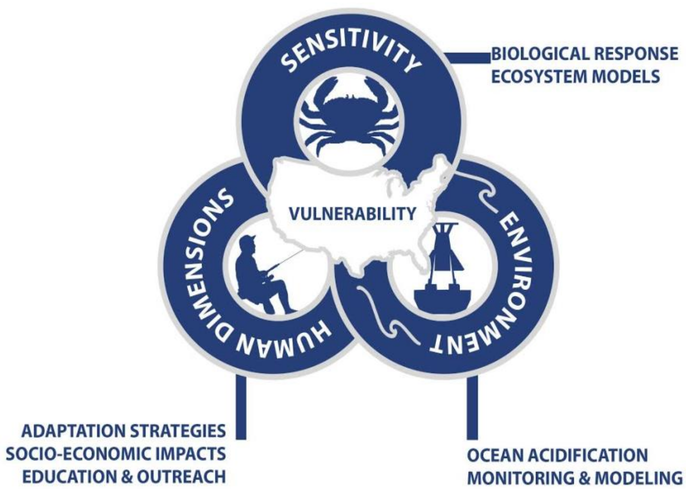

Figure 1. The OAP aims to better understand the nation's vulnerability to OA by utilizing a three-pronged approach to document environmental change, characterize species and ecosystem sensitivity to it, and better understand the human dimensions of projected change.

NATIONAL

Prior to the founding of the OAP, NOAA was conducting OA science in a largely uncoordinated fashion across many parts of the organization. The OAP has worked to grow and coordinate this portfolio making these efforts more robust while increasing the visibility of OA as an issue relevant to NOAA's mission at regional, national, and international levels.

This part of the document outlines the state of the agency's progress on the national tasks detailed in the NOAA OA Plan. Specifics are given in the regional sections. We note that most projects funded by the OAP leverage support from other parts of NOAA or non-NOAA funds. We do not detail all funding sources for all projects in this narrative.

Environment

Over the past six years, the OAP has fostered the growth of the National Ocean Acidification Observation Network (NOA-ON), which utilizes stationary buoy platforms, hydrographic research cruises, and vessels equipped with autonomous sensors to quantify carbonate chemistry dynamics across a range of environments. The NOA-ON represents the U.S. contribution to the GOA-ON. At the time of the January 2017 meeting, there were 19 stationary moorings making surface carbonate chemistry observations nominally every 3 hours. Data from these stations are [readily accessible online](), currently with some latency due to quality assurance/quality control activities (Table 2, Figure 2). Additionally, the OAP funds the science cost to execute one regional, hydrographic, coastal cruise each year within designated U.S. coastal large marine ecosystems. Current funding allows for the reoccupation of the following US regions on an approximately 4-year cycle: Gulf of Alaska, California Current Ecosystem, East Coast (Nova Scotia to Florida), and the Gulf of Mexico. All of the cruises involve international partners and data collection in neighboring Exclusive Economic Zones. Volunteer observing ships (cargo ships and research vessels that act as ships of opportunity) use autonomous sensors to measure the amount of carbon dioxide (CO_2) in coastal and open ocean surface waters. Measurements from volunteer observing ships generate an extensive collection of OA-relevant measures in coastal and open ocean waters across a broad variety of ecosystems throughout the US and more remote waters globally. US scientists, NOAA, and the NOA-ON have played a key leadership role in the formation of the global network GOA-ON, which works to establish a community of practice on ocean observations and syntheses products related to OA.

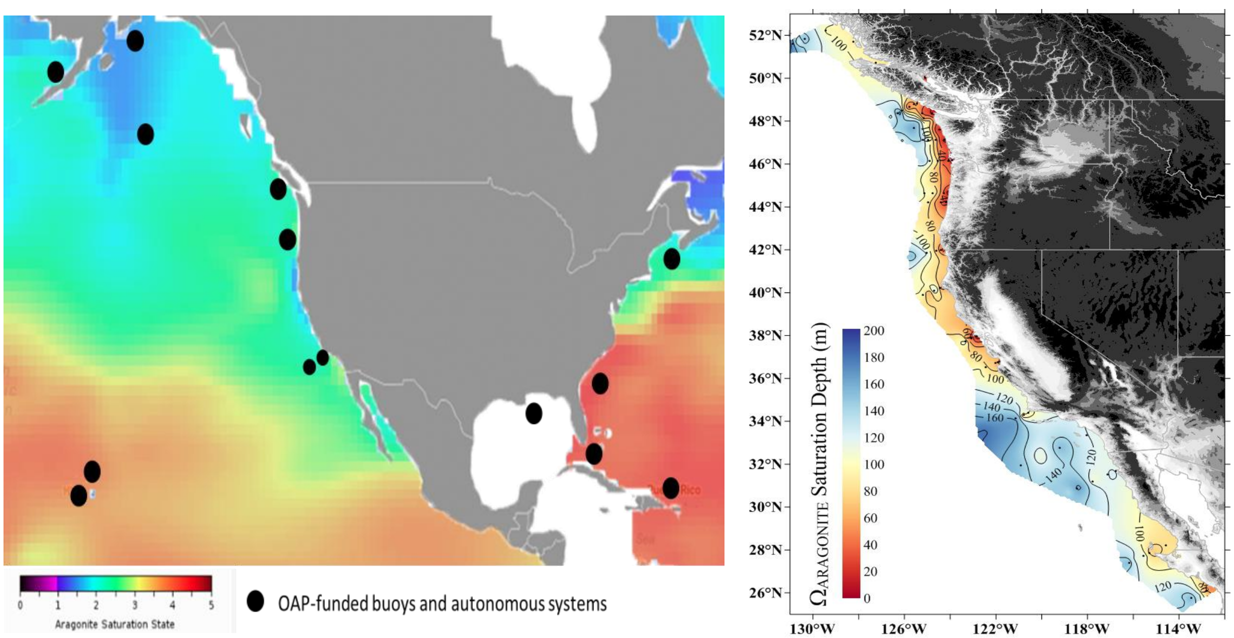

Figure 2. (Left) OA moorings in US coastal, coral reef, and open ocean areas funded primarily or in part by the OAP. Not shown are moorings in the Indian Ocean, Iceland, Micronesia, Japan, and the eastern tropical Pacific. Background shading represents empirical estimates of aragonite saturation state based on observations from Jiang et al (2015) Global Biogeochemical Cycles, 29, 1656-1673. (Right) Aragonite saturation depth (m) during the 2016 West Coast Cruise (May – June).

Table 2. Location of OA moorings that are funded primarily by the OAP or to which the OAP contributes funding. "Funding Type" refers to support of OA sensors, not necessarily support of buoy and mooring infrastructure.

Description	Location	Type	Funding Type
Gulf of Maine	Maine (USA)	Coastal	Primary
Coastal Mississippi	Mississippi (USA)	Coastal	Primary
Gray's Reef	Georgia (USA)	Coastal	Primary
La Push	Washington (USA)	Coastal	Primary
NH 10	Oregon (USA)	Coastal	Primary
CCE2	Southern California (USA)	Coastal	Primary
Gulf of Alaska	Alaska (USA), Gulf of Alaska	Coastal	Primary
M2	Alaska (USA), Bering Sea	Coastal	Primary
La Parguera	Puerto Rico (USA)	Coral Reef	Primary
Kaneohe	Hawaii (USA)	Coral Reef	Primary
Cheeca Rocks	Florida (USA)	Coral Reef	Primary
RAMA	Bengal (India), Indian Ocean	Open Ocean	Primary
Iceland	Iceland	Open Ocean	Primary
Papa	North Pacific Ocean	Open Ocean	Contributor
WHOTS	Hawaii (USA)	Open Ocean	Contributor
Stratus	Eastern Tropical Pacific	Open Ocean	Contributor
KEO	Japan	Open Ocean	Contributor
CCE1	Southern California (USA)	Open Ocean	Contributor
Chuuk	Chuuk (Micronesia)	Coral Reef	Contributor

Models that characterize and, in some cases, forecast carbon chemistry dynamics have been created for areas of the US West Coast and coral reefs in the Caribbean and in Hawaii, and the development of similar models is underway for the US East Coast, Chesapeake Bay, Gulf of Mexico, and Alaska. For example, the Ocean Acidification Product Suite is a hybrid model developed to estimate and map the key OA parameters (i.e., pH, total alkalinity, aragonite and calcite saturation states, and the partial pressure of CO_2 (pCO_2)) of surface water in the Caribbean and part of the Gulf of Mexico (Figure 3).

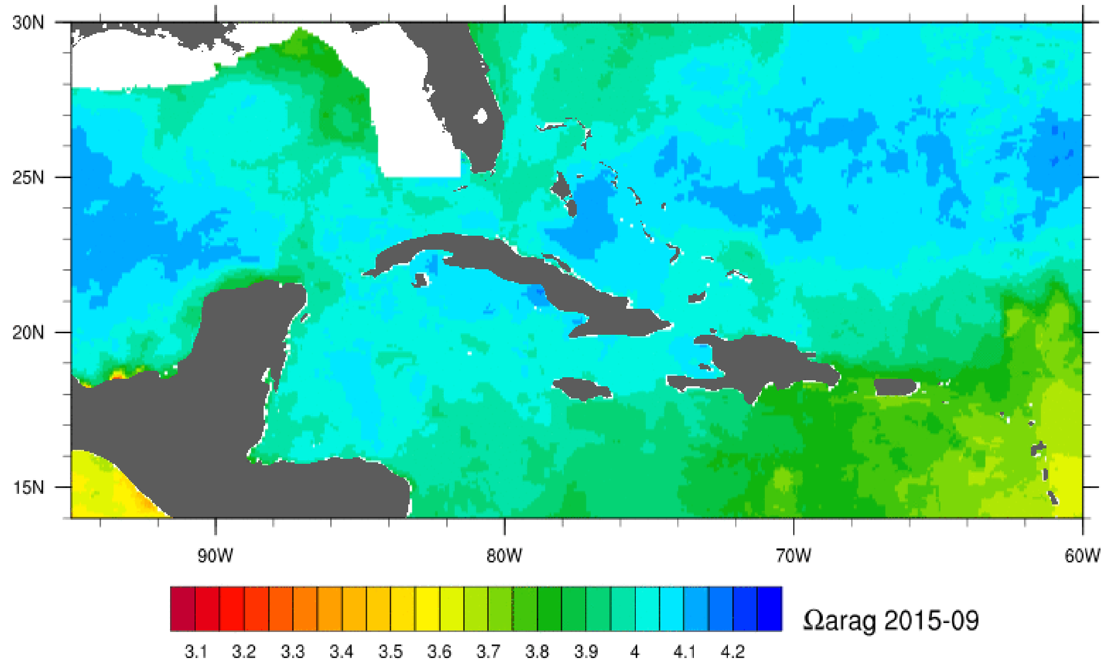

Figure 3. Projection map of aragonite saturation conditions from the Ocean Acidification Product Suite.

Relevant publications:

Using present-day observations to detect when anthropogenic change forces surface ocean carbonate chemistry outside pre-industrial bounds. Sutton, A.J., Sabine, C.L., Feely, R.A., Cai, W.-J., Cronin, M.F., McPhaden, M.J., Morell, J.M., Newton, J.A., Noh, J.-H., Olafsdottir, S.R., Salisbury, J.E., Send, U., Vandemark, D.C., Weller, R.A. Biogeosciences 13: 5065-5083, doi:10.5194/bg-13-5065-2016, September 2016.

A high-frequency atmospheric and seawater $p\mathrm{CO_2}$ data set from 14 open-ocean sites using a moored autonomous system. Sutton, A.J., Sabine, C.L., Maenner-Jones, S., Lawrence-Slavas, N., Meinig, C, Felly, R.A., Mathis, J.T., Musielewicz, S., Bott, R., McLain, P.D., Fought, H.J., Kozyr, A. Earth System Science Data 6: 353-366, doi:10.5194/essd-6-353-2014, November 2014.

Internal consistency of marine carbonate system measurements and assessments of aragonite saturation state: Insights from two U.S. coastal cruises. Patsavas, M.C., Byrne, R.H., Wanninkhof, R., Feely, R.A., Cai, W.-J. Marine Chemistry 176: 9-20, doi:10.1016/j.marchem.2015.06.022, November 2015.

Characterizing the natural system: Toward sustained, integrated coastal ocean acidification observing networks to facilitate resource management and decision support. Alin, S.R., Brainard, R.E., Price, N.N., Newton, J.A., Cohen, A., Peterson, W.T., DeCarlo, E.H., Shadwick, E.H., Noakes, S., Bednaršek, N. Oceanography 28(2):92–107, doi:10.5670/oceanog.2015.34, June 2015.

Coastal ocean acidification: The other eutrophication problem. Wallace, R.B., Baumann, H., Grear, J.S., Aller, R.C., Gobler, C.J. Estuarine, Coastal and Shelf Science 148:1-13, doi:10.1016/j.ecss.2014.05.027, July 2014.

An assessment of ocean margin anaerobic processes on oceanic alkalinity budget. Hu, X., Cai, W.-J. Global Biogeochemical Cycles 25(3), doi:10.1029/2010GB003859, July 2011.

Carbonate mineral saturation states along the U.S. east coast. Jiang, L.-Q., Cai, W.-J., Feely, R., Wang, A. Y., X. Guo, Gledhill, D. K., Hu, X., Arzayus, F., Chen, F., Hartmann, J., Zhang, L. Limnology and Oceanography,55(6): 2424-2432, doi:10.4319/lo.2010.55.6.2424, November 2010.

Alkalinity distribution in the western North Atlantic Ocean margins. Cai, W.-J., Hu X, Huang, W.-J., Jiang, L.-Q .,Wang, Y., Peng, T.-H., Zhang, X. Journal of Geophysical Research 115(8), doi:10.1029/2009JC005482, October 2010.

An international observational network for ocean acidification. Feely, R.A., Fabry, V.J., Dickson, A.G., Gattuso, J.-P., Bijma, J., Riebesell, U., Doney, S., Turley, C., Saino, T., Lee, K., Anthony, K., Kleypas, J. Proceedings of Ocean Observations, doi:10.5270/OceanObs09.cwp.29, January 2010.

Sensitivity

NOAA OAP supports species response work at several NOAA Fisheries Science Centers and academic institutions around the U.S. This research focuses on the survival, growth, and physiology of economically and ecologically important marine species. Results can be used to explore how aquaculture, wild fisheries, and food webs may change as ocean chemistry changes. OAP support has led to the development of multiple experimental systems for studying species response to changes in carbonate chemistry at NOAA facilities and universities. Experimental systems at the NOAA Fisheries Science Centers are used primarily by NOAA scientists, but have also involved collaborative work with academic scientists and students interested in species response to OA. The OAP has also provided support for modeling efforts that aim to better understand the carbon chemistry conditions that species are and will be exposed to in the wild as they move through the marine environment. This work links chemical observations to estimates of species sensitivity to carbonate chemistry conditions. For example, scientists at the Northwest Fisheries Science Center have built a system that can control carbon dioxide, temperature, and oxygen conditions and mimic the diel variability in these parameters that occurs in coastal environments (Figure 4). Scientists using this facility design variable treatments for experiments based on output of a model that combines carbonate chemistry conditions in Puget Sound with species habitat preferences and behavior.

Figure 4. Experimental system at the Northwest Fisheries Science Center's Mukilteo Research Station that was developed to study species response to OA and other stressors related to climate change. Photo credit: Benjamin Drummond/bdsjs.com.

Human dimensions

Projections of population and ecosystem change due to OA and the potential impacts of these changes for fisheries yield and protected species management have been developed for Alaska, U.S. West Coast, and the northeast U.S. Projects that aim to collect data and create models that can inform decisions about management of oyster reefs and nutrient pollution are underway. Along the U.S. West Coast, Alaska, Gulf of Maine, and Chesapeake Bay, shellfish growers, hatchery owners, and scientists are working together to understand how best to adapt to OA. They are monitoring seawater conditions, implementing management practices, and/or deploying treatment systems that maintain and increase hatchery yield.

The NOAA OAP keeps the public abreast of the research taking place and the tools available to stakeholders by communicating on various platforms, including its website and various social media accounts. The OAP fosters stakeholder engagement on a regional scale by supporting the networks of scientists, managers, and stakeholders that have formed in six coastal regions around the US.

Relevant publications:

Introduction to this special issue on ocean acidification: The pathway from science to policy. Mathis, J.T., Cooley, S.R., Yates, K.K., Williamson, P. Oceanography 28(2):10–15, doi:10.5670/oceanog.2015.26, June 2015.

Understanding, characterizing, and communicating responses to ocean acidification: challenges and uncertainties. Busch, D.S., O'Donnell, M.J., Hauri, C., Mach, K.J., Poach, M., Doney, S. C., Signorini, S.R. Oceanography 28(2):30–39, doi:10.5670/oceanog.2015.29, June 2015.

Getting ocean acidification on decision makers' to-do lists: dissecting the process through case studies. Cooley, S.R., Jewett, E.B., Reichert, J., Robbins, L., Shrestha, G., Wieczorek, D. Weisberg, S.B. Oceanography 28(2):198–211, doi:10.5670/oceanog.2015.42, June 2015.

Vulnerability and adaptation of US shellfisheries to ocean acidification. Ekstom, J.A., Suatoni, L., Cooley, S.R., Pendleton, L.H., Waldbusser, G.G., Cinner, J.E., Ritter, J., Langdon, C., van Hooidonk, R., Gledhill, D., Wellman, K., Beck, M.W., Brander, L.M., Rittschof, D., Doherty, C., Edwards, P.E.T., Portela, R. Nature Climate Change 5: 207-214, doi:10.1038/nclimate2508, February 2015.

Data Management

The NOAA National Centers for Environmental Information (NCEI) serve as the NOAA OA data management focal point under the Ocean Acidification Data Stewardship (OADS) project. OADS leverages some of the best technical infrastructure for ocean data management at NCEI, including long-term archive, version control, stable data citation with digital object identifiers (DOIs), and managing controlled vocabularies. On top of that, OADS developed a metadata standard that is capable of accommodating rich metadata information for OA data collected from research vessels, moorings, models, laboratory/mesocosm studies, and other efforts. With the modern metadata template, OADS has established metadata display formats that enable serving rich metadata information about OA data sets to users in a user-friendly interface. OADS has also developed an OA data search portal to allow users to discover and access OA data sets by using checkboxes, dropdown menus, and auto-complete text boxes. Over the last three years, OADS has been working with the Pacific Marine Environmental Laboratory to develop an advanced submission interface called Scientific Data Integration System. Upon completion, this interface will make data submission (i.e. metadata input, data uploading) much easier, which will significantly improve efficiency. It will also automate many back-end procedures within the NCEI, thus allowing OADS to be more focused on improving the scientific content of the OAP-funded data. Work on this project has focused on a metadata entry tool and data submission, data verification, and quality control tools for profile data.

Relevant publications:
Data management strategy to improve global use of ocean acidification data and information. Garcia, H.E., Cosca, C., Kozyr, A., Mayorga, E., Chandler, C., Thomas, R.W., O'Brien, K., Appeltans, W., Hankin, S., Newton, J.A., Gutierrez, A., Gattuso, J.-P., Hansson, L., Zweng, M., Pfeil, B. Oceanography 28(2):226–228, doi:10.5670/oceanog.2015.45, June 2015.

An inter-laboratory comparison assessing the quality of seawater carbon dioxide measurements. Bockman, E.E., Dickson, A.G. Marine Chemistry 171:36–43, doi:0.1016/j.marchem.2015.02.002, February 2015.

A metadata template for ocean acidification data. Jiang, L.-Q., O'Connor, S.A., Arzayus, K.M., Kozyr, A., Parsons, A.R. Earth System Science Data Discussions 8:1-21, doi:10.5194/essdd-8-1-2015, January 2015.

OAP-FUNDED REGIONAL ACTIVITIES

ALASKA

In Alaska, research has been conducted to characterize the environment, and understand species sensitivity to and human dimensions of OA.

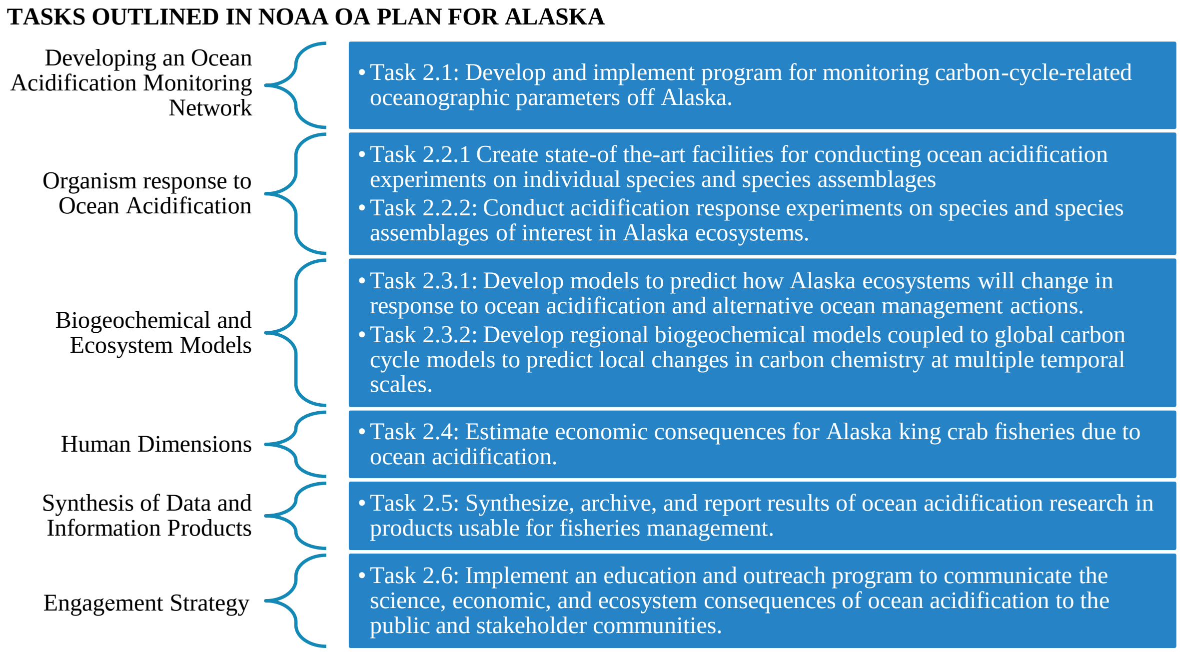

Figure 5. Summary of tasks outlined in NOAA OA Plan for Alaska

Environment

The OAP funds two moorings to characterize and track Alaska's ocean carbon chemistry, one in the northern Gulf of Alaska and the other in the Bering Sea. The five Large Marine Ecosystems that comprise Alaska's marine waters have also been targeted by research cruises, volunteer observing ships, and autonomous underwater vehicles for other monitoring and process-based work. The first Gulf of Alaska synoptic cruise occurred in 2015 with significant leverage from the National Science Foundation. The collection of observations and process studies from Alaska have revealed that subsurface waters in the Gulf of Alaska, Bering Sea, and Arctic Ocean are highly enriched in CO_2 due to remineralization of spring algal blooms. Surface waters in the Beaufort Sea are currently undersaturated with respect to aragonite (annual average), and the same is predicted for the Chukchi and Bering Seas by 2033 and 2062, respectively. In the Gulf of Alaska, current-day aragonite undersaturation results primarily from glacial melt. In the Bering Sea, OA has increased the duration of undersaturation events, such that they are now persistent enough to cause dissolution of calcium carbonate shells and skeletons. Chemistry-related activities in the Alaska research portfolio have touched on all aspects of work outlined in the NOAA OA Plan, with work related to developing regional biogeochemical models (Task 2.3.2, Figure 5) currently supported by the Alaska Ocean Observing System.

Relevant publications:
Ocean acidification in the surface waters of the Pacific-Arctic boundary regions. Mathis, J.T., Cross, J.N., Evans, W., Doney, S.C. Oceanography 28(2):122–135, doi:10.5670/oceanog.2015.36, June 2015.

Sensitivity
Sensitivity work in Alaska has focused on groundfish, crabs, and deep-sea corals. Laboratory studies at the Alaska Fisheries Science Center (AFSC) facility in Newport, Oregon indicate that the growth and survival of early life stages of Northern Rock Sole respond more negatively to OA conditions than those of Walleye Pollock. Work is currently underway to assess how OA conditions might influence behavior. AFSC researchers have pursued two avenues with deep-sea corals. A review of the mineralogy of 62 Alaska deep-sea coral species identified that some species can switch the form of calcium carbonate crystal used to build their skeleton, potentially in response to life history or environmental conditions. A laboratory exposure study on the red tree coral (*Primnoa pacifica*) was done at the Kodiak AFSC Lab. Researchers collected data on fecundity, oocyte development, and sclerite and skeletal morphology.

The Kodiak AFSC Lab has done a number of studies on king (red, blue, golden) and Tanner crab early life stages (egg, embryo, larval, juvenile) and adults; many of these studies span two generations. Response metrics include survival, development, growth, respiration, shell composition, shell mechanics, genomics, and hemolymph measurements. These research efforts show overall negative impacts of OA on crabs but evidence of phenotypic plasticity. Work is now focused on understanding the importance of OA-induced life-history trade-offs to population dynamics. Besides monitoring zooplankton on the 2015 Gulf of Alaska synoptic cruise, no other biology fieldwork has been done in this region. Development of models to predict how Alaska ecosystems will change in response to OA and alternative ocean management actions are underway as part of the NMFS-funded Alaska Climate Integrated Modeling Project. With the inclusion of this NMFS-funded project, the Alaska Enterprise research in this component addresses all sensitivity tasks in the NOAA OA Plan (Figure 5).

Relevant publications:
Ocean acidification leads to altered micromechanical properties of the mineralized cuticle of juvenile red and blue king crabs. Coffey, W.D., Yarram, A., Matoke, B., Long, W.C., Swiney, K.M., Foy, R.J., and Dickenson, G. Journal of Experimental Marine Biology and Ecology, 495:1-12, doi:10.1016/j.jembe.2017.05.011, October 2017.

Decreased pH and increased temperatures affect young-of-the-year red king crab (*Paralithodes camtschaticus*). Swiney K.M., Long W.C., Foy R.J. ICES Journal of Marine Science 74(4):1191-1200, doi:10.1093/icesjms/fsw251, April 2017.

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Elevated CO_2 does not exacerbate nutritional stress in larvae of a Pacific flatfish. Hurst T.P., Laurel B.J., Hanneman E., Haines S.A., Ottmar M.L. Fisheries Oceanography, doi:10.1111/fog.12195, January 2017.

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Human dimensions

Results from the Kodiak Lab work on red king and Tanner crabs have been used in bioeconomic models to assess how OA could influence catch and profits from these two fisheries. Researchers from a variety of disciplines and funded primarily by the Bureau of Ocean Energy Management, NOAA, and Alaska Ocean Observing System assessed and mapped the vulnerability of communities in Alaska to changes in subsistence and commercial fisheries.

The Alaska Ocean Acidification Network launched in 2016. The Network aims to engage scientists and stakeholders, expand the understanding of OA processes and consequences in Alaska, and foster adaptation strategies.

Relevant publications:

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Evaluating the impact of ocean acidification on fishery yields and profits: The example of red king crab in Bristol Bay. Punt, A.E., Poljak, D., Dalton, M.G., Foy, R.J. Ecological Modelling 285:39-53, doi:10.1016/j.ecolmodel.2014.04.017, August 2014.

Ocean acidification risk assessment for Alaska's fishery sector. Mathis, J.T., Cooley, S.R., Lucey, N., Colt, S., Ekstrom, J., Hurst, T., Cauri, C., Evans, W., Cross, J.N., Feely, R.A. Progress in Oceanography 136:71-91, doi:10.1016/j.pocean.2014.07.001, July 2014.

Research gaps identified by the stakeholder panel

To meet stakeholder needs, future research efforts should identify which culturally and/or economically important species and food webs are most vulnerable to OA and develop projections of the time horizons to OA-induced changes in chemistry or thresholds that could alter ecosystem function. There is also interest in better communication about OA to increase awareness, engagement, and education on the issue. Tribes are an audience of particular interest for these efforts given their concerns about changes in food security. However, there is also concern that the OA community does not have enough scientific capacity to answer important stakeholder questions. Researchers working in Alaska are discussing whether to focus OA research on fished species, expected hotspots of change, or an amalgam of the two approaches.

WEST COAST

The West Coast is considered the nation's leader on the issue of OA, likely because it is the site of the world's first high-profile impact of OA (Oregon and Washington oyster hatcheries) and is home to a strong community of stakeholders and scientists that have worked together on the issue over the past decade.

TASKS OUTLINED IN NOAA OA PLAN FOR THE WEST COAST

Developing an Ocean Acidification Monitoring Network

- Task 3.1.1: Develop and implement a program for monitoring carbon-cycle-related oceanographic parameters on the West Coast.
- Task 3.1.2: Establish a Pacific Center of Expertise for ocean carbon chemistry at PMEL.
- Task 3.1.3: Develop and implement a program for biological monitoring to detect ecosystem changes caused by acidification and changes in biology that affect the carbon cycle on the West Coast.
- Task 3.1.4: Establish an immediate monitoring program focused on bivalve recruitment patterns.
- Task 3.1.5: Establish Intensively Studied Marine Areas for monitoring ocean acidification.

Organism response to Ocean Acidification

- Task 3.2.1: Create a state-of-the-art NOAA facility on the West Coast for conducting ocean acidification experiments on individual species and species assemblages.
- Task 3.2.2: Support development of collaborative facilities for acidification response experiments.
- Task 3.2.3: Conduct acidification response experiments on species and species assemblages of interest in West Coast ecosystems.
- Task 3.2.4: Assess the calcium carbonate mineralogy of species important to West Coast ecosystems.
- Task 3.2.5: Correlate hindcasts of West Coast saturation states with historical biological timeseries of species abundance to estimate how species and communities responded to past changes in saturation state.
- Task 3.2.6: Explore technologies for in situ open ocean and semi-permeable mesocosm experiments to test predictions from ecosystem models and species not amenable to laboratory culture.
- Task 3.2.7: Conduct laboratory and field experiments on potential local mitigation methods.

Biogeochemical and Ecosystem Models

- Task 3.3.1: Develop regional biogeochemical models coupled to global carbon cycle models to predict local changes in carbon chemistry at multiple temporal scales.
- Task 3.3.2: Design and implement experiments and observation projects to estimate critical parameters for regional carbon models.
- Task 3.3.3: Develop and apply algorithms to reconstruct historical carbon chemistry conditions over local to regional scales.
- Task 3.3.4: Develop models to predict how West Coast ecosystems will change in response to ocean acidification and alternative ocean management actions.

Human Dimensions

- Task 3.4.1: Estimate anticipated changes to West Coast ecosystem services as a consequence of ocean acidification.
- Task 3.4.2: Develop technical tools for evaluating the consequences of potential management actions related to ocean acidification on the West Coast to create more effective management strategies.

Synthesis of Data and Information Products

- Task 3.5.1: Develop and participate in effective management and dissemination of regionally produced data and data products related to ocean acidification.

Engagement Strategy

- Task 3.6.1: Implement an education and outreach program to communicate the science and ecosystem consequences of ocean acidification to the West Coast public and stakeholder communities.

Figure 6. Summary of tasks outlined in NOAA OA Plan for the West Coast

Environment

Four OAP-funded, fixed-observing assets monitor ocean carbon chemistry along the west coast, two off California (associated with the CalCOFI project), one off central Oregon, and another off northern Washington. Regional synoptic cruises in 2007, 2011, 2012, 2013, and 2016 have provided spatially explicit datasets to complement the time-series datasets from the fixed-observing assets. Ships of opportunity, observations made by the National Marine Sanctuaries along the West Coast, and wave gliders have provided additional data to characterize the region and understand the processes driving regional carbon chemistry conditions. These data have been used to model and document the progression of OA over time, the influence of upwelling on ocean chemistry conditions, and the anthropogenic contribution to these conditions. To better understand how OA is impacting the shellfish industry, NOAA and academic scientists have partnered with industry members to monitor carbon chemistry in shellfish hatcheries. Development and testing of monitoring technology is an important part of the west coast OA portfolio. Progress has been made on all tasks in the NOAA OA plan related to chemical observations (Figure 6). A suite of modeling projects has characterized and projected west coast carbon chemistry conditions. Regional algorithms have been developed to estimate carbon chemistry conditions from measurements of ocean temperature, oxygen, and/or salinity. These relationships have been used to expand spatial understanding of carbon dynamics and hindcast past conditions. A dynamic seascape model approach has been adopted to generate a "nowcast" of current chemistry conditions using an understanding of water masses. A model characterizing ocean hypoxia and acidification using ocean circulation, biogeochemistry, and lower-trophic-level ecosystem parameters is being developed to understand the relative contributions of natural climate variability, anthropogenic climate change, and anthropogenic inputs of CO_2 and nutrients on the status and trends of hypoxia and acidification in the California Current. The [Joint Institute for the study of the Atmosphere and Ocean](#) (JISAO) Seasonal Coastal Ocean Prediction of the Ecosystem (JSCOPE) model, which provides experimental seasonal forecasts (six to nine months) of upper-ocean properties based on operational simulations by NOAA's Climate Forecast System model and dynamical downscaling

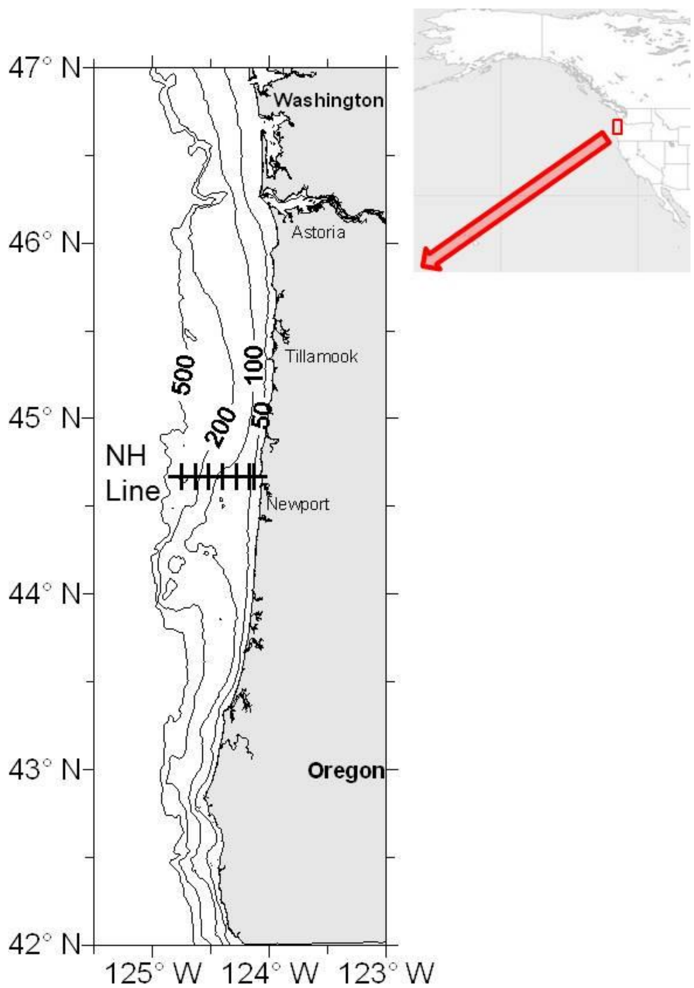

Figure 7. The Newport Line, where transects and stations are sampled during frequent cruises by National Marine Fisheries Service.

with a high-resolution version of a Regional Ocean Model System, was recently extended to develop seasonal forecasts of OA conditions in the Pacific Northwest. Collectively, this work has addressed all three chemistry modeling tasks in the NOAA OA Plan (Figure 6).

Assessment of pteropod shells collected along the west coast show patterns of dissolution that correlate with waters undersaturated with respect to aragonite. Models indicate that this dissolution is likely a modern phenomenon related to anthropogenically driven OA. Work is also underway to relate Dungeness crab megalopae distributions and condition to carbon chemistry conditions. The task in the NOAA OA Plan related to monitoring of bivalve recruitment is currently being done by some West Coast states (Task 3.1.4, Figure 6), and more needs to be done to develop a robust monitoring program for the biological impacts of OA (Task 3.1.3, Figure 6). Biological observations have been regularly collected along the Newport Line (Figure 7) since 1996, and, with discrete carbon chemistry samples and modeled hindcasts of chemistry conditions, could be used to assess potential relationships between biological communities and OA. Samples of zooplankton, harmful algal bloom species, and microbes have been collected on the West Coast synoptic cruises; these samples are the first step towards developing a monitoring program for the biological impacts of OA. OA monitoring activities conducted by West Coast National Marine Sanctuaries complement OAP-funded monitoring, providing additional valuable data sets.

Relevant publications:

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Interpretation and design of ocean acidification experiments in upwelling systems in the context of carbonate chemistry co-variation with temperature and oxygen. Reum, J.C.P., Alin, S.R., Harvey, C.J., Bednarsek, N., Evans, W., Feely, R.A., Hales, B., Lucey, N, Mathis, J.T., McElhany, P., Newton, J., Sabine, C.L. ICES Journal of Marine Science 73(3):582-595, doi:10.1093/icesjms/fsu231, March 2016.

Core principles of the California Current acidification network: Linking chemistry, physics, and ecological effects. McLaughlin, K., Weisberg, S.B., Dickson, A.G., Hofmann, G.E., Newton, J.A., Aseltine-Neilson, D., Barton, A., Cudd, S., Feely, R.A., Jefferds, I., Jewett, E.B., King, T., Langdon, C.J., McAfee, S., Pleschner-Steele, D., and Steele, B. Oceanography 28(2):160–169, doi:10.5670/oceanog.2015.39, June 2015.

Aragonite saturation state dynamics in a coastal upwelling zone. Harris, K.E., DeGrandpre, M.E., Hales, B. Geophysical Research Letters 40(11):2720-2725, June 2013.

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Scientific summary of ocean acidification in Washington State marine waters. Feely, R.A., Klinger, T., Newton, J.A., Chadsey, M. Department of Commerce, National Oceanic and Atmospheric Agency Ocean and Atmospheric Research Special Report, November 2012.

Sensitivity

Laboratory work on the west coast has focused on the response of Dungeness crab early-life stages to changes in carbon chemistry. This species shows decreased survival and development rate under high CO_2. Work on how the combination of high CO_2 and either high temperature or low oxygen levels affects the species is underway, and includes measurement of respiration rate, metabolomics, and population genetics. Laboratory and shipboard experiments have improved knowledge of how OA decreases pteropod shell condition and survival. Additional laboratory work is underway looking at pteropod survival and metabolomics under high CO_2 and low oxygen conditions. Work done in collaboration with academic colleagues has found that development rates and survival of krill larvae are lower in high CO_2 conditions. NOAA and University of Washington researchers are currently studying how high CO_2 conditions affect salmon and sablefish olfactory sensitivity and geoduck larval survival, growth, and epigenetics. A project funded by the Allen Foundation (which includes NOAA scientists) is exploring the role of kelp production as a way to mitigate OA conditions at a local level. Four of the biological research tasks (Task 3.2.1-4, Figure 6) in the NOAA OA Plan are being addressed directly, while the task on mitigation work is largely addressed by state and university scientists with non-NOAA funding sources (Task 3.2.7). Other agencies and countries have funded mesocosm-based work, which has proved technologically challenging (Task 3.2.6). The task on the correlation of biological time-series with hindcasts of ocean carbon chemistry conditions (Task 3.2.5) has not been addressed to date, but is being worked on in FY 18-20.

A variety of modeling work in the region is improving our understanding of species and ecosystem sensitivity to OA at scales not possible by manipulative experiments alone; it also serves as a regional synthesis of the research findings. Recent meta-analyses of species response studies estimate the relative sensitivity of the functional groups in the California Current ecosystem to OA and compare these estimates of relative sensitivity to a database of species mineralogy for Puget Sound species. An individually based model has been developed to estimate what carbon chemistry conditions zooplankton in Puget Sound, Washington are exposed to currently and will potentially be exposed to in the future. Results from this work are being used to design more ecologically relevant laboratory experiments. Simulations of OA have been run using Atlantis and EcoPath ecosystems models to explore how the direct and indirect effects of OA may influence food web structure, fisheries harvest, and endangered species. More work is needed to better address the ecosystem impacts of alternative fisheries and ecosystem management actions under OA (NOAA OA Plan Task 3.3.4, Figure 6).

Relevant publications:

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New ocean, new needs: Application of pteropod shell dissolution as a biological indicator for marine resource management. Bednaršek, N., Klinger, T., Harvey, C. J., Weisberg, S., McCabe, R.M., Feely, R.A., Newton, J., Tolimieri, N. Ecological Indicators, doi:10.1016/j.ecolind.2017.01.025, May 2017.

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Risks of ocean acidification in the California Current food web and fisheries: Ecosystem model projections. Marshall, K.N., Kaplan, I.C., Hodgson, E.E., Hermann, A., Busch, D.S., McElhany, P., Essington, T.E., Harvey, C.J., Fulton, E.A. Global Change Biology, doi:10.1111/gcb.13594, January 2017.

Development of *Euphausia pacifica* (krill) larvae is impaired under pCO2 levels that are currently observed in the Northeast Pacific. McLaskey, A., Keister, J.E., McElhany, P., Olson, M.B., Busch, S., Maher, M., Winans, A.K. Marine Ecology Progress Series 555: 65-78, doi:10.3354/meps11839, August 2016.

The influence of Pacific Equatorial Water on fish diversity in the southern California Current System. McClatchie, S., Thompson, A.R., Alin, S.R., Siedlecki, S., Watson, W., Bograd, S.J. Journal of Geophysical Research: Oceans, doi:10.1002/2016JC011672, August 2016.

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Pteropods on the edge: Cumulative effects of ocean acidification, warming, and deoxygenation. Bednaršek, N., Harvey, C.J., Kaplan, I.C., Feely, R.A., Možina, J. Progress in Oceanography 145:1–24, doi:10.1016/j.pocean.2016.04.002, June 2016.

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Shell condition and survival of Puget Sound pteropods are impaired by ocean acidification conditions. Busch, D.S., Maher, M., Thibodeau, P., McElhany, P. PLoS ONE 9(8): e105884, doi:10.1371/journal.pone.0105884, September 2014.

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Potential impacts of ocean acidification on the Puget Sound food web. Busch, D.S., Harvey, C.J., and McElhany, P. ICES Journal of Marine Science 70(4):823–833, doi:10.1093/icesjms/fst061, June 2013.

Potential impacts of climate change on Northeast Pacific marine food webs and fisheries. Ainsworth, C.H., Samhouri, J.F., Busch, D.S., Cheung, W.W.L., Dunne, J., and Okey, T.A. ICES Journal of Marine Science 68:1217-1229, doi:10.1093/icesjms/fsr0432011, April 2011.

Human Dimensions
All three of the human dimensions and engagement tasks in the NOAA OA Plan are addressed by West Coast projects (Figure 6). Seawater carbonate chemistry conditions are monitored at shellfish hatcheries, and these data are posted online in near-real-time. In addition, the JSCOPE forecasting model now includes advanced warning of potential corrosive conditions driven by off-shore upwelling events. These information products are helping hatcheries strategically deploy adaptive management strategies (i.e., water amendments) in response to changing ocean conditions, yielding significant benefit to the industry. Regional data synthesis and modeling efforts are generating policy relevant information by parsing out the relative contributions of natural climate variability, anthropogenic climate change, rising pCO_2, and anthropogenic nutrient loading on secular trends in hypoxia and OA within the California Current. This information is and will be communicated to coastal zone managers to help them explore potential implications for marine resource management and pollution control measures. Modeling exercises projecting future ecosystem states under OA estimate potential impacts on fisheries harvest and fishing-dependent communities. These projections are the first step towards developing appropriate fisheries and ecosystem management strategies under OA conditions. A variety of education and outreach efforts in the region (e.g., lectures, West Coast Ocean Acidification and Hypoxia Panel, Washington Blue Ribbon Panel on Ocean Acidification, displays at aquaria) have brought information to stakeholders, the public, and students to inform them about OA and its potential impacts. The Olympic Coast National Marine Sanctuary is working with a diversity of partners to designate the Olympic Coast as a sentinel site for OA, which will capitalize on Sanctuary networks and resources to advance both OA science and outreach activities. This effort may help to address goal 3.1.5 (Figure 6).

The California Current Acidification Network was founded in 2010 with the mission to: 1) coordinate and encourage development of an OA monitoring network for the west coast that serves publicly available data; 2) improve understanding of linkages between oceanographic conditions and biological responses; 3) facilitate and encourage the development of causal, predictive, and economic models that characterize these linkages and forecast effects; and 4) facilitate communication and resource/data sharing among the many groups, organizations, and entities that participate in the network or utilize it as an informational resource.

Research gaps identified by the stakeholder panel
Stakeholders on the west coast are interested in place-based information and efforts that attribute biological impacts to changes in carbon chemistry. Place-based information is needed by place-based communities, such as tribes and National Marine Sanctuaries, and by marine resource managers to understand the consequences of OA for their communities and/or management activities. Attribution efforts are important for understanding local and regional drivers of OA (e.g., atmospheric deposition vs. nutrient pollution) and consequences for ecosystems and human communities. Major stakeholders in the region are water quality managers, including the U.S. Environmental Protection Agency. At a 2016 workshop, a group of experts from academic, non-governmental, philanthropic, and California, Oregon and Washington state and federal management communities identified the following research needs for OA: 1) expand the linkage between chemical exposure and biological responses; 2) define natural variability in carbon chemistry conditions; 3) standardize and simplify operational procedures for measuring OA parameters and indicators; and 4) support co-located chemical and biological field

measurements. Scientists are an active stakeholder group on the West Coast and need support to collect OA-related data and synthesize the information for other regional stakeholders. More work needs to be done to identify all stakeholders in the region, as some potential stakeholders (i.e., local resource managers) do not have access to the OA information they need.

CORAL REEF ECOSYSTEMS

The goal of NOAA coral reef OA efforts is to establish a time-series of key ecological indicators believed to be most vulnerable to OA. This work is done as part of the NOAA Coral Reef Conservation Program's National Coral Reef Monitoring Program (NCRMP), a long-term, interdisciplinary monitoring effort. NCRMP tracks indicators in U.S. and U.S.-affiliated coral reef ecosystems in both the Pacific and Atlantic/Caribbean under four themes: benthic habitat, reef fish, climate, and socio-economics. This work addresses tasks detailed across two chapters of the NOAA OA Plan: chapter 4 discusses tasks for the Pacific Islands and chapter 5 discusses tasks for the Atlantic/Caribbean (Figure 8). Here we discuss the progress related to coral-reef ecosystems across both regions.

TASKS OUTLINED IN NOAA OA PLAN FOR PACIFIC ISLANDS

Developing an Ocean Acidification Monitoring Network

- Task 4.1.1: Implement a comprehensive program for monitoring carbon-cycle-related oceanographic parameters in the Pacific Islands.
- Task 4.1.2: Implement a comprehensive program for monitoring coral reef systems likely to be impacted by ocean acidification in the Pacific Islands.
- Task 4.1.3: Monitor cryptic species and biodiversity for the effects of ocean acidification in the Pacific Islands.
- Task 4.1.4: Monitor microbial communities for effects of ocean acidification in the Pacific Islands.

Organism response to Ocean Acidification

- Task 4.2.1: Conduct laboratory experiment to estimate the effect of ocean acidification on important species in the Pacific Islands.
- Task 4.2.2: Conduct in situ experiments manipulating CO_2 to estimate the effect of ocean acidification in the natural environment.
- Task 4.2.3: Estimate historical changes to corals as a response to fluctuating CO_2.
- Task 4.2.4: Conduct experiments on how beach forming processes will be affected by ocean acidification.
- Task 4.2.5: Behavior response experiments of cetaceans to increased ocean sound propagation with ocean acidification.

Biogeochemical and Ecosystem Models

- Task 4.3.1: Develop finescale, wave-driven hydrodynamic circulation models for coral reef habitats throughout the Pacific Islands region.
- Task 4.3.2: Develop biogeochemical models to predict Pacific Islands ecosystem responses to ocean acidification.
- Task 4.3.3: Refine existing trophic interaction ecosystem model (Ecopath with Ecosim) to predict ecosystem impacts of ocean acidification in the Pacific Islands.
- Task 4.3.4: Develop coupled sand transport and biogeochemistry models to predict the impacts of ocean acidification on critical nesting beach habitats.
- Task 4.3.5: Develop sound propagation models to predict the impacts of ocean acidification on protected cetacean species across the Pacific Islands region.

Human Dimensions

- Task 4.4: Estimate the impact of ocean acidification on socioeconomic activities.

Synthesis of Data and Information Products

- Task 4.5: Develop data and information tools for evaluating the consequences of ocean acidification in the PIR to create more effective management strategies.

Engagement Strategy

- Task 4.6: Implement an education and outreach program in the PIR to increase public understanding of ocean acidification.

TASKS OUTLINED IN NOAA OA PLAN FOR THE SOUTHEAST AND GULF OF MEXICO

Developing an Ocean Acidification Montioring Network

- Task 5.1.5: Establish the SER/GOM portion of a coral reef ocean acidification monitoring program

Organism response to Ocean Acidification

- Task 5.2.1: Conduct species-specific OA exposure experiments.
- Task 5.2.3: Conduct coral sclerochronology for retrospective OA assessment to detect the coral calcification historical response.

Figure 8. Summary of tasks outlined in NOAA OA Plan for Pacific Coral Reef Ecosystems and coral-reef-related tasked in the Southeast and Gulf of Mexico regions.

Environment

NCRMP monitoring documents the carbonate chemistry of coral reef systems at multiple scales in space and time using a nested hierarchical design with four classes (Figure 9). Class 0 sites quantify spatial variability in carbonate chemistry, temperature, and salinity at the jurisdiction or island scale. At these sites, synoptic sampling is distributed in a stratified, random fashion according to water depth, extending out to 30 m. Synoptic sampling campaigns are executed each year in a "round-robin" fashion whereby each jurisdiction/island is reoccupied once every three years in the Pacific and once every two years in the Atlantic. Class I sites have fixed temperature sensors only. Class II sites collect the same data as Class 0 and I sites, and include 1) a sensor package to record diurnal variability in carbonate chemistry and temperature and 2) deployed equipment to monitor calcification, bioerosion, and cryptic diversity. Photomosaics are also taken at the Pacific reef Class II sites. Class III sites collect the same data as Class II sites and monitor carbonate dynamics using a buoy operated by PMEL.

In Atlantic coral reef systems, Class III stations are located in La Paguera, Puerto Rico and Florida's Cheeca Rocks within the Florida Keys National Marine Sanctuary. NCRMP activities in the Atlantic region began in 2013, so the chemical and biological observing data are currently being analyzed. Early results from this work are that there is net erosion on an annual basis in southeast Florida that tropical storms may enhance acidification locally for several weeks following a storm event, and that seagrass meadows within the Keys may confer some CO_2 scavenging benefits to back-reef environments. In the Pacific, at least one $MAPCO_2$ system has been located in Oahu since 2005, and two more are planned (one will be located in American Samoa). Regional research efforts in the Pacific are working to detect trends from the variability present in the datasets, due to events such as El Niño/La Niña, and to explore patterns in how offshore climatology compares to onshore conditions. Recent work indicates that variability in calcium carbonate accretion in the Pacific reefs at the Class II sites can be explained by chlorophyll *a* concentrations, wave energy, and aragonite saturation state. Autonomous reef monitoring structures from some Pacific coral reefs are being analyzed using genomic techniques and visual analyses of mobile invertebrates. Coral cores have been collected at many monitoring sites. All of the monitoring tasks in the NOAA OA Plan are underway. The Plan's ocean circulation modeling (Task 4.3.1) has been partially addressed with funding from outside of NOAA and the coupled sand transport and biogeochemical modeling (Task 4.3.4) task have not yet been addressed as efforts have focused on characterizing the environment in coral reef ecosystems (Figure 8).

NCRMP Climate Monitoring Stations		Parameters: Physical environment: Temperature	Salinity	Dissolved oxygen	Rugosity	Carbonate chemistry: DIC and Total Alkalinity (TA)	pCO_2 and pH	Ecological impacts: Coral growth rates	Calcification rates	Bioerosion rates	Community structure	Instrumentation: STRs: Subsurface temperature recorder arrays	Automated water samplers	ADCPs: Acoustic Doppler Current Profilers *(Pacific only)*	MapCO₂: Moored autonomous pCO_2 buoys	CAUs: Calcification accretion units	BMUs: Bioerosion monitoring units	ARMS: Autonomous reef monitoring structures
Class 0	random	•	•			•												
Class I	fixed	•										•						
Class II	fixed	•	•	•	•	•		•	•	•	•	•	•	•		•	•	•
Class III	fixed	•	•	•	•	•	•	•	•	•	•				•	•	•	•

Figure 9. Class designation of various NCRMP sites. OAP investments benefit from significant leverage provided by the Coral Reef Conservation Program.

<u>Relevant publications:</u>
Coupling chemical and biological monitoring to understand the impact of ocean acidification on coral reef ecosystems. Sutton, A., Manzello, D., Gintert, B. *Oceanography* 28(2):28–29, doi:10.5670/oceanog.2015.28, June 2015.

Calcification and organic production on a Hawaiian coral reef. Shamberger, K.E.F., Feely, R.A., Sabine, C.L., Atkinson, M.J., De Carlo, E.H., Mackenzie, F.T., Drupp, P.S., Butterfield, D.A. Marine Chemistry 127: 64–75, doi:10.1016/j.marchem.2011.08.003, December 2011.

Sensitivity
In collaboration with academic colleagues, scientists from the NOAA Pacific Islands Fisheries Science Center used a laboratory mesocosm and settlement plates incubated on coral reefs (autonomous reef monitoring structures) to better understand how OA may influence reef communities (Task 4.2.1). NOAA researchers at the Atlantic Oceanographic and Meteorological Laboratory were involved in laboratory experiments on the response of an octocoral species to OA using funding from sources other than the OAP (Task 5.2.1). Coral skeletons from reefs have been analyzed to understand how carbonate chemistry affects coral reef growth and erosion again using funding from sources other than the OAP (Task 5.2.3). The NOAA OA Plan tasks related to conducting *in situ* OA experiments (Task 4.2.2) and beach formation processes (Task 4.2.4) are currently unmet by NOAA, but extensive *in situ* experiments have been conducted by investigators funded by the U.S. Geological Survey, National Science Foundation, and others. Since the publication of the NOAA OA Plan, new research found that OA will not have a large influence on ocean sound propagation. As such, both tasks in the NOAA OA Plan related to sound propagation have not been addressed, nor are they likely to be addressed in the near-term given that the research community has determined that changes in sound will not be appreciable (Task 4.2.5, 4.3.5). Two ecosystem modeling tasks in the NOAA OA Plan (Tasks 4.3.2, 4.3.3) have been partially addressed by Atlantis ecosystem modeling work led by the Pacific Islands Fisheries Science Center that was not funded by the OAP (Figure 8).

Relevant publications:

Elevated colonization of microborers at a volcanically acidified coral reef. Enochs, I.C., Manzello, D.P., Tribollet, A., Valentino, L., Kolodziej, G., Donham, E.M., Fitchett, M.D., Carlton, R., Price, N.N. PLoS ONE, 11(7): e0159818, doi:10.1371/journal.pone.0159818, July 2016.

Micro-CT analysis of the Caribbean octocoral *Eunicea flexuosa* subjected to elevated pCO2. Enochs, I.C., Manzello, D.P., Wirshing, H.H., Carloton, R., Serafy, J. ICES Journal of Marine Science 73(3): 910-919, doi:10.1093/icesjms/fsv159, March 2016.

Opposite latitudinal gradients in projected ocean acidification and bleaching impacts on coral reefs. van Hooidonk, R., Maynard, J.A., Manzello, D., Planes, S. Global Change Biology, doi: 10.1111/gcb.12394, October 2013.

Ocean acidification alters the otoliths of a pantropical fish species with implications for sensory function. Bignami, S., Enochs, I.C., Manzello, D.P., Spaunagle, S., Cowen, R.K. Proceedings of the National Academy of Sciences, doi:10.1073/pnas.1301365110, April 2013.

Human dimensions

The NOAA Coral Reef Conservation Program is developing "report cards" for all coral reefs in U.S. jurisdictions to track indicators and provide "scores" that indicate condition. The Coral Reef Ecosystem Program of the Pacific Islands Fisheries Science Center is using these indicators as a tool to communicate with the public, natural resource managers, and Congress. Although these report cards aren't specific to OA, they do assess the socioeconomic impacts of changes to coral reefs generally and can inform effective management. These efforts partially fill the human exposure tasks in the NOAA OA Plan (Tasks 4.4, 4.5, 4.6, Figure 8).

Relevant publications:

Incorporating climate and ocean change into extinction risk assessments for 82 coral species. Brainard, R.E., Weijerman, M., Eakin, C.M., McElhaney, P., Miller, M.W., Patterson, M., Piniak, G.A., Dunlap, M.J., Birkeland, C. Conservation Biology 27:1169-1178, doi: 10.1111/cobi.12171, December 2013.

Research gaps identified by the stakeholder panel

Stakeholders in coral reef regions are interested in regularly timed, locally tailored, science translation products that provide actionable information on potential local changes in ecosystem services within the next ten years. A number of science efforts are needed to build these products: monitoring and data synthesis activities at relevant spatial and temporal scales, better knowledge of the sensitivity and adaptive capacity of key coral reef species and of the ecological and physical processes that influence reef systems (e.g., blue carbon sequestration and water movement near reefs), and vulnerability assessments to define OA-sensitive ecosystem services and how they may respond to multiple stressors.

Southeast and Gulf of Mexico

Although carbonate chemistry observations have been ongoing in the Southeast and Gulf of Mexico for over a decade, research to understand the sensitivity of marine life to OA and the potential human dimension impacts of OA has only recently begun. Activities related to the coral-reef tasks are discussed in the previous section.

TASKS OUTLINED IN NOAA OA PLAN FOR THE SOUTHEAST AND GULF OF MEXICO

Developing an Ocean Acidification Monitoring Network
- Task 5.1.1: Establish requisite analytical capability for conducting high-quality carbonate chemistry measurements and training at AOML.
- Task 5.1.2: Establish SER/GOM ocean acidification coastal/oceanic mooring network.
- Task 5.1.3: Conduct SER/GOM ocean acidification hydrographic/geochemical ship surveys.
- Task 5.1.4: Regional carbonate chemistry synoptic mapping.
- Task 5.1.6: Establish a seagrass OA monitoring program.
- Task 5.1.7: Establish an estuarine OA monitoring program.

Organism response to Ocean Acidification
- Task 5.2.1: Conduct species-specific OA exposure experiments.
- Task 5.2.2: Conduct lab and/or field experiments to determine OA impacts on key species interactions (e.g., competition, predation, facilitation).

Biogeochemical and Ecosystem Models
- Task 5.3.1: Develop regional biogeochemical forecast models coupled to global carbon cycle models to predict local changes in carbon chemistry at multiple temporal scales.
- Task 5.3.2: Develop regional biogeochemical hindcast models to evaluate historical changes in carbonate chemistry within the SER/GOM.
- Task 5.3.3: Develop regional ecoforecast models.

Human Dimensions
- Task 5.4.1: Forecast impacts to ecosystem services within the SER/GOM.
- Task 5.4.2: Conduct necessary social impact and vulnerability assessments to ascertain probable social impacts of OA and identify possible mitigation strategies within the SER/GOM.
- Task 5.4.3: Develop mitigation and community adaptation strategies.

Synthesis of Data and Information Products
- NONE OUTLINED

Engagement Strategy
- Task 5.6.1: Create and distribute media that clearly and concisely describe the chemistry of OA as well as the known and hypothesized impacts.
- Task 5.6.2: Create an interactive website focused on OA in the SER/GOM.
- Task 5.6.3: Develop regular summary literature that provides a State of the Science of OA and Known Impacts in the SER/GOM.
- Task 5.6.4: Install interactive displays at aquaria in the southeastern United States.
- Task 5.6.5: Create education modules and curricula that can be used by teachers to help describe OA and its impacts to students.

Figure 10. Summary of tasks outlined in NOAA OA Plan for the Southeast and Gulf of Mexico.

Environment

Carbonate chemistry monitoring in the region has historically focused on estimating air-sea carbon flux and carbon cycling associated with the hypoxia region of the northern Gulf of Mexico. Since the inception of the OA Program, many of the region's surveys and underway sampling programs have been altered to specifically quantify OA. Both sub-regions host a coastal OA mooring (coastal Mississippi and Georgia's Gray's Reef National Marine Sanctuary) and also engage in further monitoring using volunteer observing ships, for example the quarterly sampling in the Flower Garden National Marine Sanctuary (from winter 2013 onward). Synoptic cruises that covered both the Gulf of Mexico and the East Coast occurred in 2007 and 2012. As of 2015, separate cruises are used to monitor the Southeast and Gulf of Mexico sub-regions; the Southeast was included in the 2015 East Coast OA cruise (cruise extended from the Scotian Shelf to Miami, Florida) and the Gulf of Mexico had its own cruise in 2017. These observations have found that the Gulf of Mexico is a small sink for CO_2 and that aragonite saturation state in the region changed ten times more rapidly than expected from absorption of atmospheric CO_2 alone, likely due to natural variability in regional water masses. Freshwater and nutrient run-off drive coastal acidification events in the region's estuaries and near-shore waters, particularly along the southeast coast. An effort is currently underway to identify the primary driver(s) of coastal acidification events in Texas estuaries in northwestern Gulf of Mexico. A number of regional modeling efforts have been used to describe patterns in past, current, and future OA conditions. Quasi-operational synoptic maps of the carbonate chemistry conditions of Gulf of Mexico and Caribbean surface waters are now regularly released by AOML using the Ocean Acidification Product Suite (Figure 3). The NOAA OA Plan calls for more extensive monitoring with moorings than is currently occurring including targeted monitoring programs for regional seagrass and estuarine environments (Tasks 5.1.6, 5.1.7, Figure 10). Regional ecoforecast models have not yet been developed (Task 5.3.3, Figure 10).

Relevant publications included:

Effects of eutrophication and benthic respiration on water column carbonate chemistry in a traditional hypoxic zone in the Northern Gulf of Mexico. Hu, X., Li, Q., Huang, W.-J., Chen, B., Cai, W.-J., Rabalais, N.N., and Turner, R.E. Marine Chemistry 190**(**33-42), doi:10.1016/j.marchem.2017.04.004, April 2017.

Time series $p\mathrm{CO}_2$ at a coastal mooring: Internal consistency, seasonal cycles, and interannual variability. Reimer, J.J., Cai, W.-J., Xue, L., Vargas, R., Noakes, S., Hu, X., Signorini, S.R., Mathis, J.T., Feely, R.A., Sutton, A.J., Sabine, C.L., Musielewicz, S., Chen, B., Wanninkhof, R. Continental Shelf Research 145(95–108), doi:10.1016/j.csr.2017.06.022, August 2017.

Sea surface aragonite saturation state variations and control mechanisms at the Gray's Reef time-series site off Georgia, USA (2006–2007). Xue, L., Cai, W.-J., Sutton, A.J., Sabine, C.L. Marine Chemistry 195(27–40), doi:10.1016/j.marchem.2017.05.009, June 2017.

Sea surface carbon dioxide at the Georgia time series site (2006-2007): Air-sea flux and controlling processes. Xue, L., Cai, W.J., Hu, X., Sabine, C., Jones, S., Sutton, A.J., Jiang, L.-Q., Reimer, J.J. Progress in Oceanography 140(14-26), doi:10.1016/j.pocean.2015.09.008, January 2016.

Long-term alkalinity decrease and acidification of estuaries in Northwestern Gulf of Mexico. Hu, X., Beseres Pollack, J., McCutcheon, M.R., Montagna, P.A., Ouyang, Z. Environmental Science & Technology 49:3401-3409, doi: 10.1021/es505945p, February 2015.

Tropical cyclones cause $CaCO_3$ undersaturation of coral reef seawater in a high-CO_2 world. Manzello, D., Enochs, I., Musielewicz, S., Carlton, R., Gledhill, D. Journal of Geophysical Research Oceans 118, doi:10.1002/jgrc.20378, October 2013.

Eutrophication induced CO_2-acidification of subsurface coastal waters: interactive effects of temperature, salinity, and atmospheric P_{CO2}. Sunda, W.G., Cai, W.-J. Environmental Science & Technology 46(19):10651–10659, doi:10.1021/es300626f, August 2012.

Acidification of subsurface coastal waters enhanced by eutrophication. Cai, W.-J., Hu, X., Huang, W., Murrell, M.C., Lehrter, J.C., Lohrenz, S.E., Chou, W.-C., Zhai, W., Hollibaugh, J. T., Wang, Y., Zhao, P., Guo, X., Gundersen, K., Dai, M., Gong, G.-C. Nature Geoscience 4:766-770, doi:10.1038/ngeo1297, April 2011.

Sensitivity
OAP has not been the primary funder of species sensitivity experiments, observations, or modeling in the region. NOAA researchers at the Atlantic Oceanographic and Meteorological Laboratory were involved in laboratory experiments on the response of cobia to OA using funding from sources other than the OAP (Task 5.2.1). Activities related to coral reef ecosystems in this region are conducted in partnership with NCRMP (see 'Corals' section above for more details).

Human dimensions
OAP investments inform the regularly produced NCRMP report cards tailored to coral reef jurisdictions (see 'Corals' section above for more details). The OAP has not supported projections of the social and economic impacts of OA, adaptation or mitigation work, or much education and outreach work in the region, leaving seven tasks in the NOAA OA Plan largely unmet by NOAA (Tasks 5.4.1-3 and 5.6.1-5; Figure 9). Researchers funded by other sources are addressing some of these tasks. The OAP's initial focus on cold-water regions of the continental U.S., a legacy of how NMFS focused its initial OA work, led to this gap in the OAP portfolio. The OAP is seeking to rectify this gap within its limited budget. To help develop OA work in this region, the OAP fostered the launch of the Southeast Ocean and Coastal Acidification Network in 2014 and the Gulf Coast Coastal Acidification Network in 2016. The Southeast Ocean and Coastal Acidification Network aims to enhance collaborations on and communications about ocean and coastal acidification regional drivers, approaches to monitoring, state-of-the-art science, and vulnerable species and ecosystems. The Gulf Coast Coastal Acidification Network aims to identify the needs of the stakeholder community of the Gulf Coast region.

Research gaps identified in the stakeholder panel
Stakeholder needs suggest research gaps relate to: species sensitivity to multiple stressors (i.e., simultaneous consideration of OA with temperature change, disease, and increased freshwater input); the connection between blue carbon and OA, especially in the region's marshes and mangroves; the drivers and impacts of coastal acidification; and further development of the OA monitoring network. Recreational, subsistence, and commercial fishing are vital parts of the region's culture and economy, but OA stakeholders are not as well cultivated or organized in the Southeast and Gulf of Mexico. The importance of presenting research findings in a way that is relevant to policy makers, industry, and managers is paramount. Doing so can help interested groups understand the state of OA impacts and how other stressors can be managed to lessen the impacts of OA on ecosystems and human communities.

NORTHEAST AND MID-ATLANTIC

This section covers both the Northeast and the Mid-Atlantic, as the regions were addressed together in the NOAA OA Plan. Over the past five years, OAP research has quickly developed in the Northeast. The recognition of processes that drive coastal acidification was a large factor in this strong development, as was the cultivation of engaged stakeholders in the region.

TASKS OUTLINED IN NOAA OA PLAN FOR THE NORTHEAST AND MID-ATLANTIC

Developing an Ocean Acidification Monitoring Network	• Task 6.1: Develop and conduct a monitoring program to assess the current state of ocean acidification and track its development in the northeast U.S. shelf ecosystem.
Organism response to Ocean Acidification	• Task 6.2.1: Conduct laboratory and targeted field studies to quantify the impact of ocean acidification on primary producers. • Task 6.2.2: Create a state-of-the-art capability in the Northeast for conducting acidification experiments on individual species and species assemblages of shellfish and finfish and estimate the impact of ocean acidification on Northeast ecosystem resource species.
Biogeochemical and Ecosystem Models	• Task 6.3: Develop and implement models to assess the effects of ocean acidification on singlespecies dynamics, multi-species interactions, and overall ecosystem productivity.
Human Dimensions	• Task 6.4: Estimate anticipated changes to northeast ecosystem services as a consequence of OA and develop a decision framework for adaptation strategies.
Synthesis of Data and Information Products	• Task 6.5.1: Provide a first integrated assessment of the effects of OA on the northeast U.S. continental shelf ecosystem.
Engagement Strategy	• Task 6.6: Identify target audiences and determine appropriate programs and products utilizing innovative approaches for community involvement.

Figure 11. Summary of tasks outlined in NOAA OA Plan for the Northeast and Mid-Atlantic.

Environment

The northeast has one OA mooring, located off New Hampshire in the Gulf of Maine, to characterize its complex chemistry. A new OA mooring is targeted for deployment in the Chesapeake Bay in 2017. In 2007 and 2012, synoptic cruises characterized the carbon chemistry of the US East Coast and Gulf of Mexico; in 2015, the first synoptic cruise dedicated to the U.S. East Coast occurred. This 2015 cruise included measurement of oxygen consumption and net community production to better understand what drives regional and seasonal dynamics in aragonite saturation state. The carbon chemistry of the region’s coastal waters is highly influenced by biological activity. Regular fisheries stock assessment cruises from Nova Scotia, Canada to Cape Hatteras, which are run by the Northeast Fisheries Science Center (NEFSC), occur four to six times a year and collect samples for carbon chemistry. These cruises provide spatially and temporally explicit datasets paired with biological measurements. Ships of opportunity also monitor carbon chemistry in the region. pCO_2 sensors are being used in the region to monitor carbon chemistry conditions in shellfish hatcheries from Maine to the Chesapeake Bay. Autonomous alkalinity sensors are being field tested on ships of opportunity to obtain the elusive "second" parameter to constrain OA dynamics. This suite of monitoring activities addresses the monitoring task in the NOAA OA Plan (Task 6.1, Figure 11). Recently, modeling exercises in the Gulf of Maine and elsewhere in the region have emphasized the importance of freshwater input and regional circulation in controlling aragonite saturation state. A biogeochemical and hydrographic model is being developed to study OA and eutrophication in the Chesapeake Bay and how they may affect restoration of the Bay's oyster reefs.

Relevant publications included:

Redox reactions and weak buffering capacity lead to acidification in the Chesapeake Bay. Cai, W.J., Huang, W.J., Luther III, G.W., Pierrot, D., Li, M., Test, J., MingXue, A.J., Mann, R., Brodeur, J., Xu, Y.Y., Chen, B., Hussain, N., Waldbusser, G.G., Cornwell, J., Kemp, W.M. Nature Communications 8(369), doi:10.1038/s41467-017-00417-7, August 2017.

Hypoxia and acidification in ocean ecosystems: Coupled dynamics and effects on ocean life. Gobler, C., Baumann, H. Biology Letters 12(5), doi:10.1098/rsbl.2015.0976, May 2016.

Ocean and coastal acidification off New England and Nova Scotia. Gledhill, D.K., White, M.M., Salisbury, J., Thomas, H., Mlsna, I., Liebman, M., Mook, B., Grear, J., Candelmo, A.C., Chambers, R.C., Gobler, C.J., Hunt, C.W., King, A.L., Price, N.N., Signorini, S.R., Stancioff, E., Stymiest, C., Wahle, R.A., Waller, J.D., Rebuck, N.D., Wang, Z.A., Capson, T.L., Morrison, J.R., Cooley, S.R., Doney, S.C. Oceanography 28(2):182–197, doi:10.5670/oceanog.2015.41, June 2015.

Ocean acidification along the Gulf Coast and East Coast of the USA. Wanninkhof, R., Barbero, L., Byrne, R., Cai, W.-J., Huang, W.-J., Zhang, J.-Z., Baringer, M., Langdon, C. Continental Shelf Research 98: 54-71, doi:10.1016/j.csr.2015.02.008, April 2015.

Experience with moored observations in the western Gulf of Maine from 2006 to 2012. Irish, J.D., Vandemark, D., Shellito, S. and Salisbury, J. Marine Technology Society Journal 47:19-32, doi:10.4031/MTSJ.47.1.7, February 2013.

Contribution of non-carbonate anions to total alkalinity and overestimation of pCO_2 in New England and New Brunswick rivers. Hunt, C.W., Salisbury, J.E., Vandemark, D. Biogeosciences 8: 3069-3076, doi:10.5194/bg-8-3069-2011, October 2011.

Temporal and spatial dynamics of CO_2 air-sea flux in the Gulf of Maine. Vandemark, D., Salisbury, J., Hunt, C., McGillis, W., Sabine, C., Maenner, S.M. Journal of Geophysical Research 116:C01, doi:10.1029/2010JC006408, January 2011.

Sensitivity

An experimental system was built at the NEFSC's Milford Laboratory in Connecticut to understand the sensitivity of a variety of species to changes in ocean carbon chemistry. Milford scientists found the following responses to elevated CO_2 conditions: little change in the growth rate of several phytoplankton species (*Thalassiosira pseudonana*, *T. rotula*, two strains of *T. weissflogii, T. oceanica, Chlorella autotrophica, Dunaliella salina*); no effect on growth, otolith condition, survival, or the skeleton of juvenile Scup (Mid-Atlantic fish); and a decrease in filtration and particle clearance in eastern oysters. Scientists at the NEFSC Howard Laboratory in

Sandy Hook, New Jersey have found that high CO_2 treatments cause detrimental changes in survival, growth, and development of early life stages of summer flounder and decreased larval survival and prey consumption in winter flounder. Other OAP-funded work in the region has found that: surf clam larvae are smaller and grow slowly in high CO_2 treatments, sea scallops have thinner shells and more deformities when high CO_2 treatments are combined with low food availability, and diurnal fluctuations in carbon chemistry conditions do not provide relief from OA impacts to bay scallops, hard clams, or eastern oysters. Research, co-funded by Sea Grant, is currently underway on ecologically and economically important species including lobster, sandlance, blue mussel, hard clam, and eastern oyster.

A variety of modeling projects are increasing the understanding of the impacts of OA on northeast ecosystems. OA simulations were run in an Atlantis model of the northeast ecosystem food web to project potential impacts on the food web and fisheries. An integrated assessment model was developed to explore the influence of OA on scallop fisheries, and an individually based model is being built and parameterized to explore the influence of OA on winter flounder. The latter two projects include web-based dashboards for the public to access their findings. Together these biology-focused experiments and modeling projects meet all of the tasks outlined in the NOAA OA Plan, except for the integrated ecosystem assessment of the effects of OA on the northeast U.S. continental shelf ecosystem (Task 6.5.1, Figure 11).

Relevant publications:

Assessing the effects of ocean acidification in the Northeast US using an end-to-end marine ecosystem model. Fay, G., Link, J.S., Hare, J. A. Ecological Modelling 347:1–10, doi:10.1016/j.ecolmodel.2016.12.016, March 2017.

Do diurnal fluctuations in CO2 and dissolved oxygen concentrations provide a refuge from hypoxia and acidification for early life stage bivalves? Clark, H., Gobler, C. Marine Ecology Progress Series 558:1–14, doi:10.3354/meps11852, October 2016.

Ocean acidification accelerates the growth of two bloom-forming macroalgae. Young, C.S., Gobler, C.J. PLoS One 11(5):e0155152, doi:10.1371/journal.pone.0155152, May 2016.

A vulnerability assessment of fish and invertebrates to climate change on the Northeast U.S. continental shelf. Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M.M., Teeters, J., Griffis, R.B., Alexander, M.A., Scott, J.D., Alade, L., Bell, R.J., Chute, A.S., Curti, K.L., Curtis, T.H., Kircheis, D., Kocik, J.F., Lucey, S.M., McCandless, C.T., Milke, L.M., Richardson, D.E., Robillard, E., Walsh, H.J., McManus, M.C., Marancik, K.E., Griswold, C.A. PLoS ONE 11(2):e0146756, doi:10.1371/journal.pone.0146756, February 2016.

Effects of CO_2 on growth rate, C:N:P, and fatty acid composition of seven marine phytoplankton species. King, A., Jenkins, B., Wallace, J., Liu, Y., Wikfors, G.H., Milke, L., Meseck, S. Marine Ecology Progress Series 537:59-69, doi:10.3354/meps11458, October 2015.

Effect of ocean acidification on growth and otolith condition of juvenile scup, *Stenotomus chrysops*. Perry, D.M., Redman, D.H., Widman Jr., J.C., Meseck, S., King, A., Pereira, J.J. Ecology and Evolution 5(18):4187-4196, doi:10.1002/ece3.1678, September 2015.

Ocean and coastal acidification off New England and Nova Scotia. Gledhill, D.K., White, M.M., Salisbury, J., Thomas, H., Mlsna, I., Liebman, M., Mook, B., Grear, J., Candelmo, A.C., Chambers, R.C., Gobler, C.J., Hunt, C.W., King, A.L., Price, N.N., Signorini, S.R., Stancioff, E., Stymiest, C., Wahle, R.A., Waller, J.D., Rebuck, N.D., Wang, Z.A., Capson, T.L., Morrison, J.R., Cooley, S.R. Doney, S.C. Oceanography 28(2):182–197, doi:10.5670/oceanog.2015.41, June 2015.

Effects of elevated CO_2 in the early life stages of summer flounder, *Paralichthys dentatus*, and potential consequences of ocean acidification. Chambers, C., Candelmo, A.C., Habeck, E.A., Poach, M.E., Wieczorek, D., Cooper, K.R., Greenfield, C.E., Phelan, B.A. Biogeosciences 11:1613-1626, doi:10.5194/bg-11-1613-2014, March 2014.

Hypoxia and acidification have additive and synergistic negative effects on the growth, survival and metamorphosis of early life stage bivalves. Gobler, C.J., De Pasquale, E.L., Griffith, A.W., Baumann, H. Plos ONE 9(1): e83648, doi:10.1371/journal.pone.0083648, January 2014.

Short- and long-term consequences of larval stage exposure to constantly and ephemerally elevated carbon dioxide for marine bivalve populations. Gobler, C.J., Talmage, S.C. Biogeosciences 10:2241-2253, doi:10.5194/bg-10-2241-2013, April 2013.

Human dimensions

The OAP has not funded socioeconomic work besides the modeling projects and hatchery monitoring work described above. The Northeast Coastal Acidification Network (NECAN), launched in 2013, is active in coordinating and guiding regional observing, research, and modeling endeavors focused on ocean and coastal acidification, and in soliciting stakeholder input on OA activities. The Mid-Atlantic Coastal Acidification Network (MACAN), launched in fall 2016, works to develop a better understanding of the causes of estuarine, coastal, and ocean acidification and to predict the impacts on marine resources. MACAN is also devising ways that local communities and industries can prevent and/or decrease the negative impacts caused by OA. There were no tasks focused on human dimension in the NOAA OA Plan (Figure 11).

Research gaps identified in the stakeholder panel

Stakeholders in the northeast are interested in how other water quality issues and stressors will interact with OA and affect marine species and ecosystems. Science efforts needed to address this information gap include: more chemistry monitoring in nearshore and estuarine systems; compact, reliable instruments that will provide high-quality chemical-observing data to citizen scientists and other stakeholders; short time-scale (e.g., day, season, and decade) models of carbon chemistry conditions; species response studies that address more life stages and multiple stressors and capture the processes of acclimation and adaptation; and economic modeling to project the monetary losses from OA-impacts on economically important species. Regional scientists are looking to better partner with other Federal and state agencies in the U.S. and Canada and with the shellfish industry and to engage in more robust two-way exchanges with stakeholders.

Relevant publications:
An integrated assessment model for helping the United States sea scallop (*Placopecten magellanicus*) fishery plan ahead for ocean acidification and warming. Cooley, S.R., Rheuban, J.E., Hart, D.R., Luu, V., Glover, D.M., Hare, J.A., Doney, S.C. PLoS ONE 10:e0124145, doi:10.1371/journal.pone.0124145, May 2015.

INTERNATIONAL

The OAP engages in a number of international efforts that advance OA research and monitoring and foster collaboration among nations. These efforts benefit U.S. activities on OA and help the U.S. maintain a leadership role in ocean research. As the only truly long-term ocean acidification program, NOAA OAP is regarded as an important partner and leader for much OA monitoring and research around the world.

Environment
NOAA, U.S. scientists, and the NOA-ON have played a key leadership role in the formation of GOA-ON. This global network uses a collaborative approach to document the chemical changes and biological impacts of ocean acidification in open-ocean, coastal, and estuarine environments and to provide the spatially and temporally resolved biogeochemical data necessary to optimize modeling for OA. The network recently released an interactive map which displays real-time data from participating platforms, provides an overlay of aragonite saturation state and surface CO_2 concentrations globally, and allows users to find platforms based on region, type, and variables. This map greatly increases the accessibility of OA data globally.

Relevant publications:
Mixed-layer carbon cycling at the Kuroshio Extension Observatory. Fassbender, A.J., Sabine, C.L., Cronin, M.F., Sutton, A.J. Global Biogeochemical Cycles 31:272-288, doi:10.1002/2016gb005547, February 2017.

Net community production and calcification from 7 years of NOAA Station Papa Mooring measurements. Fassbender, A.J., Sabine, C.L., Cronin, M.F. Global Biogeochemical Cycles 30:250–267, doi:10.1002/2015GB005205, February 2016

Climatological distribution of aragonite saturation state in the global oceans. Jiang, L.Q., Feely, R.A., Carter, B.R., Greeley, D.J., Gledhill, D.K., Arzayus, K.M. Global Biogeochemical Cycles 29, doi:10.1002/2015GB005198. October 2015.

Ocean acidification in the surface waters of the Pacific-Arctic boundary regions. Mathis, J.T., Cross, J.N., Evans, W., Doney, S.C. Oceanography 28(2):122–135, doi:10.5670/oceanog.2015.36, June 2015.

Seasonal variations in the aragonite saturation state in the upper open-ocean waters of the North Pacific Ocean. Kim, T., Park, G, Kim, D., Lee, K., Feely, R.A., Millero, F.J. Geophysical Research Letters 42(11):4498-4506, doi:10.1002/2015GL063602, June 2015.

Including high frequency variability in coastal ocean acidification projections. Takeshita, Y., Frieder, C.A., Martz, T.R., Ballard, J.R., Feely, R.A., Kram, S., Nam, S., Navarro, M.O., Price, N.N., Smith, J.E. Biogeosciences Discussions 12:7125-7176, doi:10.5194/bgd-12-7125-2015, May 2015.

Spectrophotometric measurement of calcium carbonate saturation states in seawater. Easley, R.A., Patsavas, M.C., Byrne, R.H, Liu, X., Feely, R.A., Mathis, J.T. Environmental Science & Technology 47:1468–1477, doi**:** 10.1021/es303631g, December 2013.

The changing carbon cycle of the coastal ocean. Bauer, J.E., Cai, W.-J., Raymond, P.A., Bianchi, T.S., Hopkinson, C.S., Regnier, P. Nature 504:61–70, doi:10.1038/nature12857, December 2013.

Building an integrated ocean observing network for the US. Mathis, J.T., Feely, R.A. Elementa, Science of the Anthropocene 1(7), doi: 10.12952/journal.elementa.000007, December 2013.

Surface ocean pCO_2 seasonality and sea-air CO_2 flux estimates for the North American east coast. Signorini, S., Mannino, A., Najjar, R., Friedrichs, M.A.M., Cai, W.-J., Salisbury, J., Wang, Z., Thomas, H., Shadwick, E. Journal of Geophysical Research Oceans 118(10):5439–5460, doi:10.1002/jgrc.20369, August 2013.

The marine inorganic carbon system along the Gulf of Mexico and Atlantic coasts of the United States: Insights from a transregional coastal carbon study. Wang, Z., Wanninkhof, R., Cai, W.J., Byrne, R.H., Hu, X., Peng, T.S., Huang, W.J. Limnology and Oceanography 58:325-342, doi:10.4319/lo.2013.58.1.0325, March 2013.

Assessment of sample storage techniques for total alkalinity and dissolved inorganic carbon in seawater. Huang, W.-J., Wang, Y., Cai W.-J. Limnology and Oceanography-Methods 10:711-717, doi:10.4319/lom.2012.10.711, January 2012.

Sensitivity

Due to the diversity of marine life and ecosystems globally and varied OA drivers, regional networks have developed through the GOA-ON community to better answer questions about the sensitivity of particular species and ecosystems that are integral to various cultures and economies. To date, networks have formed in both South America and Africa. Both of these regions' coasts meet Eastern boundary currents where cold, CO_2 rich water is upwelled onto the coast and drive shifts in carbonate chemistry. These upwelling areas can serve as natural laboratories to understand species and ecosystem response to environmental change. Efforts are underway to launch a North American regional network.

Relevant publications:

CO_2 sensitivity experiments are not sufficient to show an effect of ocean acidification. McElhany, P. ICES Journal of Marine Science 74(4): 926–928, doi:10.1093/icesjms/fsw085, May 2017.

Appropriate pCO$_2$ treatments in ocean acidification experiments. McElhany, P., Busch, D.S. Marine Biology 160:1807-1812, doi:10.1007/s00227-012-2052-0, August 2013.

Extensive dissolution of live pteropods in the Southern Ocean. Bednarsek, N., Tarling, G.A., Bakker, D.C.E., Fielding, S., Jones, E.M., Venable, H.J., Ward, P., Kuzirian, A., Leze, B., Feely, R.A., Murphy, E.J. Nature Geoscience Letters, doi:10.1038/NGEO1635, November 2012.

Human dimensions
GOA-ON is working to understand the drivers and impacts of OA on marine ecosystems by building capacity in vulnerable regions around the globe. With 354 scientists from over 65 countries, the network is continuing to grow. Ocean acidification experts, including those from NOAA, are building global capacity to address OA by training members in OA monitoring methodologies and best practices and by helping to develop new, lower-cost observing technologies. To ensure that knowledge related to OA continues to grow, the NOAA OAP spearheaded the creation of a mentoring network (Pier2Peer). This program matches senior scientists with new GOA-ON members to support the development of OA monitoring and research in emerging regions. Many NOAA and US scientists are serving as mentors.

4. The OAP Looks Forward

The January 2017 OAP Principal Investigator meeting provided an opportunity to reflect on the OAP's efforts to date and gather input on potential directions, priorities, and considerations for the next three-year funding cycle. A few themes emerged from these conversations.

Fostering collaboration
The community encouraged the OAP to continue its efforts to foster science collaboration among regions, scientific disciplines, parts of NOAA, and academic and non-governmental institutions. There is interest in having national OAP meetings every two to three years, and also for the OAP to organize smaller, discipline-focused meetings (i.e., cruise leads and modelers) in interim years. Principal Investigators would also like to see collaboration fostered through more opportunities for regional or discipline-based phone or web-conference meetings. Participants were enthusiastic about the web-based center for collaboration on OA that the Interagency Working Group on OA hopes to develop, especially if it includes a database of OA researchers, provides the opportunity for two-way exchanges with stakeholders, and could host stories about the vulnerability of ecosystems and communities to OA.

Investing in synthesis efforts
Significant headway can be made on understanding OA and its impacts and on developing information suitable for stakeholders through synthesis efforts. Principal Investigators would like more funding opportunities targeted to developing and conducting synthesis projects, similar to some of the funding opportunities which the OAP recently initiated. Areas of interest for such projects are improving the understanding of the differences in the drivers of OA among regions, linking interdisciplinary work through synthesis analysis, and developing accurate information for policy makers.

Characterizing the environment
There is interest in growing the network of OA monitoring assets, potentially including “sentinel sites” that focus not only on observations of OA and its impacts, but on education and outreach. That said, there is recognition that observation optimization studies are needed to design effective expansion strategies, and that maintaining and properly managing existing assets remains a challenge from the point of view of sustaining infrastructure and data transfer and management.

Expansion of monitoring efforts is needed to better integrate chemical and biological observations. The best practices for characterizing ocean carbon chemistry are well-defined, but those for documenting the biological impacts of OA are not. Efforts to develop best practices for the biological component of OA monitoring in various habitat types are underway by the GOA-ON. Opportunities to develop monitoring sites that coincide with restoration projects should be explored as such efforts could generate unique data that is highly relevant to adaptation and mitigation efforts.

There is also interest in having modelers and empiricists/observationalists work together on model validation, potentially through intensive field campaigns. Structured model intercomparisons in which model with analogous outputs for the same region are compared in a rigorous way should also be used to assess the robustness of regional and global models.

Understanding sensitivity
Work on the sensitivity of species and ecosystems to OA would benefit from better coordination and sharing of lessons learned across regions and ecosystems. The research community has embraced the concept of studying OA in the context of other stressors, and now is focused on the processes of adaptation and acclimation. Characterizing the mechanisms that drive species response to OA can be used to understand both, and fieldwork is needed to define how laboratory results differ from processes occurring in the natural environment and to document potential effects of OA on wild populations.

Studying the social and economic implications of and adaptation to OA
A major gap in the national OA portfolio is socioeconomic work. Such work is vital for understanding and communicating the implications of OA on human communities and for developing robust ways to adapt to ocean change that cannot be prevented. A variety of disciplines could be engaged to do this work, including economics, anthropology, geography, public health, policy, and law.

Stakeholders are looking for multiple types of models to address various questions: there is interest in the generation of both operational and strategic output from models and in developing intermediate range (e.g., 10 year) projections and forecasts. Modelers recognize that they need to work across disciplines to address the multidisciplinary field of OA, and consider modeling consortia/working groups as a sound way to do so. Such group efforts could aid in addressing uncertainty, both between empiricists and modelers and among disciplines, and in developing event timelines for potential ecological effects of OA.

Appendix 1. National and regional tasks in the NOAA OA Plan color coded by whether each task has been addressed (green), partially addressed (yellow), or not addressed (blue) by NOAA OAP. Some of the tasks not addressed by NOAA OAP-funded work are being addressed by work funded by other entities.

National	Alaska	West Coast	Pacific Islands	SE and Gulf of Mexico	Northeast and Mid-Atlantic	Great Lakes
Task 1.1: Develop and implement program for monitoring carbon-cycle-related oceanographic parameters in U.S. coastal, Great Lakes, and open-ocean waters.	Task 2.1: Develop and implement program for monitoring carbon-cycle-related oceanographic parameters off Alaska.	Task 3.1.1: Develop and implement a program for monitoring carbon-cycle-related oceanographic parameters on the West Coast.	Task 4.1.1: Implement a comprehensive program for monitoring carbon-cycle-related oceanographic parameters in the Pacific Islands.	Task 5.1.1: Establish requisite analytical capability for conducting high-quality carbonate chemistry measurements and training at AOML.	Task 6.1: Develop and conduct a monitoring program to assess the current state of ocean acidification and track its development in the northeast U.S. shelf ecosystem.	Task 7.1.1: Develop and implement a monitoring network to measure lake carbon chemistry parameters related to acidification, with coverage across all five lakes and all seasons.
Task 1.2: Conduct ocean acidification experiments on individual species and species assemblages. Create state-of-the-art NOAA facilities for these experiments which will also be available for non-NOAA researchers.	Task 2.2.1 Create state-of the-art facilities for conducting ocean acidification experiments on individual species and species assemblages	Task 3.1.2: Establish a Pacific Center of Expertise for ocean carbon chemistry at PMEL.	Task 4.1.2: Implement a comprehensive program for monitoring coral reef systems likely to be impacted by ocean acidification in the Pacific Islands.	Task 5.1.2: Establish SER/GOM ocean acidification coastal/oceanic mooring network.	Task 6.2.1: Conduct laboratory and targeted field studies to quantify the impact of ocean acidification on primary producers.	Task 7.1.2: Develop and implement a Great Lakes strategy to monitor biological response to lake acidification.
Task 1.3.1: Develop regional biogeochemical models coupled to global carbon cycle models to predict local changes in carbon chemistry at multiple temporal scales	Task 2.2.2: Conduct acidification response experiments on species and species assemblages of interest in Alaska ecosystems.	Task 3.1.3: Develop and implement a program for biological monitoring to detect ecosystem changes caused by acidification and changes in biology that affect the carbon cycle on the West Coast.	Task 4.1.3: Monitor cryptic species and biodiversity for the effects of ocean acidification in the Pacific Islands.	Task 5.1.3: Conduct SER/GOM ocean acidification hydrographic/geochemical ship surveys	Task 6.2.2: Create a state-of-the-art capability in the Northeast for conducting acidification experiments on individual species and species assemblages of shellfish and finfish and estimate the impact of ocean acidification on Northeast ecosystem resource species.	Task 7.2.1: Build NOAA capacity to study organismal response to lake acidification in manipulation experiments where effects of environmental factors on species can be studied individually and in combination
Task 1.3.2: Develop regional ecological and bioeconomic models coupled to regional biogeochemical models to predict local changes in ecosystem, food web, and economic interactions	Task 2.3.1: Develop models to predict how Alaska ecosystems will change in response to ocean acidification and alternative ocean management actions	Task 3.1.4: Establish an immediate monitoring program focused on bivalve recruitment patterns.	Task 4.1.4: Monitor microbial communities for effects of ocean acidification in the Pacific Islands.	Task 5.1.4: Regional carbonate chemistry synoptic mapping.	Task 6.3: Develop and implement models to assess the effects of ocean acidification on singlespecies dynamics, multi-species interactions, and overall ecosystem productivity.	Task 7.3.1: Develop and test coupled physical/biogeochemical and food web models and scenarios to address lake acidification effects on each of the Great Lake ecosystems.
Task 1.4.1: Estimate anticipated changes to ecosystem services as a consequence of ocean acidification and evaluate alternative management options	Task 2.3.2: Develop regional biogeochemical models coupled to global carbon cycle models to predict local changes in carbon chemistry at multiple temporal scales	Task 3.1.5: Establish Intensively Studied Marine Areas for monitoring ocean acidification.	Task 4.2.1: Conduct laboratory experiment to estimate the effect of ocean acidification on important species in the Pacific Islands.	Task 5.1.5: Establish the SER/GOM portion of a coral reef ocean acidification monitoring program.	Task 6.4: Estimate anticipated changes to northeast ecosystem services as a consequence of OA and develop a decision framework for adaptation strategies.	Task 7.4.1: Estimate anticipated changes to ecosystem services as a consequence of lake acidification and evaluate alternative management options.

National	Alaska	West Coast	Pacific Islands	SE and Gulf of Mexico	Northeast and Mid-Atlantic	Great Lakes
Task 1.4.2: Test mitigation approaches under laboratory and field conditions. Develop adaptation strategies.	Task 2.4: Estimate economic consequences for Alaska king crab fisheries due to ocean acidification	Task 3.2.1: Create a state-of-the-art NOAA facility on the West Coast for conducting ocean acidification experiments on individual species and species assemblages.	Task 4.2.2: Conduct in situ experiments manipulating CO2 to estimate the effect of ocean acidification in the natural environment.	Task 5.1.6: Establish a seagrass OA monitoring program	Task 6.5.1: Provide a first integrated assessment of the effects of OA on the northeast U.S. continental shelf ecosystem.	Task 7.4.2: Test mitigation approaches under laboratory and field conditions. Develop adaptation strategies.
Task 1.5.1: Develop data and information tools for evaluating the consequences of ocean acidification to create more effective management strategies.	Task 2.5: Synthesize, archive, and report results of ocean acidification research in products usable for fisheries management.	Task 3.2.2: Support development of collaborative facilities for acidification response experiments	Task 4.2.3: Estimate historical changes to corals as a response to fluctuating CO2.	Task 5.1.7: Establish an estuarine OA monitoring program.	Task 6.6: Identify target audiences and determine appropriate programs and products utilizing innovative approaches for community involvement.	Task 7.5.1: Develop data and information tools for evaluating the consequences of lake acidifi- cation and potential management actions to facilitate more effective management.
Task 1.6: Implement an education and outreach program to communicate the science and ecosystem consequences of ocean acidification to the public and stakeholder communities.	Task 2.6: Implement an education and outreach program to communicate the science, economic, and ecosystem consequences of ocean acidification to the public and stakeholder communities	Task 3.2.3: Conduct acidification response experiments on species and species assemblages of interest in West Coast ecosystems	Task 4.2.4: Conduct experiments on how beach forming processes will be affected by ocean acidification	Task 5.2.1: Conduct species-specific OA exposure experiments.		Task 7.6.1: Develop and implement coordination, education, and outreach schemes to communicate the science and ecosystem consequences of ocean acidification to the public and stakeholder communities and to facilitate effective communication among regional collaborators.
		Task 3.2.4: Assess the calcium carbonate mineralogy of species important to West Coast ecosystems.	Task 4.2.5: Behavior response experiments of cetaceans to increased ocean sound propagation with ocean acidification	Task 5.2.2: Conduct lab and/or field experiments to determine OA impacts on key species interactions (e.g., competition, predation, facilitation).		
		Task 3.2.5: Correlate hindcasts of West Coast saturation states with historical biological timeseries of species abundance to estimate how species and communities responded to past changes in saturation state.	Task 4.3.1: Develop finescale, wave-driven hydrodynamic circulation models for coral reef habitats throughout the Pacific Islands region.	Task 5.2.3: Conduct coral sclerochronology for retrospective OA assessment to detect the coral calcification historical response.		
		Task 3.2.6: Explore technologies for in situ open ocean and semi-permeable mesocosm experiments to test predictions from ecosystem models and species not amenable to laboratory culture.	Task 4.3.2: Develop biogeochemical models to predict Pacific Islands ecosystem responses to ocean acidification.	Task 5.3.1: Develop regional biogeochemical forecast models coupled to global carbon cycle models to predict local changes in carbon chemistry at multiple temporal scales.		

National	Alaska	West Coast	Pacific Islands	SE and Gulf of Mexico	Northeast and Mid-Atlantic	Great Lakes
		Task 3.2.7: Conduct laboratory and field experiments on potential local mitigation methods	Task 4.3.3: Refine existing trophic interaction ecosystem model (Ecopath with Ecosim) to predict ecosystem impacts of ocean acidification in the Pacific Islands.	Task 5.3.2: Develop regional biogeochemical hindcast models to evaluate historical changes in carbonate chemistry within the SER/GOM.		
		Task 3.3.1: Develop regional biogeochemical models coupled to global carbon cycle models to predict local changes in carbon chemistry at multiple temporal scales.	Task 4.3.4: Develop coupled sand transport and biogeochemistry models to predict the impacts of ocean acidification on critical nesting beach habitats.	Task 5.3.3: Develop regional ecoforecast models		
		Task 3.3.2: Design and implement experiments and observation projects to estimate critical parameters for regional carbon models	Task 4.3.5: Develop sound propagation models to predict the impacts of ocean acidification on protected cetacean species across the Pacific Islands region.	Task 5.4.1: Forecast impacts to ecosystem services within the SER/GOM.		
		Task 3.3.3: Develop and apply algorithms to reconstruct historical carbon chemistry conditions over local to regional scales.	Task 4.4: Estimate the impact of ocean acidification on socioeconomic activities.	Task 5.4.2: Conduct necessary social impact and vulnerability assessments to ascertain probable social impacts of OA and identify possible mitigation strategies within the SER/GOM.		
		Task 3.3.4: Develop models to predict how West Coast ecosystems will change in response to ocean acidification and alternative ocean management actions.	Task 4.5: Develop data and information tools for evaluating the consequences of ocean acidification in the PIR to create more effective management strategies.	Task 5.4.3: Develop mitigation and community adaptation strategies.		
		Task 3.4.1: Estimate anticipated changes to West Coast ecosystem services as a consequence of ocean acidification.	Task 4.6: Implement an education and outreach program in the PIR to increase public understanding of ocean acidification.	Task 5.6.1: Create and distribute media that clearly and concisely describe the chemistry of OA as well as the known and hypothesized impacts.		
		Task 3.4.2: Develop technical tools for evaluating the consequences of potential management actions related to ocean acidification on the West Coast to create more effective management strategies.		Task 5.6.2: Create an interactive website focused on OA in the SER/GOM.		

National	Alaska	West Coast	Pacific Islands	SE and Gulf of Mexico	Northeast and Mid-Atlantic	Great Lakes
		Task 3.5.1: Develop and participate in effective management and dissemination of regionally produced data and data products related to ocean acidification.		Task 5.6.3: Develop regular summary literature that provides a State of the Science of OA and Known Impacts in the SER/GOM.		
		Task 3.6.1: Implement an education and outreach program to communicate the science and ecosystem consequences of ocean acidification to the West Coast public and stakeholder communities.		Task 5.6.4: Install interactive displays at aquaria in the southeastern United States.		
				Task 5.6.5: Create education modules and curricula that can be used by teachers to help describe OA and its impacts to students.		

Appendix 2. Agenda for the January 2017 NOAA OA Program Principal Investigators' meeting.

NOAA OA PI Meeting Agenda
Pacific Marine Environmental Laboratory, Seattle, WA
January 4-6, 2017

DAY 1	**"Where we have been" (open to all)**
0745	**Registration**
0815 - 0830	**Workshop Welcome and Logistics** **Objective**: Workshop Welcome and Introduction by Chris Sabine and Libby Jewett
0830-0915	**OA – The NOAA Program and Global Perspective** a. Introduction to OAP (**Dwight Gledhill**) b. OA in a Global Context (**Libby Jewett)**
0915-1015	**OAP Funded Science Presentations: Nat'l Coral Reef Monitoring Program (NCRMP)** **Objective:** Update participants on coral-focused scientific activities of various NOAA labs, programs and partners.
1015-1045	**Break - Coffee and snacks available**
1045 1215	**OAP Funded Science PANEL Presentations: West Coast** **Objective**: Update participants on scientific activities of various NOAA labs, programs and partners
1215-1315	**Lunch**
1315-1400	**OAP Funded Science PANEL Presentations: Gulf of Mexico** **Objective**: Update participants on scientific activities of various NOAA labs, programs and partners
1400-1515	**OAP Funded Science PANEL Presentations: East Coast** **Objective:** Update participants on scientific activities of various NOAA labs, programs and partners
1515-1545	**Break - Coffee and snacks available**
1545-1630	**OAP Funded Science PANEL Presentations: US Arctic and Alaska** **Objective:** Update participants on scientific activities of various NOAA labs, programs and partners
1630-1700	**Reflections on a day of OAP funded science - Libby Jewett**

1700-1900	**Poster Session**
1900	**Adjourn** **Homework:** Think about what you've seen today and tomorrow we will identify gaps and make plans to address those gaps

DAY 2	"Ways forward for NOAA OAP" (open to all registered participants)
800	**Arrival and get through Security**
0815-0830	**Introductions:** Go around the room and introduce each participant (name and affiliation)
0830 - 0945	**Ways forward** **Activities/Interactions:** 1. State of OAP during the FY15-17 **(Libby Jewett)** 2. **Panel Discussion** with stakeholders 3. **Charge to Breakouts**
0945-1000	**Break--Coffee and snacks**
1000-1200	**Regional Breakout Discussions** **Objective**: Small group discussions—organized by region--to identify and opportunities for NOAA, broadly, and the OAP, specifically.
1200 - 1300	**Lunch**
1300-1345	**Breakout Group Report out**
1345-1500	**Ways Forward for NOAA: Partnerships** **Objective**: Participants learn about ways OAP can foster and utilize partnerships to advance the field and help fill the gaps identified in the previous breakouts. **Activities/Interactions:** 1. **Presentation** to outline current partnerships and ***(Shallin Busch)*** 2. **Panel discussion** about how and why existing partnerships have been successful 3. **Charge to Breakouts**
1500-1545	**Breakout Discussions: Partnerships** **Objective**: Small group discussions on partnerships inside and outside of NOAA. This breakout will be useful to share approaches and partnerships that have worked in one region with

	participants from other regions. ***Total time: 45 min***
1545-1600	**Break - Coffee and snacks**
1600-1620	**Breakout Group report out**
1620-1700	**Reflections on the Meeting (Libby Jewett)**
1800-2000	**Meeting Dinner**

DAY 3	"**Ways forward for NOAA OAP – Internal planning" (OAP PIs only)**
0830-0900	**Coffee and snacks**
0900 - 1030	**OAP FY18-20 Planning Session** **Objective**: Provide programmatic context for work going forward **Activities/Interactions:** **1. Recap** Days 1 and 2 **(Jenn Mintz /Dwight Gledhill)** **2. How outreach can work for you** (**Jenn Mintz)** **3. Discuss** near- and long-term priorities for OAP **(Libby Jewett)** *4.* **FY 18-20 workplan** process and timeline **(Erica Ombres)**
1030-1100	**Break - Coffee and snacks**
1100-1200	**Data Management -** **Presentations by Liqing Jiang and Eugene Burger** **Objective**: Update participants about partners' data management groups' recent advances, current capabilities/development and review requirements.
1200 - 1345	**Working Lunch (Breakouts)** **Objective:** Breakout by thematic area (e.g., species response experiments, ocean chemistry modeling, **integrated** interdisciplinary OA monitoring, hydrographic cruises etc.) to discuss how research in various **regions** can be more **inter-comparable** and more **complementary**. **Activities/Interactions:** Breakout discussion 1. Species response: Chris Chambers 2. Monitoring: Gabrielle Canonico 3. Cruises: Leticia Barbero 4. Modeling (including ecological modeling): Beth Turner

1345-1430	**Breakout Discussion Report Out**
1430-1500	**Meeting Wrap Up – Libby Jewett**
1500	**Adjourn**

Appendix 3. Participants at the January 2017 NOAA OA Program Principal Investigators meeting.

PARTICIPANT LIST

Name	Affiliation
Adrienne Sutton	NOAA Pacific Marine Environmental Laboratory, University of Washington Joint Institute for the Study of the Atmosphere and Ocean
Alex Harper	NOAA Ocean Acidification Program
Amanda Kelley	University of Alaska Fairbanks
Andrew Dickson	Scripps Institution of Oceanography, UC San Diego
Andrew Dittman	NOAA National Fisheries Service, Northwest Fisheries Science Center
Becky Briggs	NOAA National Sea Grant Office
Beth Phelan	NOAA National Fisheries Service, Northeast Fisheries Science Center, Howard laboratory
Beth Turner	NOAA, National Ocean Service, Center for Sponsored Ocean Research
Burke Hales	Oregon State University
Caren Braby	Oregon Department of Fish and Wildlife
Carol Bernthal	NOAA, National Ocean Service, Olympic Coast National Marine Sanctuary
Carol Stepien	NOAA Pacific Marine Environmental Laboratory
Chase Williams	University of Washington
Chris Caldow	NOAA National Ocean Service, Channel Islands National Marine Sanctuary
Chris Chambers	NOAA National Fisheries Service, Northeast Fisheries Science Center
Chris Harvey	NOAA National Fisheries Service, Northwest Fisheries Science Center
Chris Long	NOAA National Fisheries Service, Alaska Fisheries Science Center
Chris Melrose	NOAA National Fisheries Service, Northeast Fisheries Science Center
Chris Sabine	NOAA Pacific Marine Environmental Laboratory
Dan Wiezorak	NOAA National Fisheries Service, Northeast Fisheries Science Center
Danielle Lipski	NOAA National Ocean Service, Cordell Bank National Marine Sanctuary
Danielle Perez	NOAA National Fisheries Service, Northwest Fisheries Science Center
Darcy Dugan	Alaska Ocean Observing System
David Murphy	SeaBird
Derek Manzello	NOAA Atlantic Oceanographic Meteorological Laboratory
Dwight Gledhill	NOAA Ocean Acidification Program
Emily E Bockmon	Cal Poly San Luis Obispo
Emily Osborne	NOAA Arctic Program
Eric Heinen De Carlo	Oceanography, SOEST, University of Hawaii at Manoa
Erica Ombres	NOAA Ocean Acidification Program

Eugene Burger	NOAA Pacific Marine Environmental Laboratory
Hollie Putnam	University of Washington / University of Rhode Island
Gabrielle Canonico	NOAA U.S. Integrated Ocean Observing System/ U.S. MBON
George Waldbusser	Oregon State University
Ian Enochs	NOAA Atlantic Oceanographic Meteorological Laboratory, University of Miami Cooperative Institute for Marine and Atmospheric Studies
Isaac Kaplan	NOAA National Fisheries Service, Northwest Fisheries Science Center
Jacqueline Padilla-Gamiño	University of Washington
Jameal Samhouri	NOAA National Fisheries Service, Northeast Fisheries Science Center
Jan Newton	University of Washington
Jan Roletto	NOAA National Ocean Service, Greater Farallones National Marine Sanctuary
Jennifer Bennett-Mintz	NOAA Ocean Acidification Program
Jenny Waddell	NOAA National Ocean Service, Olympic Coast National Marine Sanctuary
Jeremy Mathis	NOAA Arctic Program
Jessica Cross	NOAA Pacific Marine Environmental Laboratory
Jill Brandenberger	Pacific Northwest National Laboratory
Joseph Salisbury	University of New Hampshire
Justine Kimball	NOAA Coral Program
Kathy Tedesco	NOAA Climate Program Office
Kevin Grant	NOAA National Ocean Service, Olympic Coast National Marine Sanctuary
Kevin O'Brien	NOAA Pacific Marine Environmental Laboratory, University of Washington Joint Institute for the Study of the Atmosphere and Ocean
Kimberly Puglise	NOAA National Ocean Service, National Centers for Coastal Ocean Science
Krista Nichols	NOAA National Fisheries Service, Northwest Fisheries Science Center
Laura Bianucci	Pacific Northwest National Laboratory
Laura Francis	NOAA National Ocean Service, Channel Islands National Marine Sanctuary
Leslie Wickes	NOAA Ocean Acidification Program/ Southeast Ocean and Coastal Acidification Network
Leticia Barbero	NOAA Atlantic Oceanographic Meteorological Laboratory
Libby Jewett	NOAA Ocean Acidification Program
Linda Rhodes	NOAA National Fisheries Service, Northwest Fisheries Science Center
Liqing Jiang	NESDIS/NCEI
Maria Kavanaugh	Woods Hole Oceanographic Institution
Mark Strom	NOAA National Fisheries Service, Northwest Fisheries Science Center
Matthew Poach	NOAA National Fisheries Service, Northeast Fisheries Science Center, Sandy Hook Laboratory

Meg Chadsey	Washington Sea Grant, University of Washington
Melissa Poe	Washington Sea Grant, University of Washington and NOAA National Fisheries Service, Northwest Fisheries Science Center
Michael Li	NOAA National Fisheries Service, Northwest Fisheries Science Center Intern
Michael Maher	NOAA National Fisheries Service, Northwest Fisheries Science Center
Michael Rust	NOAA Office of Aquaculture
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Mitchell Tartt	NOAA National Marine Sanctuaries
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