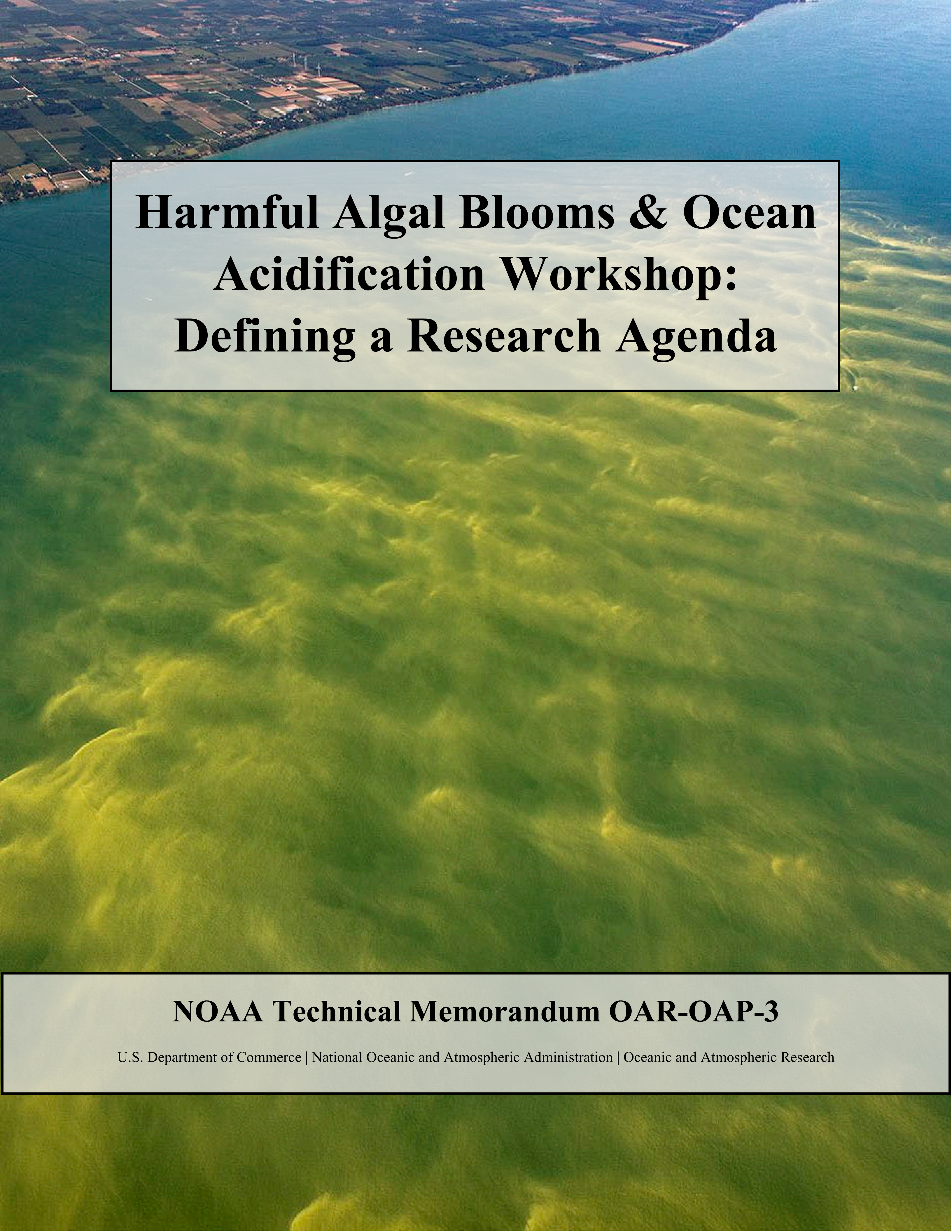

Harmful Algal Blooms & Ocean Acidification Workshop: Defining a Research Agenda

NOAA Technical Memorandum OAR-OAP-3

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

Harmful Algal Blooms & Ocean Acidification Workshop: Defining a Research Agenda

Convened by NOAA Ocean Acidification Program and the National Centers for Coastal Ocean Science Competitive Research Program
August 11-13, 2020

Elizabeth Turner, Erica Ombres, Jennifer Bennett-Mintz, Quay Dortch, Maggie Broadwater, Halle Berger, and Michelle Harris

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Photo: Harmful algal (*Microcystis*) bloom in Lake Erie on August 14, 2017. This image was taken as part of a NOAA Great Lakes Environmental Research Laboratory effort led by Dr. Andrea VanderWoude to improve the mapping and detection of harmful algal blooms in the Great Lakes. Credit: Zachary Haslick, Aerial Associates Photography, Inc.

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Acknowledgements

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List of Abbreviations

AOAN	Alaska Ocean Acidification Network
AOOS	Alaska Ocean Observing System
CeNCOOS	Central and Northern California Ocean Observing System
CMIP	Coupled Model Intercomparison Project
CRP	Competitive Research Program
EPP/MSI	Educational Partnership Program with Minority Serving Institutions
ERDDAP	Environmental Research Division's Data Access Program
ESP	Environmental Sampling Processor
GCOOS	Gulf of Mexico Coastal Ocean Observing System
GLODAP	Global Ocean Data Analysis Project
HAB	Harmful Algal Bloom
HABHRCA	Harmful Algal Bloom and Hypoxia Research and Control Act
IFCB	Imaging FlowCytobot
IOOS	U.S. Integrated Ocean Observing System
IOOS RA	U.S. Integrated Ocean Observing System Regional Association
NANOOS	Northwest Association of Networked Ocean Observing Systems
NCCOS	NOAA National Centers for Coastal Ocean Science
NERRS	NOAA National Estuarine Research Reserve System
NMS	NOAA National Marine Sanctuaries
NOAA	National Oceanic and Atmospheric Administration
OCADS	Ocean Carbon Data System
OA	Coastal and Ocean Acidification
OAP	Ocean Acidification Program
ODFW	Oregon Department of Fish and Wildlife
PNW	Pacific Northwest
SCCOOS	Southern California Coastal Ocean Observing System
SCCWRP	Southern California Coastal Water Research Project
SCOR	Scientific Committee on Oceanic Research
SOCAT	Surface Ocean CO_2 Atlas
WA DOH	Washington State Department of Health
WCOFS	Operational West Coast Ocean Forecast System

Executive Summary

The National Oceanic and Atmospheric Administration (NOAA) Ocean Acidification Program (OAP) and NOAA National Centers for Coastal Ocean Science (NCCOS) Competitive Research Program (CRP) are working to better understand interactions between stressors such as harmful algal blooms (HABs) and coastal and ocean acidification (OA). Both HABs and OA are threats to marine ecosystems and human communities in the coastal zone, and understanding OA-HAB interactions emerged as a national priority in the 2020 NOAA Ocean Acidification Research Plan (Jewett et al., 2020).

While research to date has provided insights into the many factors that regulate HAB dynamics, toxicity, and impacts, only a few of these have included OA. Similarly, OA studies have examined ocean biogeochemistry and impacts to marine resources and economies and have started to expand into multi-stressor research studies (e.g., with hypoxia and warming). Recent studies indicate that increased CO_2 concentrations support higher phytoplankton densities and that carbonate chemistry (e.g., pCO_2 and pH) have variable effects on growth rate and cellular toxin production in different HAB species and strains. There is a growing need to understand OA-HAB interactions and their cascading impacts to coastal ecosystems, communities, and economies to inform management decisions. OA and HABs can impact the same coastal resources (e.g., aquaculture, wild fisheries, and tourism) in different ways and there may be synergistic or antagonistic effects that are not recognized by current research efforts. OA and HABs have some common drivers in coastal areas and often co-occur in space and time, which will likely become more common in the future.

The virtual Harmful Algal Blooms and Ocean Acidification Workshop was held August 11-13, 2020. The workshop was designed to identify research needs and priorities at the intersection of OA and HABs by asking:

- How are OA and HAB dynamics linked?
- How does OA influence growth or toxicity of HABs?
- What are the food web impacts of OA and HABs in concert?
- Are some marine species more vulnerable or more resilient to combined OA and HAB impacts?
- What are the synergistic OA and HAB impacts to fisheries and coastal economies?
- Can we make projections about future conditions on relevant timescales for both OA and HABs?
- How can we encapsulate information about combined OA and HAB impacts into useful information for management and policy makers?
- What are the major gaps in our understanding?

Preceding the workshop, several experts in the field presented a series of webinars discussing the current understanding of OA-HAB interactions in various regions, estuaries, and the Great Lakes. Webinar speakers were asked to share their thoughts about the greatest knowledge gaps and "grand challenges" related to OA-HAB interactions; these are listed in the "OA & HABs Across the U.S.: Laying the Scientific Foundation" section of this report (pp. 9-14). The pre-workshop webinars were recorded and archived[1]. Participants had the opportunity to work in groups to identify regional information knowledge gaps and needs, and relevant products to meet the needs identified in the Great Lakes, East Coast, Gulf of Mexico, West Coast, and Alaska regions.

The overarching need that emerged across the workshop is that future research should include a holistic approach to multi-stressor ecosystem research. Several research needs were common across regions:

- The need to recognize that OA is a multi-stressor involving a host of different chemical species (e.g., pCO_2, pH, CO_3^{2-}, etc.), each of which may have different impacts.
- OA occurs along with other environmental conditions such as eutrophication and hypoxia, which have their own impacts on HABs.
- Basic information is needed on OA impacts on HABs at many levels: species, population, community, food web, and ecosystem.
- Expanding studies to include important resource species, such as shellfish, and coastal economies and social systems will be necessary.
- Co-monitoring of OA and HABs is desperately needed to discern relationships and start to build understanding.

With sufficient understanding, predictions, vulnerability assessments, and other products can be produced to communicate impacts and risks. Research products that will address cross-regional needs should incorporate:

- Modeling at multiple spatial and time scales for prediction, attribution (including both direct and indirect effects), and sensitivity testing;
- Advice to monitoring programs and leveraging monitoring assets to add OA and HAB parameters measured simultaneously with other ecosystem stressors (e.g., temperature, hypoxia, nutrients);
- Data management to foster the integration of research on different ecosystem stressors;
- Data product development, while making data available in near real time for integration and synthesis; and
- Continued and enhanced communication and outreach efforts, both as a delivery mechanism for research results and for identification of stakeholder needs.

It will be important to understand how increasing temperature and decreasing pH, or changes in carbonate chemistry, affect both HABs that produce toxins harmful to human shellfish consumers and HABs that harm fish and shellfish and, therefore, affect the industries reliant on these species.

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[1] https://oceanacidification.noaa.gov/HABOA2020.aspx

Acidification & Harmful Algal Blooms Across the US: Lightning Talks and Panel Discussion (Day 1)

Welcoming Remarks

Dwight Gledhill, Deputy Director of the NOAA Ocean Acidification Program, and David Kidwell, Director of the NOAA National Centers for Coastal Ocean Science Competitive Research Program both highlighted the individual importance of HABs and OA, demonstrated by Congressional interest through the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA, 33 USC 4008) and the Federal Ocean Acidification Research and Monitoring Act. In addition, interest about the interactions between OA and HABs has been on the rise both in the scientific community and at the Congressional level.

OA & HABs Across the U.S.: Laying the Scientific Foundation

Recaps of the webinars followed in lightning talk format. Speakers were asked to summarize their presentation, provide their grand challenges, and reflect on how the information they presented was similar or different from other regions and systems.

NOAA uses the following definitions for this report:

- Harmful Algal Bloom (HAB) means marine and freshwater phytoplankton that have proliferated to high concentrations, resulting in nuisance conditions or harmful impacts on marine and aquatic ecosystems, coastal communities, and human health through the production of toxic compounds or other biological, chemical, and physical impacts of the algae outbreak (33 USC 4008(3)). "High concentrations" of phytoplankton are relative to baseline conditions or abundances observed during non-bloom or non-nuisance conditions, or in the absence of harmful impacts.
- Ocean Acidification (OA) is driven predominantly by ocean uptake of atmospheric carbon dioxide (CO_2), resulting in global-scale changes in ocean chemistry with predictions of broad-scale ecosystem impacts. Coastal acidification, which refers to a pH decline over decadal or longer time scales, resulting not only from atmospheric CO_2, but also from changes in coastal biogeochemical and hydrographic processes, is recognized as the coastal subset of OA. Throughout this workshop report the term "OA" is used to represent both ocean and coastal acidification processes in marine and Great Lakes ecosystems.

"HABs and Ocean Acidification: Additive, Synergistic, Antagonistic, or Otherwise?"

Christopher Gobler (Stony Brook University) portrayed HABs as the "fourth horseman" of the ocean climate change apocalypse in addition to temperature, OA, and hypoxia. HABs can cause ocean acidification and hypoxia (OAH) through their decomposition, as well as respiration of HABs which can be heterotrophic. Some HABs grow faster or become more toxic in acidified waters, although this is not uniform across genera, species, and strains. The co-effects of HABs and OAH on aquatic life are largely unexplored, with three published studies to date (Griffith and Gobler 2020; Raven et al., 2020; Wallace et al. 2014), but it is likely that the co-occurrence of HABs and OAH will become more common in the future.

Christopher Gobler brought up four grand challenges in his webinar:

- What are the precise duration and intensity of exposure of aquatic life to HABs and OA?
- How will the duration and intensity of HABs and OA change in future oceans?
- What are the consequences of environmentally realistic (today, future) levels of OA and HABs for aquatic life?
- When and for which HABs will OA matter (most)?

Notable regional differences include:

- Eutrophic northeast and Mid-Atlantic Bight estuaries are particularly vulnerable to OA during warmer months due to accelerated rates of respiration and low buffering capacity compared to other regions.
- Intense buffering, oversaturation of calcium carbonate minerals, and warmer temperatures in the Gulf of Mexico and the southeast US make acidification less likely in this region, particularly within surface waters (although the relative magnitude change in carbonate mineral saturation may be greater in these regions).
- The west coast OA is more strongly associated with upwelling events that may also influence HABs.

"Acidification, eutrophication, and HABS in estuarine waters: What do long-term data tell us?"

Hans Paerl (University of North Carolina) stressed that many factors influence pH in estuaries: eutrophication, freshwater input, storms, land use, etc. He provided data from Chesapeake Bay and the Albemarle-Pamlico Sound System/Neuse River Estuary and compared interacting drivers at different places in these estuaries.

Grand challenges mentioned by Hans Paerl were:

- Interpreting long-term data sets in the context of eutrophication, watershed processes, hydrology, storms, and other influencing factors.
- The need for continuous, high resolution water quality monitoring to capture events/impacts over relevant scales, coupled to remote sensing and sampling.
- The need for nutrient and carbon local, regional, and global management strategies to be responsive to climatic changes and extremes.

"Synergies between OAH and HAB networks: California as a case study"

Raphael Kudela (University of California Santa Cruz) focused on how eastern boundary currents show extreme natural vulnerability and long-term anthropogenic forcing. Multi-stressor experiments are difficult to carry out correctly and there are few studies from California (Sun et al., 2011; Tatters et al., 2012; Tatters et al., 2013). Species and strain variability is considerable, and he noted that caution should be taken in extrapolating from a handful of studies. However, there is benefit in linking OA and HABs through synergistic observations (i.e., via IOOS Regional Associations) and modeling efforts, to then derive higher trophic level impacts.

Grand Challenges presented by Raphael Kudela:

- How representative of natural conditions are existing data from small scale experiments on HABs and OA? Is there enough information to parameterize models?
- How will HAB organisms respond to short-term and long-term drivers? Are multiple stressors synergistic, antagonistic, or neutral?
- How do we effectively link HAB response to higher trophic levels in a changing ocean?
- Can we better coordinate between HAB and OAH communities to take advantage of the overlap in data, tools (i.e., models), and predictions?

Raphael Kudela noted that regional commonalities emerged from presentations such as:

- A need for community experiments (multi-organism interactions) and multi-stressor experiments.
- The opportunity to take advantage of high-resolution observations with better carbonate chemistry and higher resolution biological observations.
- Multiple regions are moving forward with advanced models. Can we move towards attribution in these models?
- HABs and OA are a global problem but are strongly driven by regional and local processes. Therefore, there are similarities across regions, but often only at a high level.

"Alaska OA and HABs: Networking and coastal variability"

Kris Holderied (NOAA National Centers for Coastal Ocean Science) brought us to Alaska, where coastal communities have strong dependence on marine resources, many of which are vulnerable to HABs. High variability is the norm in Alaska's coastal ecosystems. She highlighted the need to understand HAB/OA/climate intersections and build state-wide networking and capacity building to address new threats and help remote communities.

Kris Holderied offered a stakeholder view of grand challenges:

- What is happening now, what are the current conditions? Monitoring targeted at quantifying variability in HAB & OA conditions at time and space scales that matter for stakeholder resource management, harvest, and mariculture operations and new development. Monitoring designed to support development of risk and vulnerability assessment products. Accurate, cost-effective field test kits for PSP toxins.
- How will HABs and/or OA affect my species? Species sensitivity research for harvested and prey species to assess vulnerability and understand food web impacts. Incorporate realistic, regionally specific environmental condition information (thresholds/variability) from enhanced monitoring data. Identify synergistic effects on species between climate change, OA, and HABs.
- Should I be worried now? If not now, when? Modeling of environmental conditions in nearshore and offshore waters, resolved sufficiently in time and space to assess impacts on coastal resources. Incorporate temperature, freshwater, carbonate chemistry and ice

changes. Combine monitoring, species response and modeling information to develop species-specific, multi-stressor vulnerability assessments and public health risk assessments.

In reflecting on similarities and differences, she noted that Alaska is similar to other regions in the need to integrate multiple threats from HABs, OA and climate change and improve testing for HAB toxins. Notable ways Alaska differs from other regions include:

- The number of remote communities with high dependence on marine resources;
- Glacial melt and changes in sea ice coverage lead to large variability in Alaska coastal ecosystems; and
- There are relatively limited observations and coastal modeling of environmental conditions compared to other regions, despite the high variability in Alaska waters.

"A marginal sea of variability in ocean acidification and harmful algal blooms in the Gulf of Mexico"

Beth Stauffer (University of Louisiana at Lafayette) pointed out that OA and HABs in the Gulf of Mexico are both spatially variable. Many HABs in the Gulf of Mexico show increased growth at high pCO_2 levels in the lab (e.g., *Karenia brevis*, toxic cyanobacteria) which can lead to changes in community structure. Beth Stauffer stressed the importance of biomass vs. size structure of the phytoplankton community, and that HABs have variable trophic modes. This means it may be necessary to quantify prey or *in situ* species interactions (i.e., facilitating species that promote bloom initiation or maintenance) to understand HAB responses to OA.

Given the spatial and temporal variability of OA and HABs in the Gulf of Mexico, and the challenge of community change, Beth Stauffer outlined these grand challenges:

- How do we effectively study a system with multiple drivers of OA and diversity of HAB species?
- How can we best attribute effects on single HAB species and natural communities to OA versus other co-stressors?
- How do we disentangle direct and indirect effects of OA on food web dynamics?
- Can we better understand OA effects on HABs if we allow them to exist along other community changes?

When comparing the Gulf of Mexico to other regions the following observations were shared:

- Eutrophication-enhanced OA is a persistent feature in coastal and estuarine systems.
- The need to integrate complexity in our research, while still using experimental approaches and hypotheses that can generate important insights.
- The need for single or multi-species experiments to be run on appropriate time scales and periodicity.
- The severe lack of robust OA and HAB observational data in the Gulf of Mexico, outside of certain locations and seasons/years.

"Acidification and harmful algal blooms in the Great Lakes"

Reagan Errera (NOAA Great Lakes Environmental Research Laboratory) provided an introduction to primary production processes and biogeochemistry in the Great Lakes. Offshore processes in the Great Lakes are similar to offshore processes in the oceans, whereas the nearshore is impacted by watersheds leading into estuaries and coastal systems. In the Great Lakes, model predictions show decreased pH in 2100 without warming, but increased pH with warming. Monitoring data suggest that currently variability can be as much as 0.05 unit change per day, but current biogeochemical/carbonate chemistry monitoring is severely insufficient. HABs occur in all five Great Lakes. Cyanobacteria have evolved strategies for dealing with CO_2 limitation. There may be a succession of carbon uptake genotypes of *Microcystis* during a bloom, but it is unknown how this may be related to genotypes capable of producing toxins.

Reagan Errera shared that the greatest needs in the Great Lakes are:

- High frequency measurements of multiple inorganic carbon parameters in more locations across the Great Lakes.
- Further understanding of synergistic effects between temperature, nutrients, and the carbonate system in freshwater systems.
- Impacts of changes in the carbonate chemistry to the food web (i.e., invasive mussels).
- Examination of isolated HAB strains specific to Great Lakes, but also use of natural communities to understand how species interact *in situ.*

"Effects of Ocean Acidification on HABs: A review of what we do and don't know"

Melissa McCutcheon (Texas A&M University at Corpus Christi) provided selected results from a literature review of OA and HAB studies, she undertook with The Nature Conservancy. She found that physiological responses of HABs to OA differed among studies for both growth rate and toxin production. Both species and strain-specific responses were observed, even within a given controlled study (e.g., *Alexandrium* spp.). Changes have also been seen in phytoplankton community composition in response to OA. There is evidence that HAB species may outcompete non-HAB species in response to OA, which leads to changes in ecosystem dynamics (e.g., competition, predation, etc.).

Melissa McCutcheon noted the following grand challenges and needs associated with OA-HAB studies:

- Continue filling in the gaps of OA-HAB species-level investigations to address missing taxa and add context with multiple stressors.
- Broaden understanding of the effects of OA on HAB species as they occur in full community assemblages.
- Propose regionally specific water and land use management strategies based on evidence for coastal water quality outcomes including HABs and OA.

Some common needs that Melissa McCutcheon observed that were consistent across the various regions were:

- Increased scientific understanding of OA-HAB linkages.
- Monitoring at temporal and spatial scales that are relevant.
- Species sensitivity research in context with multiple stressors.
- Forecasting and risk/vulnerability assessment products.

Common Themes on OA & HABs Across the U.S.

Several themes emerged from the presentations:

1. The need to recognize that OA is itself a multi-stressor involving changes across a range of chemical species (e.g., pCO_2, pH, CO_3^{2-}), each of which may have different impacts.
2. OA occurs along with other environmental conditions such as eutrophication and hypoxia, which have their own impacts on HABs.
3. Basic information is needed on OA impacts on HABs at many levels: species, population, community, food web and ecosystem.
4. Expanding studies to include important resource species, such as shellfish, and coastal economies and social systems will be necessary.
5. Co-monitoring of OA and HABs is desperately needed to discern relationships and start to build understanding.
6. With sufficient understanding, predictions, vulnerability assessments, and other products can be produced to communicate impacts and risks.

Plenary Discussion: OA & HABs Across the U.S.

After lightning talks from the various regions and systems, discussion opened with a question from the moderator asking, "If there was sufficient monitoring in your geographic area/system, what would be the next biggest limitation to understanding OA-HAB interactions?" Speakers offered that even with adequate monitoring of coastal waters, there is a need to link the chemistry with an understanding of watershed processes and nutrient/organic matter loading into the system. Monitoring the biology is important, and where there is co-occurrence of OA and HABs, HAB toxin production and movement of toxins through the food web needs to be tracked and understood. Due to high variability of both carbonate chemistry and HAB bloom production, time series need to be long enough to detect a signal (i.e., time of emergence). More lab and mesocosm experiments are needed to understand the impacts of multi-stressors (i.e., OA and HABs in context with warming, hypoxia, and nutrients). There is a need to understand HAB species sensitivity to OA and incorporate this knowledge into models, risk assessments, and public health advisories.

General discussion during the plenary brought up several points regarding the time scales of monitoring. HAB growth processes occur on a scale of hours to days, so single point measurements of HAB, OA, and other environmental parameters may not be adequate for determining a relationship because there is often a temporal disconnect. For example, the nutrients or pH measured during a HAB event of any sort are more likely the residual of the event than the cause. This is often overlooked and the cause of a lot of misinterpretation of monitoring data. High-resolution data over relevant time periods, e.g., measurements on the minute to hour timescale, would allow those time lags to be considered, but daily to weekly sampling is likely insufficient (unless the models are sufficiently resolved).

The Cha'ba mooring[2] off of the outer Washington coast is one example of co-located higher frequency monitoring for HABs, OA, and environmental parameters; this site could be used as a case study. This buoy location is a hot spot for both OA and HABs. Remote sensing can help with monitoring, but the tradeoff between temporal and spatial sampling in remote sensing products is an issue. For example, Landsat[3] and Sentinel 2[4] provide 30 and 10 m resolution, but only weekly or every 3-4 days, while Sentinel 3[5] provides daily observations at 300m. Stationary time series data can be compared with remote sensing observations, but comparing field samples (i.e., towed instrumentation) with remote sensing data can provide higher spatial resolution. Other potential data sources to build on included a coastal mooring network along the Olympic Coast, through NOAA's National Marine Sanctuary (NMS) Program with over two decades of data. Those samples are taken six times between May and October. NOAA's National Estuarine Research Reserve System (NERRS) sites around the country also have a lot of water quality monitoring data including data for HABs.

The participants also expressed interest in maps of HAB frequency. The current maps are based on event reports. There are likely under-reporting issues based on different regional monitoring capacity, and baseline or undetected abundances are not easily found.

Other discussion threads focused on the ability of experiments to discern OA effects on HABs. Future experiments must be designed to differentiate among pH, pCO_2, and calcium carbonate (aragonite and calcite) saturation state effects; these are generally lacking in past studies. Typical experimental approaches employ an acute change of the CO_2 system in the experiment, changing all parameters at once. Understanding which component(s) of the carbonate system is(are) driving changes in HABs must be evaluated, especially if the trajectories of pH, pCO_2, and Ω_{ar} are different in some coastal settings with varying freshwater end-member characteristics. It is also important to appreciate that toxin production data are typically provided as cellular toxin levels (i.e., toxin concentrations normalized to cell abundance). These ratio data do not elucidate whether toxin production (i.e., synthesis) rates are increased overall, or simply increased relative to cell abundance. This is key when examining exponential vs. stationary phases of growth.

Synthesis of OA-HAB Needs from Pre-workshop Webinar Presentations

To wrap up the first day, Mya Sharpe, a NOAA Educational Partnership Program with Minority Serving Institutions (EPP/MSI) Undergraduate Scholar working jointly with NOAA/OAP and

[2] https://www.pmel.noaa.gov/co2/story/La+Push
[3] https://coast.noaa.gov/digitalcoast/data/landsat.html
[4] https://coastwatch.noaa.gov/cw/satellite-data-products/imagery/msi-sentinel2.html
[5] https://coastwatch.noaa.gov/cw/satellite-data-products/ocean-color/near-real-time/olci-sentinel3.html

NOAA/NCCOS/CRP, presented her analysis of audience and workshop participant responses to the pre-workshop webinars. Data from webinar transcripts, questions, comment boxes and Google survey forms were binned into categories and analyzed to determine reoccurring themes. The importance of field studies, observations, modeling, multi-stressor studies (especially as it relates to warming, hypoxia and eutrophication) and trophic interactions (blue bars in Fig. 1) were highlighted. Comments and questions from the audience emphasized these as well, along with the need for management tools (orange bars, Fig. 1). The Google survey form responses, although fewer in number overall, also highlighted observations, multi-stressor evaluations and lab and field experiments including impacts of OA to toxicity (pink bars, Fig. 1).

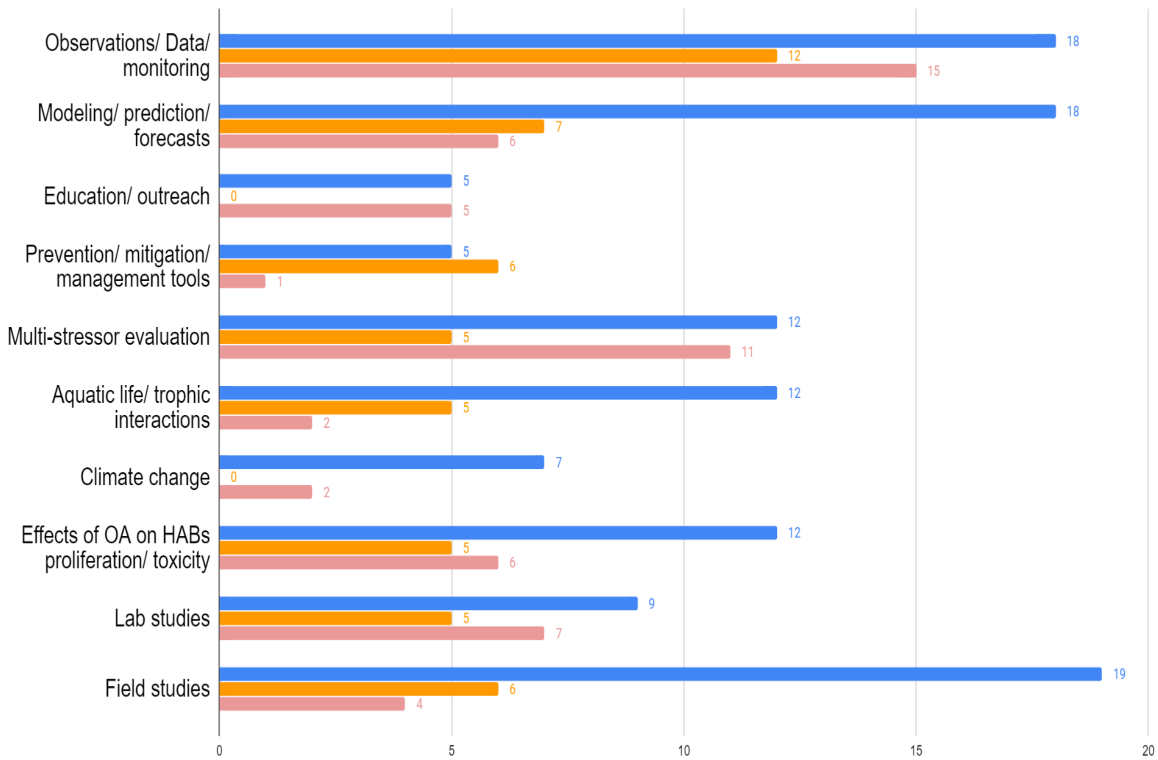

Figure 1. Number of responses from webinar speakers, attendees and google forms binned by category of response, where blue bars represent expert recommendations, orange bars represent attendee interest, and pink bars represent attendee form comments, respectively.

Mya Sharpe stressed that outreach and education activities are important even though they did not emerge as a major category based on this analysis. This may reflect the fact that there are so few studies of OA and HABs together, so it is difficult to know what and how to message with regard to risk. There is also a need to bring a diversity of stakeholders to the table to see if their opinions differ from those of the experts/academia.

Identifying Stakeholder Needs (Day 2)

Day 2 featured a panel of stakeholders including representatives from shellfish hatcheries, state governments and NOAA programs with direct outreach to local and regional communities.

Stakeholder Needs Panel

Meredith White (Mook Sea Farm, Damariscotta River, Maine)[6] discussed questions around how OA affects seed oyster growth (as opposed to larvae, which are more commonly studied). Sublethal thresholds are important as well as lethal impacts. While most HAB studies focus on species resulting in public health concerns, species that affect shellfish themselves (e.g., *Margalefidinium*, formerly known as *Cochlodinium*) are of major concern to hatcheries and grow out operations. Some blooms and bloom by-products (e.g., polyunsaturated fatty acids and polyunsaturated aldehydes from diatom blooms) may not affect human health but could affect the shellfish industry. While no HAB closures have affected Mook Sea Farm, it is likely a matter of time. Given a 28-day residence time in the Damariscotta River estuary, a HAB closure could be devastating. Meredith White indicated support for two types of research projects: 1) understanding if and how culturing shellfish would enhance or limit HABs, and 2) modeling the conditions necessary for HABs to enter and become established in an estuary.

Bill Dewey (Taylor Shellfish Farms, Puget Sound, Washington)[7] supports adaptations to changing ocean carbon chemistry on farms and in open water nurseries. One example of this is using eelgrass to potentially limit or mitigate OA effects and suppress HABs. Bill surveyed the Pacific Coast Shellfish Growers Association for input. Currently, most shellfish growers consider OA and HABs to be separate issues and are not thinking of ways to address them in concert. Priority research ideas included:

- Understanding cues and triggers for HABs and what impacts the scale of blooms, tools and training to monitor and predict OA and HAB events (e.g., University of Washington's Live Ocean Model)[8], alarms and warnings sent directly to growers rather than expecting them to check a website for model output.
- Reiterating support for studies of HABs that kill shellfish, not just have human impacts (e.g., *Akashiwo sanguinea*, a harmful macroalgae).
- Identifying actions shellfish growers can take to avert or minimize impacts.
- Monitoring buoys that detect both HABs and carbonate chemistry parameters.

Bill Dewey also presented responses from **Jerry Borchert** and **Tracie Berry** (Washington Department of Health Shellfish Program, WA DOH)[9]. Their concerns include monitoring of OA

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6 https://www.mookseafarm.com/

7 https://www.taylorshellfishfarms.com/

8 http://faculty.washington.edu/pmacc/LO/LiveOcean.html

9 http://www.doh.wa.gov/AboutUs/ProgramsandServices/EnvironmentalPublicHealth/EnvironmentalHealthandSafety/ShellfishProgram

conditions in conjunction with their HAB monitoring program. Understanding which harmful species might have a competitive advantage under OA has implications for outcompeting beneficial/benign species (i.e., oyster food), altering food webs and potentially decreasing productivity.

Some of the questions related to OA and HABs are:

- How can we better assess the feedback loops among blooms, production/decomposition, OA and hypoxia and accompanying synergies?
- Does OA decrease shellfish growth rates and/or increase shellfish toxicity?

There is a need to measure local HAB species cell density and toxin production under current and OA conditions. Currently HAB cell density is used to trigger action alerts and this will need to be modified for expected low pH conditions in the future. If OA conditions are conducive to more toxin production even with less cell density, smaller blooms could result in more shellfish closures and guidelines should be adjusted. This presents compelling reasons to study HABs and OA in conjunction.

Chris Kinkade (NOAA National Estuarine Research Reserve System, NERRS)[10] introduced the NERRS as the thirty federal-state partnerships for research, land stewardship, K-12 education, and public engagement. In addition to work at individual reserves, the program sponsors competitive funding for collaborative research and has monitoring capabilities through their System-Wide Monitoring Program. HAB research at NERRS focuses mostly on monitoring, and only a few NERRS sites are monitoring OA parameters. Most NERRS sites are not currently thinking about linking HABs and OA given that the sensors, time scales and methods differ for monitoring each of these. Questions of importance to the NERRs are:

- How to use information generated from separate HAB and OA monitoring for management initiatives?
- Can HAB and OA managers assess needs together for both OA and HABs?

Chris Kinkade referenced NCCOS CRP's Monitoring and Event Response for HABs (MERHAB)[11] research program as a model for coastal management research. The MERHAB program builds capacity for enhanced monitoring and response to HABs to help NOAA and state partners identify HAB risks and make informed decisions to protect public health and coastal economies.

Steve Gittings (NOAA National Marine Sanctuaries, NMS)[12] stressed the NMS role in science communication, resource protection, and efforts to maintain and improve ecosystem quality. NMS managers need to know the combined consequences of gradual OA changes and rapid-onset HAB events to understand how to respond, protect and restore habitat to influence changes

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[10] https://coast.noaa.gov/nerrs/

[11] https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/merhab/

[12] https://sanctuaries.noaa.gov/

in OA or the frequency, severity, and duration of HABs. NMS sites provide not only research and monitoring sites, but also have direct links to local community leaders and the media. They also issue condition reports, which could (and in some cases, do) incorporate information on HABs and OA status and trends.

Molly McCammon (Alaska Ocean Observing System, AOOS)[13] highlighted the Alaska OA Network[14] and the Alaska HAB network[15], both of whom work with a wide range of stakeholders across the state including shellfish industry, tribes, and public officials. These groups are concerned with OA and HAB impacts to the shellfish industry and to commercial fishing for crab and salmon. They are also concerned with HAB impacts on the public health of subsistence and recreational users, particularly given the many rural and remote communities in Alaska. Stakeholders have questions surrounding what is happening now, how that will change, and what they should worry about more or first. The state of Alaska has a huge coastline and extreme variability among regions. There is a decided need for sustained monitoring and observations and understanding of the relationship of OA and HABs to wildlife mortalities, specifically the cumulative impacts, the role of OA and HABs in these, and which species/life stages are most sensitive. Additionally, will COVID research provide an opportunity to use PCR capabilities for HAB research in the future? Molly McCammon noted the importance of:

- Having the ability to integrate data and share with stakeholders.
- Providing sustained support for networks and statewide action plans.
- Identifying overlap of the most vulnerable communities and species, and providing public health bulletins along with training to increase awareness regarding HAB toxicity and events.

Martha Sutula (Southern California Coastal Water Research Project, SCCWRP)[16] has direct linkages to water quality and state resource managers. Their concerns include HABs, warming, OA, and deoxygenation. Event-driven closures of fisheries (e.g., Dungeness crab, Northern anchovy, etc.) have resulted from HAB events and warming conditions. One question she has is how to best prepare people to react to changing conditions. California is promoting policies to address some of these issues. A challenge is that paradigms for regulating water quality are not well equipped to address issues "beyond the pipe". Water quality managers need to see an established link between land-based stressors and ocean impacts. Another question Martha Sutula is interested in is how warming and other stressors may exacerbate deoxygenation. Data are needed to evaluate multiple stressors and the biological impacts (both acute impacts vs. sublethal chronic exposure, and static vs. dynamic stressors). The west coast is an upwelling dominated system. Modeling and operational forecasts can provide ecosystem predictions, validation, and uncertainty analysis. Identifying place-based solutions with high efficacy and low environmental impacts or 'no regret' solutions is a priority. Finally, estuaries are 'ground zero'

[13] https://aoos.org/
[14] https://aoos.org/alaska-ocean-acidification-network/
[15] https://aoos.org/alaska-hab-network/
[16] https://www.sccwrp.org/

for climate change impacts, and research outcomes must inform adaptive management responses and provide appropriate solutions such as kelp aquaculture/co-culture and carbon/nutrient trading.

Caren Braby (Oregon Department of Fish and Wildlife, ODFW)[17] works on fish management, habitat conservation and restoration, and marine policy related to human impacts and climate change. Prioritizing research is difficult because there are so many needs. Oregon is concerned with HABs and general ocean change because it is an early indicator for global OA changes. Multi-stressor problems need multi-stressor solutions. This will require projection of future events, *in situ* multi-stressor and ecosystem interaction experiments and dissemination of information such as the Pacific Northwest HAB Bulletin[18]. Oregon has created the Oregon Coordinating Council on Ocean Acidification and Hypoxia[19], which provides recommendations to the state on dealing with these two inter-related issues. These include the Oregon Ocean Acidification and Hypoxia Action Plan (2019-2025)[20]. Research needs[21] include advancing scientific understanding of OAH, including biological and chemical monitoring and socio-economic vulnerability assessments, reducing causes of OAH, and creating resilience to restore, protect, and sustain vulnerable habitats and species.

Plenary Discussion: Stakeholder Needs

The discussion that followed the panel presentations highlighted many overarching needs. Advancing scientific understanding of HABs and OA through research and monitoring is necessary but not sufficient. Strategies to reduce causes and impacts of these stressors are also needed. In some regions, HABs and OA may be symptoms of a more complex environmental management issue. Managers and scientists should seek opportunities to discuss local contributions (e.g., fertilizer use, land use, runoff control) as well as large-scale global drivers. Holistic solutions are necessary, and support will be required to foster collaborations among the science community, shellfisheries, and other stakeholder communities.

Sustained monitoring efforts will be required, including new ways to monitor biology through molecular methods. A shared toolkit of biological indicators using molecular methods would be helpful. Volunteer monitoring is also essential; these communities are well positioned to collect data. Community based monitoring networks have continued during the COVID pandemic when other state-based programs have had to shut down. Instrumentation at many aquaculture sites has continued to run through this time as well. In bridging OA-HAB monitoring, it is worth strengthening the partnerships with stakeholders who provide key monitoring assets. To make

[17] https://www.dfw.state.or.us/
[18] http://www.nanoos.org/products/habs/forecasts/bulletins.php
[19] https://www.oregonocean.info/index.php/ocean-acidification
[20] https://www.oregonocean.info/index.php/ocean-documents/oah-hypox/oah-action-plan-2019-2025/1958-8-19-19-oah-action-plan-d9/file
[21] https://www.oregonocean.info/index.php/ocean-documents/oah-hypox/oah-action-plan-2019-2025/1962-8-20-19-research-needs-d8/file

those efforts most effective, standardized indicators and training programs should be implemented, while allowing each stakeholder the autonomy to collect their own data given they have the best understanding of local and cultural needs and challenges. Autonomous and remote methodologies are also key to sustaining observations over the long term. Blending fieldwork with remote sensing methods and modeling is a very powerful way to address certain monitoring challenges.

There was also a discussion about NOAA's definitions of HABs and OA. The definitions used during the workshop are provided at the beginning of this report (p. 9). NOAA funds research on all HABs affecting marine and Great Lakes ecosystems, including those that produce toxins and have other impacts. NOAA does not fund research on the direct health impacts of toxins on humans.

Participants then virtually dispersed into regional breakout groups for the Great Lakes, East Coast, Gulf of Mexico, West Coast/California Current Ecosystem, and Alaska. The goal of the first breakout session was to identify 3-5 informational gaps or research needs that were considered most important for each region.

Identifying informational gaps and needs: Regional breakout groups

Regional breakout summaries are available in Appendix 3. After the breakout sessions concluded, participants convened in a plenary to report out on the major research priorities coming from each region, which are listed below.

Great Lakes

- Examine cyanobacteria strains specific to the Great Lakes, but also use natural communities for multi-stressor experiments combining carbonate chemistry, eutrophication and other environmental variables.
- Extend temporal and spatial coverage for multiple inorganic carbon parameters needed.
  - YSI pH sensors lack precision and other carbonate parameters required.
  - Winter data are especially lacking.
- Advance understanding of interactions within the food web, especially the role of zebra mussels which has not yet been examined.
- Investigate the effects of overwintering and pH on bloom initiation.
- Investigate the role of tributaries as a source of local variations in carbon inputs, nutrient inputs and cyano-HAB inoculation.
- Identify causes of increases in benthic algae, including *Cladophora* and toxic cyanobacteria; carbonate chemistry changes along with other stressors may be a factor.

East Coast

- Conduct multi-stressor experiments utilizing best practices.
- Tease out the relative importance of local and climate driven stressors and the biological

feedbacks among them including temperature, nutrient cycling, storms, land-use, hypoxia and organic carbon increase.

- Understand drivers of HABs and OA on varied time and spatial scales, e.g., understand what drives a bloom before it happens. Multiple ways to monitor a system will be required for full understanding of drivers, as well as models that can be scaled up in time and space and sensitivity testing to ensure those models are robust.
- Implement monitoring efforts that meet stakeholder needs. Given the large variety of stressors, local or regional stakeholder needs should determine what should be monitored, how, and when?
    - What should be monitored to improve models? There is a need to fully characterize the carbonate system. Algorithm development for HABs, attenuation depth, turbidity, and other parameters are important for both monitoring and modeling.
    - Stakeholder input is needed to prioritize data collection for monitoring and other issues. What are the thresholds of concern? These may differ by location.
- Measure trophic interactions among all plankton members (including mixotrophy), and energy flow throughout the system.
- Identify decision points where algal bloom activity and toxin intersects with human management options.

Gulf of Mexico

- Conduct multi-stressor studies (field and lab based) that look at the impact of not only OA and HABs but the other relevant stressors in the GOM on both individuals and communities.
- Increase monitoring for both OA and HABs.
- Understand the linkages and connectivity of the estuaries to the coast to the open ocean to identify drivers of both OA and HABs.
- Increase citizen science and stakeholder engagement to increase knowledge and monitoring of these issues in the region.
- Centralize data submission and access.
- Identify local solutions for HABs and OA.

West Coast / California Current Ecosystem

- Parameterize models with more coordinated experiments (in the lab and via natural experiments).
- Take an ecological approach to interaction of HABs, OA, and other changing ocean conditions (i.e., impacts of grazers, competition, etc.).
- Mine and analyze existing data, model output, and data streams.
- Couple and downscale ocean-estuary systems to understand exchange of HABs and OAH vs. autochthonous HAB and OAH development in estuaries and food web impacts in

enclosed areas.
- Link human dimensions to research (i.e., economic impacts, human health).
- Effectively communicate and deliver products into the hands of people. This was identified as a short-term goal, as many data products currently exist in this region.
- Consider a variety of HABs, those that affect humans and those that affect non-human species (i.e., important shellfish).

Alaska

- Integrate/overlay new information for community vulnerability for local groups/industries for HABs/OA/climate variability. This would integrate data from more recent coastal environmental and species sensitivity to OA, and would be geared towards information for fishermen, oyster farmers, subsistence harvesters, and state agency managers.
- Create statewide HAB monitoring plan, prioritizing western Alaska, Bering Strait, and North Slope communities. Requirements include a data management plan and standardized QA/QC methods.
- Develop robust saxitoxin testing, including effective field test kits.
- Aggregate/integrate HAB and OA data into current research efforts, continuous monitoring, and community sampling efforts to ensure data are combined, interpreted, and published where possible.
- Develop information dashboards and risk assessment tools and ensure sustained service over time.
- Collect continuous high-temporal resolution measurements to understand relationships between temperature, salinity, carbonate chemistry and HABs (i.e., shore station observations from Burke-o-lators and IFCBs at Auke Bay Lab and Aluutiq Pride Shellfish Hatchery).
- Add ecosystem monitoring buoys in a few sites (Sitka, Prince William Sound, and Kachemak Bay).
- Leverage community monitoring to build information on biogeochemical relationships over time across multiple areas (e.g., collecting phytoplankton samples with known water volume, temperature and salinity and using qPCR to analyze for cell abundance).
- Observe and/or model temperature, salinity and CO_2 parameters at depth (for crab, groundfish, etc.). Evaluate existing observations (which are very limited) for utility. Identify common research gaps.

Common Information Gaps and Needs Across Regions

Some commonalities emerged as key needs across regions:

1. Investigation of OA impacts to HABs in both lab and natural communities.
2. Evaluate attribution of HAB events and toxicity to OA (including the different carbonate system parameters) vs. other stressors.

3. Include locally important HABs, and those that produce both human impacts via toxicity and impacts to environmental/economic resources (e.g., shellfish and fish-killing HABs).
4. Understand multi-stressor impacts and interactions to multiple species and life stages, along with community and food web interactions via lab, mesocosm, and field experiments.
5. Identify linkages among the open ocean, estuaries, watersheds, and specifically the role of tributaries in delivering nutrients and controlling carbonate chemistry.
6. Incorporate HAB and OA data into modeling efforts for prediction, attribution, and sensitivity testing.
7. Incorporate stakeholder input into monitoring programs and leverage assets to measure OA and HAB parameters simultaneously.
    a. Mine existing data and coordinate among monitoring systems.
    b. Include data management in monitoring efforts to foster integration and data product development.
    c. Make data available in near real time for integration and synthesis.
8. Communicate and engage with stakeholders/affected groups to deliver information and identify needs.

Plenary discussion: Regional Gaps and Needs

Discussion brought out some recurring themes. Participants were interested in appropriate time scales for modeling. Five-year projections can give growers and other fishers and managers a sense of what is to come, but seasonal forecasts are very important. Given the focus on OA and the connection between HABs and climate change, there is a need to start thinking about long term forecasting on decadal scales for comparison with the Coupled Model Intercomparison Project (CMIP)[22] modeling efforts. There are challenges with these timescales. Global models are hard to apply in coastal systems on a decadal timescale for the parameters of interest. Downscaling issues are abundant. The 5-8 year window is also very hard for model predictions because of inter-annual variability. On the other hand, the 20-50 year timescale is much more predictable, especially for OA, but perhaps more limited for immediate application.

A discussion on the definitions of acidification in the coastal ocean, basification, and coastal acidification highlighted the different definitions the HAB and OA community have for these terms. After much back and forth it was concluded that all participants were referring to carbonate chemistry. This led to another definition discussion that highlighted the need to be careful about differentiating shifts in carbonate chemistry driven by anthropogenic CO_2 uptake (OA) and those that are modified by coastal processes (e.g., land use changes, nutrient inputs, hydrologic change, river alkalinity trends, etc.) referred to as coastal acidification. While this nuance is important, for the purpose of this workshop report the term “OA” includes both ocean and coastal acidification as previously defined.

[22] https://www.gfdl.noaa.gov/cmip/

Monitoring was again a key theme in the plenary discussion. There is likely more monitoring than participants are aware of, with opportunities to add more OA or HAB specific sensors/ capabilities to existing infrastructure. Linking ocean and coastal monitoring could help to define the influence of urban estuary outflows on outer coast HAB development.

Finally, there was keen interest in standardization of experimental techniques, including best practices and a community of practice well-equipped to carry these out. This was the overarching aim of a decision support tool developed by the Scientific Committee on Oceanic Research (SCOR) Working Group 149[23] and the European Commission's "Guide to best practices for ocean acidification research and data reporting"[24].

Prediction and Forecasting – Looking Ahead (Day 3)

Day 3 began with lightning talks on modeling and forecasting from different regions.

Modeling, Forecasting, and Research Products: Lightning Talks and Discussion

"State of regional Forecasting of Ocean Acidification Variables in the US and thoughts on extending those to include HABs"

Samantha Siedlecki (University of Connecticut) showed that most regions have or are developing models with forecasting on some timescales, with seasonal/interannual to decadal likely being the weakest. Skill measures need to be process-oriented to ensure forecast models are getting it right for the right reasons. This will be facilitated by co-located environmental and biological observations. Model evaluations need to be publicly accessible to build trust with the community, and uncertainty measures need to consider the historical skill of the model - this is still a developing research area. Overall, the habitat of HABs at decision points are important to consider when developing a forecast system – this will be both regionally and species specific.

Some key questions for modeling OA and HABs:

- What habitats should forecasts include for HABs in each region?
- What is the current capability for OA forecasting?
- How good is 'good enough' in terms of skill for forecasts?
- How is uncertainty currently conveyed? Can we do better?
- What do we need to simulate to properly support OA-HAB forecasting?

The grand challenge of modeling is attribution of OA in HAB dynamics – at both the event scale and longer term. This was a theme among regions as HABs have many potential drivers, and OA

[23] https://scor149-ocean.com/
[24] https://www.iaea.org/sites/default/files/18/06/oa-guide-to-best-practices.pdf

and HABs have interacting drivers. Attribution needs to be expanded to include indirect effects of OA on HABs in addition to direct; indirect meaning impacts to community composition, ecosystem pressures, and upper trophic level physiology in addition to the direct effects influencing generation of toxin and growth rates of the HABs.

Some differences among regions are community composition and specific regional ecological challenges.

"Stakeholder Requirements for HAB Forecast Models in the California Current System (Focus on California)"

Clarissa Anderson (Southern California Coastal Ocean Observing System, SCCOOS)[25] introduced the IOOS Regional Associations on the West Coast (SCCOOS, CeNCOOS[26], and NANOOS[27]) and their role in serving observations, models, and products to create a consistent national capability that addresses the needs of diverse local stakeholders across many sectors. They are now evaluating the many ecological forecast models for OA, hypoxia, and HABs on the West Coast in relation to the emerging Operational West Coast Ocean Forecast System (WCOFS)[28]. Stakeholder needs and requirements are key to this model development and engaging with stakeholders has been a concentrated focus. The California HAB Bulletin[29] aggregates data sets and model output to provide resource managers with a quick outlook of recent HABs in coastal California. Current efforts aim to expand the model domain into a West Coast-wide forecast framework, to finer spatial scales, and food web impact predictions. Clarissa Anderson also mentioned efforts to better understand the effects of land management actions on HABs in California[30], and the potential for this work to improve forecasting of domoic acid events.

Grand challenges for California Current forecasting are:

- Accurate nearshore forecasts remain elusive (aquaculture-scale). Shellfish growers sample on commercially relevant time scales, in collaboration with public health departments, which limits the utility of these data in predictive models.
- Better understanding internal variability and nonlinear dynamics for seasonal forecasts of HABs for fisheries (3-6 months lead times) – which part is deterministic, which part random?
- Predicting offshore bloom initiation relative to nearshore dynamics.
- Predicting multi-stressor interactions for ecosystem indicator assessment (e.g., HABs and OAH and development of multivariate bioindicators).

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25 https://sccoos.org/
26 https://www.cencoos.org/
27 http://www.nanoos.org/
28 https://tidesandcurrents.noaa.gov/ofs/dev/wcofs/wcofs_info.html
29 https://sccoos.org/california-hab-bulletin/
30 https://coastalscience.noaa.gov/project/can-management-actions-on-land-influence-harmful-algal-toxins-in-the-california-current/

Clarissa Anderson was struck by the overarching theme in most presentations of the need for more observations and models that directly address multi-stressor interactions. These observations and instrument placement should be optimized to examine more than one process. She encouraged participants to think deeply about ways to convey multivariate information to the public and decision-makers and build observational systems with this in mind.

"HABs in the Pacific Northwest: health, economy, ecology, culture"

Jan Newton, (Northwest Association of Networked Ocean Observing Systems, NANOOS)[31], showed how oceanographic observations led to understanding HAB dynamics in the Pacific Northwest (PNW), which enabled the capability to make forecasts. The PNW HAB Bulletin[32] describes levels of forecasted risk for *Pseudo-nitzschia* blooms. Tailored short-term forecasts enable effective management action (i.e., the PNW HAB Bulletin is used by state and tribal resource managers). Monitoring data are used for model validation.

Grand challenges for these forecasts are:
- Sustaining integrated observations and forecast modeling.
- More widely demonstrating efficacy to managers, public health, and economy.
- More widely articulating why and how this matters to coastal tribal culture and sustainability.
- Increasing scientific understanding of OA-HAB linkage, especially in context with other stressors (e.g., temperature, hypoxia).

Common themes across regions include recognition that HABs are affected by local dynamics. Therefore, sustaining diverse observations, integrating observations with models, and sustaining communication and application to the community stakeholders are paramount. Multiple stressors are involved, so the nexus between OA and HABs needs further research, especially in the context of temperature increases, given the increasing occurrence of marine heat waves. The role of tribal culture and treaty rights is critical in the PNW. Many questions about social justice have increased in importance in this region.

"Every Beach, Every Day: GoMex HAB Forecasting V2"

Barbara Kirkpatrick (Gulf of Mexico Coastal Ocean Observing System, GCOOS)[33] discussed how *Karenia brevis* toxic aerosols on Florida's west coast can cause respiratory illness in people. *Karenia* blooms are patchy; one beach may be heavily impacted and another beach a short distance away may have almost no impacts. There is a need to improve the spatial and temporal reporting of bloom impacts. This will entail improved remote sensing, increased sampling at beaches and ultimately expand the Red Tide Respiratory Forecast[34], a beach-level risk forecast

[31] http://www.nanoos.org/
[32] http://www.nanoos.org/products/habs/forecasts/home.php
[33] https://gcoos.org/about-us/
[34] https://habforecast.gcoos.org/

activated during red tide conditions that tells beachgoers what red tide impacts are expected to be at individual beaches at different times of the day.

Grand challenges associated with forecasting HABs in the Gulf of Mexico include:

- Increasing and sustaining observations.
- Using image analysis and/or artificial intelligence for rapid outputs.
- Development of automated forecasts (i.e., machine to machine).
- Creating user friendly and platform diagnostic products.
- Understanding how OA and HAB interactions may cause changes in toxicity.

Similarities across regions include the need for sustained observations, platforms and sensors that can address multiple stressors, increased spatial and temporal observations and sustained support of forecast products such as the Florida HAB Trajectory Forecast[35] and the Florida HAB Seasonal Prediction[36].

After these presentations, the regional breakout groups reconvened virtually. The goal of this discussion was to identify research products, match products with stakeholder needs identified in the stakeholder panel and link the research themes identified in the first breakout with products brought up during the discussion. Examples of research products to keep in mind for the breakouts:

- Forecasts – what is likely to happen in the future (short-term and long-term)?
- Assessments or ecosystem status reports – a snapshot in time, what is the situation now?
- Trend analyses – are things getting worse?
- Vulnerability assessments – where and what will be most affected?
- Attribution – what factors are driving HABs?
- Adaptation and management – what actions could be taken to help, and how much difference will they make?
- Guidance for harvesting or culturing – when, where, and where not?
- Alerts or warnings of episodic events – when and where is it unsafe to harvest?
- Graphics or conceptual models – how can we illustrate how parts of a system interact?

Regional breakout session summaries are available in Appendix 4.

Identifying Research Products

After the breakout discussions, participants reconvened in plenary to hear the results from each regional breakout. Priorities for products from each region are listed below.

[35] http://ocgweb.marine.usf.edu/hab_tracking/wfcom_hab.html
[36] http://ocgweb.marine.usf.edu/~liu/hab_seasonal.html

Great Lakes Research Products

- Dashboards with real time data that display:
    - Different levels of information for different stakeholder groups
    - Thresholds and warnings
- Predictive models and outputs tailored to different stakeholder groups with the following information and timeframes:
    - HABs – Seasonal and Daily
    - Acidification/CO2 limitation – Daily
    - Interaction between HABs and hypoxia
- Scenario models to predict how HABs will change in response to expected changes in OA and eutrophication in the future.
- Scenario models of OA and benthic algae (including *Cladophora* and toxic benthic cyanobacteria) to see if there is an interaction and how it will change in the future.

East Coast Research Products

- Maps of susceptibility, hot spots, superimposed with shellfish areas.
- Advance warnings of events, particle tracking.
- Likelihood of bloom based on prior conditions or watershed management practices.
- Risk assessment, combine with adaptation and mitigation strategies.
- Habitat suitability model outputs.
- Advice to monitoring programs, where, when and what they should monitor to understand combined effects of HABs and OA.

Gulf of Mexico Research Products

- HAB and OA predictions.
- Gulf-wide spatial vulnerability assessment for both OA and HABs.
- Maps of existing monitoring accompanied by easy data access.

West Coast / California Current Ecosystem Research Products

- Bulletins of real time data that highlight OA-HAB overlap and evaluate conditions for HABs, OA, hypoxia, and temperature.
    - Regional-level information that captures larger-scale oceanographic processes.
- Statistical/empirical products to predict impacts of HABs and OA at relevant time scales (e.g., 3 day, seasonal, etc.).
- Interpreted data and model output for managers (i.e., NOAA Climate Prediction Center's El Nino Watch bulletin)[37], including information on biological impacts.
    - Source attribution of HAB and OA events.
    - Integrated metric of duration and severity of OA-HAB event.

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[37] https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/ensodisc.shtml

- Methods to evaluate resource recovery and the efficacy of other "living solutions" (e.g., habitat restoration and macroalgal farming).
- Rapid response mechanisms to (unusual) events, including incident response and communication.

Alaska Research Products

- Updated vulnerability assessments for HABs and OA.
    - The need for parallel vs. independent timelines is something to be considered as it relates to monitoring and data collection.
    - Community-focused vulnerability assessment that considers OA, HABs, and climate change as multi-stressors.
- Identify next steps, gaps, and improvements using output from the vulnerability assessments and current data available (i.e., testing new technology capabilities/utility, coupling new sensors (e.g., IFCBs) with existing equipment to provide the mechanistic information for factors driving blooms to apply to distributed community sampling)
- Statewide HAB Monitoring and Response Plan that would address the current needs of Western and Northern Alaska, for example.
- Monitoring, collection, and QA/QC Protocols and standards that are accessible.
- Integrated data portal to share data for both real-time needs and to help in developing forecast and risk assessment products going forward.
- Information dashboards and risk assessment tools with sustained service delivery over time.
- An outreach document to summarize monitoring and analytical techniques for general OA-HAB audiences.

Common Research Products Across Regions

Some commonalities emerged from discussions of products in different regions including:

1. Vulnerability and/or risk assessments of combined OA-HAB impacts.
2. Maps of OA-HAB "hot spots" that are both static and forward-looking and overlap resource maps with monitoring assets.
3. Dashboards offering data access with both OA and HAB parameters.
4. Identifying thresholds and communicating warnings and/or bulletins.
5. Evaluation of recovery/mitigation strategies including scenario analyses of management actions.
6. Coordinated monitoring plans and guidance for multi-stressor monitoring (e.g., best practices and how to optimize existing monitoring assets).
7. Standardizing data collection methods and data management to facilitate collaboration in the research communities.

8. Integrate data from multiple sources (e.g., research, monitoring, resource management agencies, and citizen scientists).

Plenary Discussion: Research Products

Ensuing discussion brought up several points regarding data access, species level information on HABs, the complexity to include in models, what to include in a forecast, and how to depict risks and uncertainties in models and forecasts.

Having access to data is key, but data is only as good as how you collect it. Differences in protocols can lead to differences in observation, so it will be important to have standard methodologies (similar to protocols.io)[38]. A recent workshop[39] discussed method development and technology testing, and the IOOS Regional Associations (RAs) are working to track protocols in metadata linked to all their datasets in ERDDAP[40]. It will be important to report uncertainty about the data as well as the data themselves. The NOAA National Marine Sanctuary Programs rank confidence in their data used in condition reports with a five-bar standard[41]. Communicating confidence in data to the public in an understandable way remains a challenge.

Any data collected under a NOAA program is mandated to be publicly available. However, some stakeholders, such as aquaculture operations, can be very hesitant to collaborate because of a fear that toxin data will be released and impact their sales. This is true of some states as well, who are concerned about the impact to their seafood sales or tourism.

It will be important to have data integrated in one place that pulls together various types of information. The Alaska Harmful Algal Bloom Network[42] is one example of this kind of data integration. The California HAB Bulletin[43] recently incorporated OA, hypoxia and HAB data together. Another SCCOOS project[44] integrates data for Marine Protected Areas (MPAs) by creating portals for users to visualize Seascapes[45] maps, HAB and OA predictions, and fisheries habitat models in one place. This will allow multivariate exploration for MPAs but could serve many other purposes, such as the development of dashboards for particular locations, creation of model products for particular spots, and/or direct higher resolution observations for specific needs.

The need to assess more than just chlorophyll *a* in models and provide species and toxin-specific data was highlighted. This could be done through monitoring different algal divisions in the

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[38] http://protocols.io/
[39] https://www.frontiersin.org/articles/10.3389/fmars.2019.00399/full
[40] http://erddap.sensors.ioos.us/erddap/index.html
[41] https://sanctuaries.noaa.gov/science/condition/faq.html
[42] https://aoos.org/alaska-hab-network/
[43] https://sccoos.org/california-hab-bulletin/red-tide/
[44] https://www.cencoos.org/integrating-observing-monitoring/
[45] https://www.salttraceability.org/seascape-map/

field, remote sensing, and using species or division level information in modeling. IFCBs and ESPs can do species identifications, but are beyond the scope of many monitoring programs, and multispectral fluorometer[46] or remote sensing approaches don't allow for algal identification (i.e., HAB vs. non-HAB species). Progress made using molecular approaches is underutilized. Incorporating these approaches comes with a formidable challenge, but these methods are the next step in providing rapid warning tools. Ultimately, many fundamental HAB and OA-HAB knowledge gaps are still in need of actual experimentation to elucidate HAB physiology and ecology and how those change under different conditions (e.g., pH).

It is possible to identify HABs using standard methods and insert them into a particle tracking or "habitat envelope" model to get an estimate of transport, but that doesn't get to mechanism (vs. correlation) in changes in communities, toxins, etc. Looking at correlations can be helpful if a relationship is revealed that can be tested in another location or in the lab to determine how universal that relationship may be. In many places the relationship between OA, hypoxia, and HABs is not well known, but that is likely because they are treated separately. There is a good understanding of coastal carbonate chemistry conditions in some locations (e.g., data can be accessed from OCADS[47], GLODAP[48], and SOCAT[49] databases), on which HAB observations could be overlaid (magnitude and trends) to discern if there are detectable correlations. ESP-type instruments in select locations could augment current robust monitoring efforts. This could provide a better understanding of mechanisms and relationships and highlight needed components of an ongoing monitoring system.

There is a question of how current HAB model and forecast products would differ if they included OA. OA will likely play different and equally important roles in bloom formation, toxicity, and bloom impacts and will have unique effects on different parts of the phytoplankton community and food web. These need to be captured in data products and associated modeling, but the amount of information and complexity that should be included in a forecast, and the levels of community complexity that can be handled in most modeling frameworks is not clear. Currently, many ecosystem models represent moderate complexity but can incorporate quite a few phytoplankton and zooplankton state variables. But understanding how much complexity is good enough could inform a shared level of complexity that can work within the modeling frameworks while also providing important ecological insights.

Equally important is providing stakeholders with enough information for understanding. More unified model output and data integration will help with this but it is challenging to know what to include and omit in a multi-stressor world. Assessing stakeholder needs and engaging them in the modeling discussions is important, while working to avoid stakeholder fatigue. Meeting

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[46] http://www.act-us.info/evaluations.php#FLO2

[47] https://www.ncei.noaa.gov/access/ocean-carbon-data-system/

[48] https://www.pmel.noaa.gov/co2/story/GLODAP

[49] https://www.pmel.noaa.gov/co2/story/SOCAT

people where they are and leveraging their existing channels and networks will enhance this back-and-forth discussion on modeling and forecasting needs.

In relaying model and forecast results to managers and other stakeholders, several different concepts need to be differentiated. Hazards describe the problem and who may be affected, vulnerability shows how likely a hazard will be to affect a population or particular geographic area, and risk overlaps vulnerability and hazard to show potential impacts. As an example, the Southern California Coastal and Ocean Observing System (SCCOOS)[50] uses the word risk almost exclusively and uses the CA HAB Bulletin to convey risk relative to a suite of resources that people care about.

Uncertainty is usually model skill or the spread across a forecast resulting from many possible futures, yet model uncertainty metrics do not mean much for most managers. To build trust with managers concerning model output, they must see how well it works for them on a routine basis by comparing it with all available observations. That way they can calibrate what 70% probability means for their pixel of interest over a large dynamic range (seasonal to interannual variability). Shellfish managers are driven by the regulations, and shellfish closures are based on toxin levels in shellfish. So, the gold standard of information for this group would be predicting toxin levels in shellfish with sufficient accuracy that will help them with managing shellfish. However, this has been the hardest stakeholder group for modeling products because models don't have this level of accuracy or granularity yet.

Summary of Workshop Results

The workshop concluded with some poll questions, a summary, and next steps. Future work needs to address OA as a stressor and interactions with other stressors. Basic information is needed on both HABs and OA in isolation, but co-monitoring of OA and HABs together along with other environmental parameters is needed to tease out potential relationships and construct meaningful experiments. OA-HAB experiments should consider all carbonate system parameters, not just pH. Continued lab experimentation is necessary, but field research is critical to extend the understanding of natural communities and ocean conditions. Lab and field studies should target both toxin producing HABs that affect human health and HABs that directly affect important marine resources (e.g., shellfish aquaculture). These studies need to be pursued at many levels, such as species, population, community, and food web. An ecosystem context should be adopted that seeks linkages among open ocean, estuaries, and watershed processes, especially the role of tributaries in delivering nutrients, dissolved carbon, pH, and alkalinity.

Research products that will address cross-regional needs should incorporate:

- Modeling efforts for prediction, attribution, sensitivity testing.
- Providing advice to monitoring programs and leveraging monitoring assets to add OA and HAB parameters measured simultaneously.

[50] https://sccoos.org/

- Data management to foster integration.
- Data product development, while making data available in near real time for integration and synthesis.
- Communication and outreach efforts must be continued and enhanced, both as a delivery mechanism for research results and identification of the needs of stakeholders.

Some possible research products to aim for are vulnerability/risk assessments of combined OA-HAB impacts, maps and identification of "hot spots" (both static/current conditions and forward-looking), dashboards offering data access with both OA and HAB parameters, warnings and bulletins with identification of thresholds, evaluation of recovery/mitigation strategies, and scenario analyses of effects of management actions.

Most participants had very favorable reactions to the workshop, stating that they had learned more about OA-HAB science. It may be that cross-pollination between HAB and OA scientists is the best outcome of this workshop. The best minds and research approaches will be needed to tackle the complexities of OA-HAB interactions expressed during the workshop. The information presented over the course of the workshop will allow NOAA to craft a Request for Proposals that is realistic in terms of the state of the science, but also responsive to the needs of stakeholders. The OA-HAB community is at the cusp of new understanding of these important co-stressors.

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Appendix 1. Workshop Agenda

"Harmful Algal Bloom & Acidification: Defining a research agenda"

August 11-13, 2020
Virtually via Adobe Connect

Goal: Identify a few tractable OA-HAB research priorities for potential inclusion in an upcoming Request for Proposals

Objectives: (1) Identify gaps in OA-HAB research, (2) Identify potential useful research products that incorporate OA-HAB interactions

Day 1 Acidification & Harmful Algal Blooms Across the US: Lightning Talks and Panel Discussion

12:00-12:30pm ET – Welcoming remarks and overview

- Dwight Gledhill, NOAA Ocean Acidification Program
- David Kidwell, NOAA National Centers for Coastal Ocean Science
- Jennifer Mintz, NOAA Ocean Acidification Program

12:30-2:00pm ET – OA & HABs Across the US: Lightning Talks and Panel Discussion

- "HABs and ocean acidification: Additive, synergistic, antagonistic, or otherwise?," Christopher Gobler, Stony Brook University[51]
- "Acidification, eutrophication, and HABS in estuarine waters: What do long-term data tell us?, Hans Paerl, University of North Carolina[52]
- "Synergies between OAH and HAB networks: California as a case study," Raphael Kudela, University of California Santa Cruz[53]
- "Alaska Ocean Acidification and HABs: Networking and coastal variability," Kris Holderied, NOAA National Centers for Coastal Ocean Science[54]
- "A marginal sea of variability in ocean acidification and harmful algal blooms in the Gulf of Mexico," Beth Stauffer, University of Louisiana at Lafayette[55]
- "Acidification and harmful algal blooms in the Great Lakes," Reagan Errera, Great Lakes Environmental Research Laboratory[56]

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[51] https://www.youtube.com/watch?v=h6mFw_LyIgI
[52] https://www.youtube.com/watch?v=ySHuovuI9-k
[53] https://www.youtube.com/watch?v=H5jFA-IeKTY
[54] https://www.youtube.com/watch?v=4t-HmaEq8B8
[55] https://www.youtube.com/watch?v=mJYFp7GnBhs
[56] https://www.youtube.com/watch?v=PaZnSdz7UlE

- "Effects of Ocean Acidification on HABs: A review of what we do and don't know," Melissa McCutcheon, Texas A&M Corpus Christi[57]

2:00-2:15pm ET – Break

2:15-2:30pm ET – Mya Sharpe – Snapshot of OA & HABs Across the US

2:30-2:55pm ET – Setting up for the next 2 days

2:55-3:00pm ET – Wrap up

3:00pm ET – **Adjourn**

Day 2 Acidification & Harmful Algal Blooms: Stakeholder Needs

12:00-12:15pm ET – Welcoming remarks

12:30-1:45pm ET – Panel discussion: Stakeholder Needs and Perspectives

- Caren Braby, Oregon Department of Fish and Wildlife
- Bill Dewey, Taylor Shellfish
- Molly McCammon , Alaska Ocean Observing System
- Chris Kinkade, National Estuarine Research Reserve System
- Steve Gittings, Office of National Marine Sanctuaries
- Martha Sutula, Southern California Coastal Water Research Project
- Meredith White, Mook Sea Farm

1:45-2:00pm ET – Break

2:00pm- 3:15pm ET – Breakout Discussion: Identify regional information gaps and needs

3:15pm- 3:30pm ET – Break

3:30-4:45pm ET – Identifying regional information gaps and needs research gaps: Report outs and plenary discussion

4:45pm ET – Wrap up

5:00pm ET – **Adjourn**

Day 3 Acidification & Harmful Algal Blooms: Research Products

12:00-12:15pm ET – Welcome

12:15-1:00pm ET – Modeling, Forecasting and Research Products[58]: Lightning Talks and Discussion

- Clarissa Anderson, Southern California Coastal Ocean Observing System, University of California San Diego
- Barbara Kirkpatrick, Gulf of Mexico Coastal Ocean Observing System
- Jan Newton, Northwest Association of Networked Ocean Observing Systems, University of Washington

[57] https://www.youtube.com/watch?v=Qx9Qfzj1c5g
[58] https://www.youtube.com/watch?v=2k3Sp64L7ts

- Samantha Siedlecki, University of Connecticut

1:00-1:15pm ET – Break

1:15 -2:30pm ET – Breakout Discussion: Identifying regional research products

2:30-2:45pm ET – Break

2:30- 4:15pm ET – A summary of research gaps and products: Report outs and plenary discussion

4:15-4:30pm ET – Break

4:30- 4:45pm ET – Wrap up and thanks!

4:45pm ET – **Adjourn**

Appendix 2. Participant List

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Appendix 3. Regional Breakout Summaries: Identifying Information Gaps and Needs (Day 2)

Great Lakes Breakout: Information Gaps and Needs

The breakout began with a summary from the Great Lakes webinar by Reagan Errera that the facilitator thought would be helpful to generate priorities. These included:

- High frequency data for multiple inorganic carbon parameters in more locations across the Great Lakes
- Further understanding of synergistic effects between temperature, nutrients, and DIC system within the Great Lakes
- Impacts to the food web
    - Specifically impacts to invasive mussels
- Examine strains specific to Great Lakes but also use of natural communities
    - Impact on toxin production and secondary metabolites
    - Impact on growth and competition

The moderator started it off by saying it was not enough to say we need more monitoring. We need to be more specific about what parameters, when and where they need to be measured, to fill what gaps.

One of the first issues that came up was the need for higher frequency and higher quality measurements of OA parameters, at least pCO_2 and pH, especially in the wintertime. This led to the final list that was presented, which included all of the ancillary measurements that were needed. pH and oxygen are important for water quality managers.

There was a long discussion of the role of toxins and the role of the microbiome in toxin production. That led to discussions about the kinds of growth experiments that needed to be conducted that could look at the interaction between HABs and acidification. These need to be done both on culture studies with strains specific to the Great Lakes but also in natural communities from the Great Lakes. Experiments need to be conducted as a matrix with multiple parameters, looking at temperature, DIC, and nutrients. Nutrients need to include many forms of nitrogen and phosphorus in different ratios and also include micronutrients, such as iron, manganese, cobalt and zinc.

The question arose whether there was an interaction between HABs and OA in the Great Lakes. Finding the signal is difficult. It was felt that the answer was unknown because the YSI pH sensors in use did not have sufficient precision to see changes, there were no sensors out in the winter and the spatial and temporal coverage was inadequate. The differences between the Great Lakes were touched on. Also, it was pointed out that we should not use the term Ocean Acidification in the Great Lakes because they are not oceans and, sometimes, during big blooms, basification occurs. No consensus was reached on a single term, but carbonate chemistry seemed to be more accurate.

The role of rivers in supplying not just nutrients, but carbon in various forms, was discussed. It is not just the main rivers, but also the smaller rivers that can have a local influence. The interactions of watersheds with the nearshore could explain the spikes observed near tributaries. Further, it is not possible at present to make carbon budgets for the Great Lakes.

The interactions between HABs, acidification, and impacts on higher trophic levels could be quite complicated. For example, Lake Superior is less impacted by invasive mussels and is more acidic. Basification, which occurs in Lake Erie during cyanoHAB blooms, may favor invasive mussels. Thus, instead of invasive mussels causing CyanoHAB blooms, it may be that CyanoHAB blooms result in more invasive mussels. Participants thought that mussels pulled significant amounts of carbon out of the system, but that has not been adequately investigated. The interaction of native mussels, HABs, and acidification was not known, but was considered to be a good question.

The issue of what happens in the winter came up multiple times. Some under-ice measurements indicate that winter blooms can be as much as 60% of spring blooms. What is the role of *Microcystis* overwintering in the sediments for the initiation of the spring bloom as opposed to coming in from earlier blooms in the tributaries? Early in winter microcystin is observed, but it is not living. How is it related to blooms?

After a lively general discussion, the group worked to produce the following final priorities for presentation to the plenary session:

Examine the impact of changes in carbonate chemistry in strains specific to Great Lakes but also on natural communities on the following:

- Impact on toxin production and secondary metabolites
- Impact on growth and competition
- Episodic events as well as steady state
- Transcriptomics, metabolomics, and metagenomics during bloom succession under acidification and basification
- Factor in cHABs toxin production
- *Microcystis* physiology
- Phycosphere in non-axenic cultures and natural populations
- Test hypothesis that scum formation results from C limitation

High frequency data for multiple inorganic carbon parameters in more locations across the Great Lakes

- Data quality issue. pH data from YSI sensors not great (precision 0.2). Need sensors with precision of 0.002.
- Great spatial and temporal variability, so need greater spatial and temporal coverage of sensors, especially winter coverage
- Need all carbonate sensor, not just pH (high quality), pCO_2 mostly likely addition

- Temperature, macronutrients (quantity, form, ratios) needed to understand processes, micronutrients (Fe, Zn, Mo, Mn, Co)
- Oxygen sensors, especially winter
- Winter ice cover and under-ice solar radiation (quantity and quality)
- Validate satellite products so they can better estimate conditions in lake

Interactions with the food web

- Specifically invasive mussels--removes carbonate
- Hypoxia impacts on higher trophic levels
- Botulism from Cladophora
- Understanding role of nutrient recycling
- Need to understand community interactions. Includes algae and higher trophic levels and how they affect each other and can either limit or facilitate blooms

Bloom Initiation

- Overwintering and pH
- Sediments, tributaries, and lakes as innoculla

Role of tributaries needs to be investigated with regard to

- Control pH
- Nutrient inputs (accurate measurements of loads needed; miss episodic events)
- HAB inputs--source in spring?
- Lack measurements of carbon inputs--means can't do carbon budgets

East Coast Breakout: Information Gaps and Needs

The end goal of the first breakout session was to come up with 3-5 research priorities that we considered to be the most important for the East Coast region. The breakout began with a summary from some of the webinars that the facilitator thought would be helpful to generate priorities. These included:

From Gobler:

- What are the precise duration and intensity of exposure of aquatic life to HABs and OA?
- How will the duration and intensity of HABs and OA change in future oceans?
- What are the consequences of environmentally realistic (today, future) levels of OA and HABs for aquatic life?
- When and for which HABs will OA matter (most)?

From Paerl:

- Nutrient driven eutrophication and algal blooms play important roles.
- Hydrologic forcing, including storm-driven N, P and C loading modulating algal blooms, pH, hypoxia.

- Storms and tropical cyclones impact air-water CO_2 exchange and pH directly. CO_2 outgassing from major events can account for a large % of CO_2 fixed. Positive feedback on climate (change)?
- Immediate Needs: Tools (e.g., remote sensing, continuous water quality monitoring) to capture events/impacts over relevant scales and adaptive nutrient management in response to climatic changes and extremes.

From McCutcheon:

- Continue filling in the gaps of the OA-HABs species-level investigations –missing taxa and in context with multiple stressors
- Broaden our understanding of the effects of OA on HAB species as they occur in full community assemblages
- Propose regionally specific water and land use management strategies based on evidence for coastal water quality outcomes, including reduced HABs and OA
- Needs:
    - Increased scientific understanding of OA-HAB linkage
    - Monitoring at temporal and spatial scales that matter
    - Species sensitivity research, in context with multiple stressors
    - Forecasting and risk/vulnerability assessment products

From Stauffer:

- Eutrophication-enhanced OA is a persistent feature in coastal/estuarine systems and may represent a different scenario for HABs than open ocean OA
- The need to integrate complexity in our research (i.e., communities, nutritional modes) must be matched with experimental approaches and hypotheses that can still generate important insights
- Single- or multi-species experiments need to be run on appropriate timescales.
- The Gulf of Mexico and other regions are severely lacking robust OA data outside of certain locations and seasons/years.

Discussion was opened to consider what was missing from this list. There was general agreement that ***for the East Coast, estuaries are a major area of focus and the multi-stressor aspect is key.*** Coastal areas are not experiencing the classical definition of ocean acidification (driven solely by absorption of atmospheric CO_2). Influences from the land mass at the land-water interface don't fit the classic definition of OA. What we are having to deal with is more complex. pH fluctuations over the course of a day are greater than what we will see in the open ocean in the next 100 yrs. For the purposes of any eventual FFO coming out of this workshop, making connections to management is important. These connections are more evident near the coast, so from the east coast perspective, the RFP should slant more towards coastal acidification than the classical OA definition.

There are a variety of stressors and processes important to consider:

- **Eutrophication**: We have to be focusing on eutrophication as a regionally important issue. A lot of talk has focused on eutrophication-enhanced OA but we also see blooms with high biomass that can drive up pH. That high pH causes phosphate to come out of the sediment. pH also has effects on (de)nitrification. How do acidification and basification alter nutrient cycling through different speciation of nutrients and alteration of nutrient cycle processes?
- **Hypoxia**: The critical triad is HAB-acidification-hypoxia. How do these three interact to change community structure and functioning? OA and hypoxia often occur together, and affect each other. We don't know how they play out in the ecosystem. Are fluctuations increasing due to land-based activities? In coastal waters, phytoplankton see large changes over a day, so would they be less susceptible to OA and hypoxia? Or are they at their physiological limit, and a small perturbation will push them over the edge?
- **OA as a multiple stressor**: A lot of the conversation has been focused on pH, but OA is a multi-stressor in and of itself. There is a difference in the evolution of the historical trends of the carbonate system variables. HABs and other resources can be affected directly by pH (*e.g.*, impacts on proton pumps). In a lot of coastal systems, alkalinity can be really informative. Aragonite saturation is important for calcifiers. But if you want a good pCO_2 number, you need to measure DIC or pH.
- **Timing of natural variability and events**: How can we document a bloom and the lag that happens between the causes that trigger blooms and observing blooms themselves? Temporal variability can be driven by biology and interact with more long term OA and climate drivers, land use changes, etc. How sensitive are shellfish to perturbations in those regimes? Are they closer to a threshold, or more resilient? Are there interactive effects of stressors? *We need a systematic monitoring system with co-location of environmental and biological data to incorporate variability.*
    - A monitoring framework must simultaneously capture HABs and OAH, water and biological parameters and local drivers. What are the minimal parameters that we should be collecting to also address HABs and hypoxia? Is there a basic framework that could be developed?
- **Estuarine mixing processes**: In estuaries, very different conditions exist between surface waters, bottom sediments and biology. How can we incorporate depth profiles into our monitoring and understanding? Salinity variability also affects HAB formation and OA. How can we de-convolve these multiple effects to understand the dynamics?
- **Ocean-estuarine interactions**: HABs in the Gulf of Maine are primarily generated offshore and then advected onshore. Hypoxia is generated more within estuaries. Where, when and how do these processes interact with resources? Where is the ocean signal important?
- **Storm impacts**: We have enhanced storms bringing nutrient-rich water and leading to "brownification". What will happen in a future with more storms associated with higher spates of rainfall and runoff?

- **Impacts to living resources**: We need to understand feedback among different stressors and how they impact things that we care about. Future conditions might generate another phytoplankton community that is not a preferred food source, beyond just a HAB bloom. For HABs, where does the toxin enter the food web? Because of mixotrophy, HABs are grazing on other phytoplankton that can be impacted by all the other stressors. That aspect is not well understood and likely important. We also need to consider commercial operations as well as natural systems - the connection between what is going on inside a hatchery *vs* outside the hatchery. And we need to consider animal health as well as human health impacts.
- **Water quality management**: What can we do today to improve water quality to set us up for less damage in the future? One of the most difficult challenges from a policy perspective is nonpoint-source pollution. If a mechanistic connection can be made from what is going on in the coastal zone to up-stream processes, it will make policy decisions easier for making a difference today and in the future. Because these issues are intertwined, it makes it difficult to communicate to others. We need to dig into that complex nature and be able to show how these processes build step-wise and are relevant to the policy/management context. We need to pay attention to local differences to address stakeholder needs.

After robust discussion, we moved on to establishing priorities for research gaps. The need for the multi-stressor aspect was very evident (temperature, nutrients, storms, land use, organic carbon, hypoxia, etc.). Not just the direct impact of these stressors, but how they interact together and cause impacts on resources. Therefore, we recommended a ***strong priority for multi-stressor work in all of its aspects*** on different time scales (decadal to event-scale) and spatial scales (site-specific to global). We have many ways we can approach these problems including field observations, multifactorial lab experiments, remote sensing, time series analysis, and modeling. Many people voiced interest in a workshop for best practices for design of multi-stressor experiments. This has been addressed by a SCOR working group, and a report is available[59].

A ***strong priority emerged to be able to give advice on monitoring systems*** (where, when, what, how to monitor). Given the many things that are interacting, how can we design a monitoring system that gives us what we need? What types of monitoring are important for modeling? Any monitoring should include species/community response variables or biological parameters that are relevant to stakeholders. NECAN sent a survey through their industry working group about stakeholder needs for monitoring and modeling. The top results were more measurements in nearshore and estuarine environments, understanding bottom culture conditions, and year-round data to support year-round harvest (in Maine, instruments are removed during winter). Algorithm development will be required for remote sensing of HABs.

[59] https://scor149-ocean.com/

Trophic interactions and energy flow through the ecosystem is a major gap. How do HABs, OA and other stressors influence food web interactions? What are the key species that will be affected and how will effects cascade through the system? What are the ultimate effects on species of commercial or ecological importance? This will require lab and mesocosm experiments, field observations and modeling.

We generated draft final priorities for presentation to the plenary session:

1. Understanding the ***multi-stressor aspect and feedbacks among stressors***. Determining the relative importance of local and climate drivers and influences of biology.
2. Understanding ***drivers on varied time and spatial scales*** - we need multiple ways to monitor the system as well as models to scale up in time and space and provide sensitivity testing.
3. Giving ***advice for monitoring*** - given the large variety of stressors, what should be monitored, how, and when? What should be monitored to improve models?
    a. Stakeholder input will be needed for prioritizing monitoring and other issues. What are thresholds that they care about? These may differ on local scales.

Understanding ***trophic interactions among all plankton members*** (including mixotrophy) and energy flow throughout the system. Identification of decision points where algal bloom activity and toxin intersects with important resources and human management options.

Gulf of Mexico Breakout: Information Gaps and Needs

The end goal of the first breakout session was to come up with 3-5 research priorities that we considered to be the most important for the Gulf of Mexico region. The breakout began with a summary from some of the webinars that the facilitator thought would be helpful to generate priorities. As the discussion continued research priorities that were brought up by breakout group members were added to the list. These included:

- Gap in monitoring between estuaries and Gulf of Mexico (offshore/coastal linkages)
- Carbonate chemistry is mostly variable in US estuaries, and is controlled by interacting drivers. Nutrient driven eutrophication and algal blooms play important roles.
- Hydrologic forcing, including storm-driven N, P and C loading plays an additional role in modulating algal blooms, pH, hypoxia.
- Storms and tropical cyclones impact air-water CO_2 exchange and pH directly. CO_2 outgassing from major events can release large amounts of sediment buried carbon through both CO_2 degassing and remineralization of the mobilized organic carbon.
- What are the precise duration and intensity of exposure of aquatic life to HABs and OA?
- How will the duration and intensity of HABs and OA change in future oceans?
- What are the consequences of environmentally realistic (today, future) levels of OA and HABs for aquatic life?
- When and for which HABs will OA matter (most)?

- Immediate Needs: Tools (e.g., remote sensing, continuous water quality monitoring) to capture events/impacts over relevant scales
- Adaptive nutrient/Carbon management in response to climatic changes and extremes.
- How do we effectively study a system with multiple drivers of OA and a diversity of HAB species?
- How can we best attribute effects on single HAB species and natural communities to OA versus other co-stressors?
- How do we disentangle direct and indirect effects of OA on food web dynamics (with HABs or without)?
- Can we better understand OA effects on HABs if we allow them to exist along the mixotrophy continuum?
- Knowing that we can't monitor everything everywhere, how can we track/understand what is happening with toxin production and toxin movement through food webs?
- Understanding things that happen on a minute/hour/day scale with a monitoring network that captures events on a daily/weekly monthly/seasonal scale. Temporal and sometimes spatial disconnect
- Focus on species that impact shellfish directly rather than those shellfish transfer to the rest of the food chain follow on – need to understand actions they can take to reduce mortality to their shellfish in these cases (harvest quickly/delay harvest/treat shellfish)
- IDing natural refuges for shellfish aquaculture (seagrass), breeding resistant or more resilient shellfish species
- Need to understand cues and triggers that lead to blooms
- Need simple tools and training to monitor and predict OA and HAB events (perhaps as an alarm/email alert from live ocean?)
- Data gaps (due to down systems or seasonal sampling) is an issue
- How should we respond as managers – what can sanctuaries do in their protection efforts and restoration efforts to ameliorate OA and/or HABS? This is very site specific – what can they do in their sanctuary?
- Relationship of OA and HABs to current unexplained mortality events (whales, dolphins) (is this the case in GOM?)
- Lack of local capacity to respond (is this the case in the GOM?)
- ID the overlap of most vulnerable communities and species to OA and HABs
- Causal mechanisms that link the land-based stressors to the drivers for OA-HABs and how that might be exacerbated by climate change and then how those multi-stressors translate to the marine ecosystem
- Coastal waters and estuaries are under observed
- What are the solutions that can work locally and what is the efficacy of those solutions (in a local/place based way): pollution mgmt., living solutions (seagrasses), restoration and environmental flows
- ID multi-stressor solutions to adapt to the changes we will see

- Projection of frequency, intensity and toxicity of HABs in response to OAH and ocean conditions long term
- Understanding organismal response to the environment (still a gap to understand how fisheries will respond to changing ocean conditions)
- Need real time dashboard to help manage and track fisheries (this should be operationalized!)
- State public health concerns: community assemblage changes that affect nutrition value and then affect the food chain

We started with this list and discussed many things including how GOM is different than the other regions. Each state (and stakeholder) in the Gulf of Mexico has a different suite of multi-stressors that they are responding to/impacted by. This presents a challenge as it can be hard to get Gulf-wide action or coordination with each state/stakeholder having different needs. We also spent some time discussing GOM stakeholders since the breakout members felt the shellfish industry is not a huge OA-HAB stakeholder in this region. More important stakeholders are coral stakeholders, recreational fisheries, tourism, general public (for beach safety warnings related to HABs), water quality managers and public health managers. It can be hard to get action on OA in this region from managers/policymakers because there are many stressors and OA impacts have not yet been realized or felt in the same way they have been on the West Coast. A few groups were mentioned that are trying to coordinate in the Gulf of Mexico: Gulf of Mexico Alliance or GOMA, GCOOS (for observations and data only), GCAN for OA relevant items.

With all that said, understanding OA and HABs in a multi-stressor context will be VERY important for this region. Multi-stressors that were mentioned as important to this region include: Storms, river input, eutrophication, hypoxia, submarine groundwater discharge, oil spills and other episodic events. Another point of discussion was the importance of estuarine to coastal to open ocean observing to understand different forcings and interactions between multi-stressors.

The discussion then moved to a discussion on existing and needed observations. The need to link estuarine to the open ocean with observations was discussed. Currently nutrient monitoring exists in many estuaries and near the coast but OA observing is lacking in most estuarine and coastal areas of the GOM. Discussion turned to available sensors and the need for low cost sensors that could be used alongside water quality monitoring for nutrients.

There was a lively discussion on experimental work and the need for more research that involves multiple trophic levels. Phytoplankton competition experiments were highlighted as a greater need than understanding species specific interactions as those lab studies that are species specific may not give a realistic picture of what will occur *in situ* when competition may be the driving factor. Ideally, we all sit down and design uniform experiments that examine interacting global and regionally specific variables, community level. It doesn't all have to be field-based. Some well-designed experiments (or experimental approaches) could get us part of the way there (to a greater understanding of OA and HABs in the GOM). Synoptic field sampling at the right places/times could get us part of the way there as well.

As the discussion progressed it became apparent that this long list of research priorities was overwhelming, so all breakout members were asked to type in their top five research priorities for OA and HABs in the region. Below is a list of all research priorities as identified by the breakout group members (note: these are verbatim from the chat box with similar items lumped or grouped together):

- How to divide/classify the Gulf related to freshwater input: eutrophication, benthic respiration, storm, fluctuation in freshwater for river dominated systems in GOM
- Centralized data submission site for HABs and OA- GCOOS/GCAN
- Targeted field and lab-based uniform experimental approaches to address a variety of concerns related to multiple stressors. These could be anything from micro to mesocosms, culture-based, with or without shellfish, and other exposure studies. Co-stressor effects on either community (coastal) and specific groups (cyanobacteria) in a very fluctuating GOM: storms, river input, etc. Eutrophication, bottom driven acidification in hypoxic zones. Several of our GOM HABs rely on other organisms to grow; we need to include those community dynamics in lab and field-based studies of them. Multi-species and multi-stressor interactions (field and laboratory studies). Improve co-stressor studies: eutrophication-hypoxia-OA.
- Region-wide network is also lacking, making it hard to coordinate/get beyond the local/regional perspective
- Increased monitoring (OA and HABs); more carbonate chemistry monitoring in general, but also with HAB occurrences. Expand OA monitoring into areas where HABs occur frequently, increase monitoring spatial and temporal coverage. We still don't know clearly what a role OA plays in (Florida). HABs formation and development in coastal oceans. It would be good to install OA sensors and collect OA data on the existing moorings in important locations where the GOM HABs are thought to form and develop. GOM is under-networked/observed compared to a lot of the other systems. Need to build that out for both OA and HABs (i.e., get beyond just chlorophyll),
- Estuarine to coast to open ocean connections, need to get into estuaries, out in the Gulf, and below the surface to really follow both OA and HABs.
- Local Solutions: refugia/resilience to these stressors (HABs and OA); refugia/resilience to stressors.
- Engage citizen scientists in monitoring and detecting HABs, make technology available?
- Newer toxin detection is being developed. Stakeholder involvement. I agree with the stakeholder engagement part, with focus on the stakeholders specific to the GOM! A priority for me is stakeholder engagement. Citizen science monitoring, stakeholder engagement; stakeholder engagement and citizen science participation
- Direct and indirect effects of OA and HABs on food web dynamics.
- Work on attribution of effects to HABs and phytoplankton communities to OA vs other stressors (especially hypoxia and eutrophication for this region).
- Warming, hypoxia, eutrophication, extreme weather all have to be included as co-stressors along with OA and HABs
- Species vs. community level causes and effects,

- Understand the effect of natural/anthropogenic factors on stimulating HABs, state specific strategies

We then went through and voted (each breakout member had three votes) and identified the top 6 research priorities for the Gulf of Mexico. Below are the much shortened versions of the top priorities from above:

- Multi-stressor studies (field and lab based) that look at the impact of not only OA and HABs but the other relevant stressors in the GOM on both individuals and communities
- MORE MONITORING for both OA and HABS
- Understanding the linkages/connectivity of the estuaries to the coast to the open ocean to understand drivers of both OA and HABs
- Citizen science and stakeholder engagement to increase monitoring and knowledge of these issues in the region
- Centralized data submission
- Identifying local solutions for HABs and OA

West Coast Breakout: Information Gaps and Needs

Participants: Clarissa Anderson, Carlos Avendano, Daniele Bianchi, Caren Braby, Maggie Broadwater (facilitator), Shallin Busch, Francis Chan, William Cochlan, Bill Dewey, Steve Gittings, Maria Kavanaugh, Justine Kimball, Raphael Kudela, Danielle Lipski, Jan Newton, Jan Roletto, Jayme Smith, Martha Sutula, Jenny Waddell, Charlotte Whitefield (recorder)

Objective: Participants identify gaps and needs in OA-HAB research in the West Coast/California Current Ecosystem (CCE) region. The breakout group aim was to return to the plenary with 3-5 top research needs for the region.

The facilitator presented the grand challenges that Raphael Kudela shared in the pre-workshop webinar and workshop (Day 1) lightning talk, and the needs and products identified in the stakeholder panel and discussion.

West Coast Grand Challenges (Raphael Kudela):

- How representative are the existing experimental data on HABs and OA? Do we have enough information to parameterize models?
- How will HAB organisms respond to short (plastic) and long-term (evolution) climate drivers? Are multiple stressors synergistic, antagonistic, or neutral?
- How do we effectively link HAB responses to higher trophic levels in a changing ocean?
- Can we better coordinate between the HAB and OAH (H = hypoxia) communities to take advantage of the overlap in data, tools (e.g., models), and predictions?

Needs/products proposed by other presenters, panels, and plenary discussion:

- What is influencing the duration and intensity of HABs/OA and the intensity of exposure of aquatic life to HABS/OA? How will this change in the future? Can we predict these changes?
- What are the consequences of HABs/OA to human health, the economy, and the environment?
- When and for which HABs does OA matter (most)?
- How representative are existing data? Can we parameterize models? Can we use data/models for attribution? Can we link HAB responses to higher trophic levels? Can we predict OA contributions and related changes?
- How can we better coordinate efforts among researchers and among the management community? E.g., Coordination of experimental/modeling work, co-occurring measurements at appropriate/relevant time scales, communication, engagement (tribes, cultural concerns), and holistic approaches.

The breakout group quickly developed lists to assess current knowledge and understanding of the relative contributions and environmental drivers of both HABs and OAH.

Relative contributions/drivers for HABs	Relative contributions/drivers for OAH
• nutrients from terrestrial sources • nutrients from riverine sources • upwelling • temperature • currents/advection • sedimentary seeding • micronutrients • community interactions, including microbes and grazers	• nutrients from terrestrial sources • nutrients from riverine sources • upwelling • temperature • currents/advection

This exercise demonstrated that we have a basic understanding of the drivers and relative contributions toward HABs and OAH separately, but there is a lack of knowledge about how OAH influences HAB drivers including sedimentary seeding, availability of micronutrients and ecological community interactions, including microbes and grazers. Additionally, we lack an understanding of how acidification conditions affect cell proliferation and toxin production. Up to this point, HABs and OAH have been considered separately. The intersection of HABs, OA, and hypoxia has not been addressed through funding programs in the past. The current effort of this workshop toward prioritizing research needs for a funding opportunity that takes a more holistic ecosystem approach to understanding HABs and OAH was well received.

The group had an extensive discussion, and made several lists to address the breakout objectives -- What main themes and overarching topics do we need to understand better to move our holistic understanding of HABs and OAH forward? What specific research and management questions can be answered through research projects? What do HAB and OAH researchers need to address these questions in a coordinated manner? The suggestions, notes from the discussion, and priority research needs follow.

What main themes and overarching topics do we need to understand better to move our holistic understanding of HABs and OAH forward?

- Causal drivers, including anthropogenic contributions.
  - Understanding anthropogenic drivers can demonstrate the need for better nutrient management. Need: Modeling studies to better understand the fundamental linkages between land-based nutrients (storm water and ocean outfalls) and oceanographic processes that could be confounding observations. Notes: In California, we rely on numerical modeling studies to look at the linkage between HABs, OA, deoxygenation and land-based sources. Wildfires are of tremendous interest because it represents such a large pulse. We haven't yet tackled that question. Managers should be advised to focus on chronic inputs to the coast (urban drool, ocean discharges), as those impacts to biological resources may be easier to discern. Challenges include the limitations of NOAA programs with respect to nutrient management issues, and that states do not have the resources to build mechanistic modeling tools to address nutrient management (but are poised to use them if they become available).
  - OAH and the carbonate cycle is not as simple as collinearity with upwelling (ref: Burke Hale's student's recent research). There are subseasonal and interannual processes that affect the variability in the biogeochemistry/carbonate chemistry of water masses that require time series (point and synoptic). Need: Co-occurring nutrients, community, and multiparameter measurements taken both offshore and nearshore that can be embedded in remote sensing data or models. Notes: Understanding the relative contributions from upwelling nutrients versus terrestrial and riverine sources of nutrients is extremely important for management. These relative contributions can be studied using stable isotopes and model interrogation techniques.
  - Interaction of HABs and OAH with other drivers like DO, temperature, and ecological interactions. Some existing models may be used to identify possible connections, but it is not straightforward. For example, the LiveOcean model has been explored to test relationships between high biomass events (including HABs) and subsequent low oxygen regions on the shelf, but it is still not clear.
- Bioaccumulation and biomagnification of toxins in higher trophic levels. Need: Food web data to parameterize mechanistic models.
- Rippling effects of impacts to coastal communities and economies. Need: Research to address human dimensions.
- Summary - Martha's five major research themes:
  1. Innovations in coupled physical/chemical/biological measurements to observation of the four horsemen of the climate change apocalypse (temperature, pH, deoxygenation, HABs).
  2. Lab/field/modeling experiments to investigate drivers.
  3. Biological impacts of OAH, HABs and warming.
  4. Solutions that address multiple problems simultaneously.
  5. Human dimensions of OAH and HABs.

  Note: Separate tracks may be necessary for nearshore versus estuarine habitat.

What specific research and management questions can be answered through research projects?

- Is OA a causal driver of HABs? Are nutrients really the big thing that we can/should control?
- What is the role of sediments in supporting chronic HABs?
- Where do HABs start (offshore)?
- What is the influence of offshore/onshore interactions on HAB initiation, maintenance and termination?
- What is the role of iron in *Pseudo-nitzschia* cell proliferation and toxicity?
- Are grazers (micros and copepods) triggers for HAB toxicity? Can IFCB measurements be used to provide more information regarding ecological drivers of HAB abundance and toxicity? Scripps Plankton Camera data indicate that grazers are a predictor of abundance for some HAB species, but there are currently no corresponding toxin data.
- How can we better understand community interactions? Model interrogation or mixed assemblage/mesocosm experiments? An experimental approach is preferred to best understand the mechanistic underpinnings - mesocosm and/or culture experiments are a good initial approach.
- Is it possible to estimate impacts to the shellfish industry (and others) that may be realized by HABs and OA in the next 5-8 years? Growers make decisions on multiple year crops and need to understand future conditions predictions. Due to interannual variability, 5-8 years is the hardest time scale for prediction from the modeling point of view. Longer term projections (20-50 years) are more feasible, but may not be as useful. Beyond cultured shellfish crop mortalities, we observe mortalities of non-commercial species. Thus, there are implications for other natural resources.

What approaches, resources, or tools can HAB and OAH researchers use to address these questions in a coordinated manner?

- Overarching needs: Innovative ways to combine observations and co-occurring measurements at appropriate/relevant time scales.
- Can we exploit the natural latitudinal variability in upwelling intensity and intermittency from WA, OR, and CA as a natural experiment? E.g., regional comparisons within the CCE. The CCE is a unique system, and HABs and OAH should be considered together. There is value in using the variability in upwelling in the CCE as a natural experiment. It is possible to use natural geographic differences to study similarities/differences based on proximity to rivers and other sources of relative contributions. Many participants indicated support for comparative studies across the CCE and estuaries.
    - Kudela ECOHAB[60] project compared Monterey Bay and SoCal, and found definite differences.
    - Allen ECOHAB[61] is collecting data for latitudinal comparisons from Monterey Bay to San Diego, similar to Kudela data.
    - Other locations to consider are coastal OR (straight coastline) and estuaries. Why are West Coast estuaries fairly resistant to HAB events?

[60] https://coastalscience.noaa.gov/project/emerging-algal-toxins-in-the-california-current-system-responding-to-known-threats-preparing-for-the-future/
[61] https://coastalscience.noaa.gov/project/oceanographic-and-cellular-controls-on-domoic-acid-production-in-the-central-and-southern-california-current-system/

- How sophisticated must data/instruments/models be to meet stakeholder needs? How frequently must data/measurements be collected? We need "community-able" measurements. Is the level of effort/expertise too high for stakeholder support or is implementation too difficult?
- We need a roadmap from more complex experiments and models to "useful" output, as defined by stakeholders/managers/decision makers. We need to integrate data across platforms to address relevant and often differing spatiotemporal time scales to extract mechanistic interaction between HABs and OA from observations. IOOS can help with data integration. RFP should include a specific request for analysis of historical/existing data - positive agreement from several participants. IOOS struggles to justify governmental funding for long time series data sets. Perhaps IOOS could collaborate with NCCOS (or OAP?) to broaden how historic data and models are mined to extract data/information relevant to these issues. Data mining will likely identify critical knowledge gaps, but more will be required to achieve formal attribution of the roles of OA, nutrients, etc. in HABs. We also need multi-factorial lab experiments to parameterize mechanistic models, and specifically to understand the role of iron *in Pseudo-nitzschia* blooms and domoic acid production.
- Can remote sensing of phytoplankton functional types (PFTs) be more useful for HABs? E.g., in upcoming missions like NASA PACE or current models like C-HARM? Currently, PFT applications to HABs have not been useful for decision making. The Rrs (wavelength) is still too coarse to get beyond classification to broad phylogenetic categories - "diatoms" "dinoflagellates" - and the coastal bio-optics (water and atmosphere) present challenges. Remote sensing PFTs are fundamentally limited to a few groups, and are not useful for identification to genus/species, so they are only helpful in the case where something observable is very unusual about a HAB. Some such oddities occur when domoic acid is present in *Pseudo-nitzschia* blooms, but we do not yet understand why. Some NASA PACE projects will look at the utility of remote sensing PFTs, but not specifically for *Pseudo-nitzschia*/domoic acid oddities. Would creating/validating PFTs to measure co-occurrence with toxin production be useful?
- Are there candidate HAB species that would be useful coast-wide indicators and still be relevant on a local scale? *Pseudo-nitzschia* (diatom) suggested for the west coast, but what about dinoflagellates? *Alexandrium* is best due to serious human health issues from paralytic shellfish poisoning, but second to *Pseudo-nitzschia* on the west coast because of lower incidence of exposure. One suggestion was to build a knowledge infrastructure around a common "indicator" species (e.g., *Pseudo-nitzschia*) and then add different species (*Alexandrium* and others) to increase complexity. Note: Sanctuaries (and MPAs, etc.?) issue conditions reports using ecosystem indicator species.
- Funded researchers should be encouraged (required?) to coordinate experimental work with modeling work, even if the projects are funded separately.

The following five research gaps and needs were collated for voting/prioritization:

- <u>Data mining and analysis of existing models and datasets</u>. This is important to prioritize for current researchers and students working under restrictions related to COVID. We can move forward immediately, using what data and models we have to maximize resources and understanding.

- Effective awareness communication. A greater effort to get relevant, actionable, and timely information directly to the people who need it in a condensed, understandable format.
- Human dimensions and management. We need to put the appropriate products directly in the hands of the people who need data for decisions - an applied, place-based “tool kit” for industry and regional managers. The RFP should have a “MERHAB” type of focus to incorporate management needs with research activities.
- Use of coordinated field and laboratory experiments to parameterize and validate models. Targets should focus on evaluating model uncertainty in a multi-stressor system and at regional to local scale effects.
- What are the multi-stressor drivers of changes in phytoplankton communities? We need to focus on the interconnections of biology/ecology and chemistry with multi-stressors of OA, DO, HABs, and temperature. It’s time to break down the siloed experiments and models. Attribution should be the overall goal, achieved by combining scales and devising new approaches to look at questions from a broader perspective.

Voting/prioritization was difficult, as future research will progress linearly and many of these topics must be considered in parallel. A variety of HABs, including those that affect humans and those that affect non-human species, should be studied in this region. Communication is something that can be done in the short-term, and larger research gaps can be addressed as a decadal goal.

One clear, overarching focus was the need to work toward attribution of HABs and OAH to nutrients, temperature, and other anthropogenic and environmental factors. Reliable attribution will require experiments, modeling, observations, and synthesis. Attribution must be answered at a variety of scales from organismal to landscape, with separate determinations for nearshore versus estuarine habitat. Measurements should include nutrients, micronutrients, nutrient speciation (e.g., types of N) and source (e.g., upwelling, riverine, sediment, storm water, urban drool, ocean outfall/discharges, WWTP), temperature, and advective processes (that may transport “seed” for blooms). Attribution studies can provide a basis for better nutrient management.

The following research gaps were identified for the West Coast/California Current Ecosystem region and presented in the plenary session:

- Parameterized models realized via more coordinated experiments (in both the laboratory and natural environment).
- Ecological approaches to study the interaction of HABs, OA, and other changing ocean conditions (i.e., impacts of grazers, competition, etc.)
- Data mining/analysis of existing model output and existing data streams.
- Ocean-estuary coupling and downscaling to understand exchange of HABs and OAH vs. autochthonous HAB and OAH development in estuaries and food web impacts in enclosed areas.
- Human dimensions link to research - this should encompass economic impacts and human health.
- Effective communication - getting the right products into the hands of people to address needs.

- A variety of HABs should be studied thoroughly - HABs that affect humans and those that affect non-human species (e.g., shellfish).
- Communication can be done in the short-term; bigger research products can be on a longer timeline (e.g., decadal goals).

Alaska Breakout: Information Gaps and Needs

For the first breakout session, the objective was to identify 3-5 regional research priorities within the Alaska region. To facilitate the discussion, the moderator connected participants with research needs and gaps identified during the lightning talks presented in the plenary. This included revisiting three identified research 'needs':

1. Monitoring targeted at ***quantifying variability in HAB and OA conditions*** at time and space scales that matter for stakeholder resource management, harvest, and mariculture operations and new development. Monitoring designed to ***support development or risk and vulnerability assessment products***. Accurate, cost-effective field test kits for PSP toxins.
2. Species sensitivity research for harvested and prey species to ***assess vulnerability and understand food web impacts***. Incorporate realistic, regionally specific environmental condition information (thresholds/variability) from enhanced monitoring data. ***Identify synergistic effects on species*** between climate change, OA and HABs.
3. Modeling of environmental conditions in nearshore and offshore waters, resolved sufficiently in time and space to assess impacts on coastal resources. Incorporate temperature, freshwater, carbonate chemistry and ice changes. Combine monitoring, species response and modeling information to ***develop species-specific, multi-stressor vulnerability assessments*** and public health risk assessments.

The following discussion set out to identify any missing needs (if applicable), and to suggest 3-5 research priorities for the Alaska region. Across the participants, there was a consensus on the need for ***consistency across sampling methods and data sharing***. Data gaps were discussed as they pertained to sampling procedures, lab testing standards, and collaboration across various programs (e.g., AHAB, OAN). Some of the key topics related to sampling and data sharing included:

Characterizing measurement and sampling uncertainty: To allow for comparison of discrete measurements, a solid understanding of uncertainty is necessary, particularly with respect for carbonate measurements.
Need for subsurface measurements: Current efforts are prioritized to surface monitoring, but subsurface measurements are necessary to monitor for impact to benthic species (e.g., groundfish, crabs). Surface conditions are limited in their ability to give system-wide conditions necessary for forecasting needs. This relates to environmental, animal, human, and economic impacts.
Enhanced Communication and Outreach: If future effort is targeted to include community sampling and monitoring (citizen science), an effort needs to be made to connect local

communities and ensure they have access to online products and capabilities. Outreach needs to be a larger component for success with community-based monitoring efforts.
Satellite Observations have limitations: Remote sensing products have limitations in Alaska, particularly due to cloud cover and ice. Our group discussed the role of satellite data for identifying site selection for research gaps that could be tackled by community-based sampling. Further, we discussed the roles of various observing platforms (buoys, moorings, current BoL systems) that collect information at various scales, and the question of what spatial and temporal scale is most successful for Alaska. Ultimately, more observations are needed for real-time ingestion for future forecasting needs. The group also discussed different mechanisms for filling the gaps for HAB and OA data collection, including the use of gliders or various samplers.
Enhanced Statistical Analysis: One area of discussion without the breakout session focused on improving statistical analysis within testing procedures or labs. If testing protocols could be standardized across the state, confidence and support for the data would feed into the local community. This also feeds into QA/QC procedures for sampling that would benefit from a standardized procedure or process outlined in a statewide plan to address HABs, OA, and multi-stressors. This would allow for local communities to collaborate to a greater extent to share data, products, and results.

After a robust discussion, the following research priorities were identified as the most important for the Alaska region and were presented during the plenary session:

1. Integrate/overlay new information for community vulnerability for local groups/industries for HABs/OA/climate variability. This would integrate data from more recent coastal environmental and species sensitivity to OA, and would be geared towards information for fishermen, oyster farmers, subsistence harvesters, state agency managers.
2. Statewide HAB monitoring plan, especially. for western AK, Bering Strait, North Slope communities. A data management plan or standardization/ QA/QC methods would be helpful. First priority is robust saxitoxin testing (including effective field test kits).
3. There is a need to aggregate/integrate HAB and OA data across research, continuous monitoring and community efforts and sampling to ensure they are being combined, interpreted, published, etc. Develop information dashboards/risk assessment tools and figure out sustained service delivery over time.
4. Continuous high-temporal resolution measurements to understand relationships between temp/salinity/carbonate chemistry/HABs. Shore station obs -Burk-o-laters, IFCBs (Auke Bay Lab, Aluutiq Pride Shellfish Hatchery). Add ecosystem monitoring buoys in a few places (Sitka, PWS, and Kachemak Bay?). Can also leverage community monitoring, for example collecting phytoplankton samples with known water volume and temp/salinity and using qPCR to analyze for cell abundance - one way to build up info on relationships over time across multiple areas.
5. Need observations/modeling of temperature/salinity/CO_2 parameters at depth (for crab, groundfish, etc.). Evaluate existing observations (which are very limited) for utility. AOOS has planned glider surveys to help fill gaps.

Appendix 4. Regional Breakout Summaries: Identifying Research Products (Day 3)

Great Lakes Breakout: Research Products

The question of whether the Great Lakes were experiencing acidification was raised in the first Great Lakes break-out session. A link was provided to a paper addressing that issue[62], which makes the case that the acidification will be similar to that in the ocean, but due to spatial and temporal variability, the existing monitoring system was inadequate to accurately measure the decrease. In discussing the role of OA and HABs it was pointed out that OA and nutrient limitation work synergistically[63]. It is even more complicated, because of the switch from nitrate to urea for fertilizer. During the basification and the resultant CO_2 limitation, which occurs during CyanoHAB blooms, urea can supply the C needed by Microcystis for growth[64]. Also, application of P fertilizer has changed from topical treatment to injection into the soil. The former would result in greater surface runoff and the latter faster runoff in the tile drains.

For CyanoHABs two, overlapping groups of stakeholders, were identified who needed different products. There were the decision makers and the public, who needed information in a format that was readily accessible so that decisions could be made quickly (Fig 1). The products in Fig. 1, were based on a much more comprehensive understanding of the interaction of HABs and OA and other environmental factors (Fig. 2) that was required by scientists and policy makers. The two are clearly related. For example, how does agricultural runoff affect acidification in the environment? What is the role of zebra mussels in determining the carbon budget? One participant asked if there were any engineering solutions available/possible for mitigating the effects of OA and HABs, but that question was not answered.

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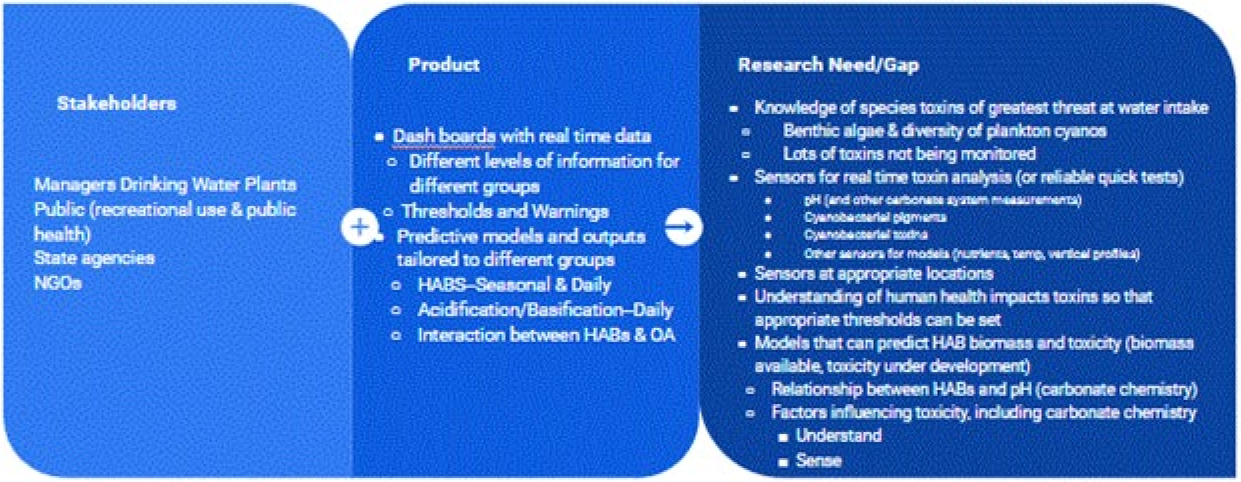
[62] https://tos.org/oceanography/article/the-potential-for-co2-induced-acidification-in-freshwater-a-greatlakes-case
[63] https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0051590
[64] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6536089/

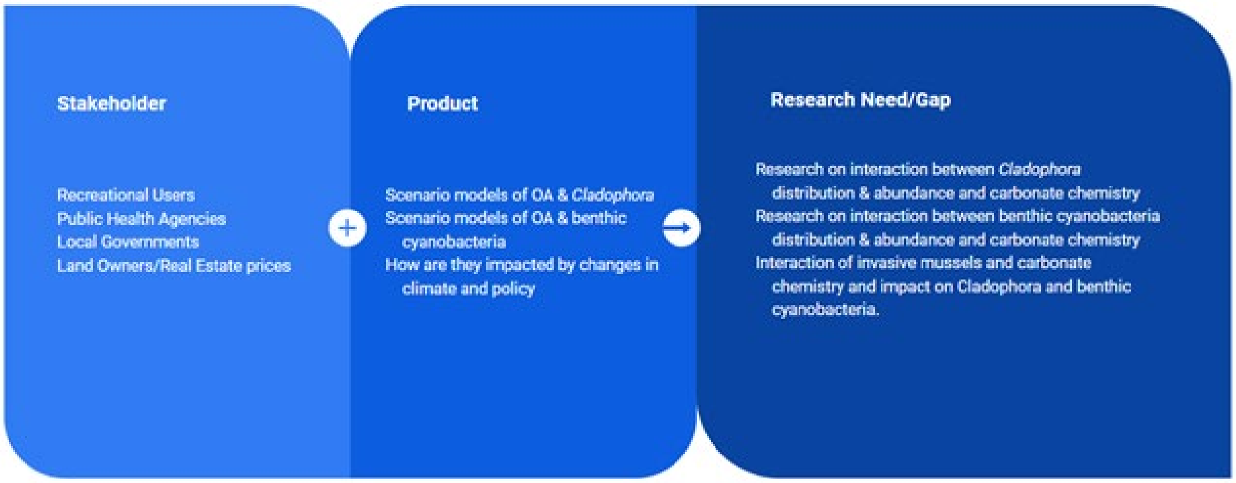


Appendix 4, Figure 1. Products required by decisions makers and the public in order to manage CyanoHABs and their impacts.

Appendix 4, Figure 2. Products required by scientists and decision makers in order to manage CyanoHABs and their impacts.

The issue of benthic algae has been minimally addressed. Spikes in anatoxin and saxitoxin suggest that benthic cyanobacteria have become a greater problem. This may be because the invasive mussels cause the water to be clearer. The relationship of invasive mussels and benthic algae to carbonate chemistry is unknown. A recent EPA workshop[65] was held on benthic HABs. Another benthic HAB is Cladophora, which is not toxic, but piles up on beaches and impacts real estate prices.

[65] https://www.epa.gov/cyanohabs/benthic-harmful-algal-blooms-habs-discussion-may-27-2020



Appendix 4, Figure 3. Products required in order to determine the interaction between OA and two emerging HAB issues in the Great Lakes, Cladophora and benthic CyanoHABs.

East Coast Breakout: Research Products

We began with the summary points from the stakeholder panel (day 2) and the types of research products that were introduced in our plenary session immediately prior to the breakouts.
Reminders:

- We want to be able to have research products that address OA and HABs, not just one.
- We want research products that can address a stakeholder need
- We want to be able to see how the research gaps we identified will link to an eventual research product.

We began by identifying **stakeholder groups** in the East Coast region that might be most in need of information or most affected by HABs and OA. These included

- East Coast Shellfish Growers Association and the aquaculture industry; concerned about HABs that affect humans and HABs that affect shellfish. Not just when and where blooms are toxic, but also earlier in the life stage (of the shellfish). It's not just the final product. It's getting the organisms to grow in the first place
- Wild fish and shellfish industries (lobster, blue crab, surf clam, scallop, oyster)
- State regulatory agencies. They are the ones that make the decisions about closures for harvesting market shellfish
- Health care providers, epidemiologists and extension agents, recreational users.
- Wildlife and resource managers. Fate of toxins in the food web and broader impacts.
- Coastal resource managers (longer-term stakeholders); wastewater and stormwater management, nutrient and runoff control, restoration management. Should include terrestrial managers and people who regulate land use.
- Monitoring agencies and operations
- Recreational users and harvesters, beach managers

- Researchers/aquariums/ holding facilities. Problems with toxins in the water, even when algae are filtered out
- Utilities that make use of water as coolant. Warm water lagoons could contribute to bloom formation. HABs could also clog filters on cooling plants
- Offshore wind farms and structures that could be platforms for monitoring

With a list of stakeholders, we moved on to what **types of products** we might be able to provide.

- Maps: Regions that are free of HABs and OA. Regions that could be hot spots for both. Superimposed on growing areas for shellfish. Maps could be used for interdecadal time scales and also what will happen tomorrow. Dynamic, not just static, including retrospective analyses.
- Which clean-up steps would best remove toxins or cells so that it doesn't get into their facilities (best management practice)
- Forecasts and particle tracers in a model that lets stakeholders know when a HAB is approaching or when there will be a hypoxic event. Build products that they can use on their laptops and smartphones. HAB and OA models need to be aligned in terms of temporal and spatial scales
- Likelihood of bloom formation in given locations
- Forecast that links cell concentration of a bloom to toxicity in shellfish tissue or cell abundance in the environment vs. how much toxin is making it into the hatchery to effects on production. Might need to be species specific. Good tool for shellfish growers and state regulatory agencies. Separate products for effects on humans and effects on animals. OA and/or hypoxia might affect the shape of HAB toxicity curves.
- Forecast of bloom or when toxin production starts, with a way to get rapid communication to public about where and when blooms occur (IFCBs)
- Model forecasts that can connect upstream inputs to probabilities of blooms. Will help inshore to offshore axis and stakeholders like utilities. These are likely longer-term products
- Long-term, seasonal, decadal scale tools or products. Time scale is a way to break out forecast types among stakeholders. Long-term forecast skill is in progress, seasonal forecast doesn't look as good. Interannual might be more feasible.
- Scenario analyses and management options. Managers are also really interested in climate change and how things will look 20-30 years from now (only scientists are really interested in 2100).
- Habitat suitability models - the likelihood of bloom development based on underlying conditions
- Translate model output into risk assessment framework. Combine these with adaptation and mitigation strategies.
- Provide advice or guidance to monitoring

The facilitator began matching products with stakeholder groups:

- Best management practices- growers, hatcheries, recreational managers
  - Folks starting aquaculture farm might want to know how it will look in 20 years; also investors in this category
- Habitat suitability models, risk assessment - resource managers, water quality managers, aquaculturists, harvesters, economists
  - An integrated measure of risk to the system that is responsive to decision point
- Advice/guidance to monitoring - monitoring groups and agencies
- Forecasts and event warnings - general public, growers, harvesters, beach/recreation managers
  - Forecasts should consider impacts, not just toxin levels or OA conditions. Because the impacts are what is going to affect stakeholders. Hard to know what a toxin level means to a stakeholder. Any actual impact would be due to the combination of HAB toxin and other stressors (such as OA and hypoxia) an animal experiences.
  - Public health departments and/or city managers would also be interested in bloom impacts

We drafted products for presentation in the plenary session:

Product	**Stakeholder**	**Research need from Day 1**
Maps of susceptibility, hot spots, superimposed with shellfish and management areas	growers and harvesters, resource managers (interannual), water intake managers, beach and recreational managers, resource economists, NGOs	Mechanistic driver understanding Forecast impact of blooms, not just where/when bloom will occur Forecast in relation to other stresses (co-occurring or sequential) and shellfish health Needs to be matched to management
Advance warnings of events, particle tracing	growers, harvesters, resource managers, water quality groups, public health, city managers	Mechanistic driver understanding Where do we already have some knowledge? - can help to target initial attempts
Likelihood of bloom based on prior conditions or watershed management practices	resource managers, water quality managers, watershed managers, land use managers, aquaculturists (when setting up or opting out), harvesters, investors, economists, NGOs	Relative importance of local and climate drivers and influence of biology, feedbacks.

Risk assessment, combined with adaptation and mitigation strategies	resource managers, water quality managers, aquaculturists (when setting up or opting out), harvesters, investors, economists	Mechanistic driver understanding, feedbacks
Habitat suitability model outputs and scenario analyses, both present time and forecasting to future	resource managers, water quality managers, aquaculturists (when setting up or opting out), harvesters, investors, economists	Mechanistic driver understanding, feedbacks
Advice/guidance for monitoring and industry, best management practices	Agencies, resource managers, water quality managers, aquaculturists	What should be monitored, how, and when?

Gulf of Mexico Breakout: Research Products

The goal for this session was to identify up to four research products that are responsive to stakeholder needs in the Gulf of Mexico.

We started our discussion by looking at the needs and products that were proposed during the previous day's stakeholder panel. I have grouped these by theme below:

- Monitor and Predict OA and HAB events – This includes co-located monitoring of OA and HAB conditions, adding OA-HAB sensors to existing monitoring assets and the creation of bulletins, alarm or warning notifications

- Understand resource interactions with HABs and OA - Which species are most affected? Conducting vulnerability and risk assessments for a variety of managed species. Are there feedback loops between HABs and their influence on resources like shellfish and shellfish grazing on HABs? Which species will have an advantage in future ocean conditions? How will ocean change affect the phytoplankton community and will it result it food web impacts? Will there be an increase in toxicity under OA? Will there be a lower threshold of HAB density for same amount of toxin? Understanding chronic versus acute impacts due to these stressors. And along those lines, understanding the static vs dynamic nature of these two stressors.

- Potential solutions - Mitigation, restoration, conservation of habitat (such as Eelgrass, kelp). Are there estuary and watershed restoration impacts that can mitigate OA and HABs?

The breakout group was then reminded of the research priorities identified in the previous day (listed below for your reference):

- Multi-stressor studies (field and lab based) that look at the impact of not only OA and HABs but the other relevant stressors in the GOM on both individuals and communities
- MORE MONITORING for both OA and HABS
- Understanding the linkages/connectivity of the estuaries to the coast to the open ocean to understand drivers of both OA and HABs
- Citizen science and stakeholder engagement to increase monitoring and knowledge of these issues in the region
- Centralized data submission
- Identifying local solutions for HABs and OA

And the discussion turned to identifying products that are needed in the Gulf of Mexico. During this discussion a number of other needs came up for the region including OA-HAB toxicity studies and the **need to translate information to management** to help inform and perhaps even change existing regulations. Currently it was mentioned that the research communities themselves are doing much of the research-to-policy work and there was some discussion about if that was the best approach moving forward.

As one of the main needs in the Gulf of Mexico was **increased observations**, the conversation turned to products that could enable more observations. We discussed *citizen science* and ways to enhance or increase citizen science for OA and HABs. These included a guide that lists all of the available sensors, their cost, what they are best suited for and any other notes on how to use them in combination with existing efforts to maximize data collection. Another way that was suggested was to increase the coverage of *Ships of Opportunity* in the Gulf of Mexico that collect carbonate chemistry parameters and also perhaps leveraging these existing efforts and adding on some HAB sampling. We also discussed how to best leverage the interest of oil companies and BOEM in this region to help increase sampling. It was mentioned that sensors could be put on their platforms. Another way to increase observations was to deploy low cost sensors and use the data to *develop algorithms*. Once an algorithm was established that could be used with parameters that are easier to obtain to give an idea of the carbonate chemistry.

We then moved our conversation to specific products, the research needed to develop those products and the stakeholders for those products. Below you will see the products linked with the stakeholders and the research needs we identified:

Appendix 4, Figure 4. The research needed to develop OA and HAB predictions for Gulf of Mexico stakeholders.

Appendix 4, Figure 5. The research needed to develop spatial OA and HAB vulnerability assessments for Gulf of Mexico stakeholders.

West Coast Breakout: Research Products

Participants: Clarissa Anderson, Carlos Avendano, Daniele Bianchi, Caren Braby, Maggie Broadwater (facilitator), Shallin Busch, Francis Chan, William Cochlan, Bill Dewey, Steve

Gittings, Maria Kavanaugh, Justine Kimball, Raphael Kudela, Danielle Lipski, Jan Newton, Jan Roletto, Jayme Smith, Martha Sutula, Jenny Waddell, Charlotte Whitefield (recorder)

The facilitator began the breakout session by presenting the objective: define a roadmap by identifying stakeholders or users of HAB and OAH research products, and list the products that can serve specific stakeholder needs.

The output from the breakout session presented at plenary should define STAKEHOLDER + PRODUCT --> RESEARCH NEED/GAP.

The facilitator reviewed the products proposed by the stakeholder panel during the plenary session:

- Monitor and Predict OA and HAB events (and predict effects/impacts)
    - Co-locate monitoring of OA and HAB conditions
    - Add OA-HAB sensors to existing monitoring assets
    - Bulletins, alarm or warning notifications
- Understand resource interactions with HABs and OA
    - Which species are most affected?
    - Vulnerability and risk assessments
    - HAB influences on resources
    - Shellfish grazing influence on HABs, feedback loops?
    - Which species will have an advantage?
    - How will this affect the phyto community?
    - Resulting food web impacts?
    - Increase in toxicity under OA? Lower thresholds of HAB density for the same amount of toxin?
- Mitigation, restoration, conservation of habitat
    - Eelgrass, kelp, estuary and watershed restoration impacts
- Multi-stressor impacts
    - Chronic vs acute impacts
    - Static vs dynamic stressors

The breakout brainstormed stakeholders, stakeholder needs, and products to meet these needs. Results of this discussion are listed here.

Stakeholders/User groups:

- Public health
    - Regional human health managers
    - Tribes
- Animal/wildlife health
    - Oyster growers
    - Dungeness crabs fisherman
    - Pink shrimp
- Managers and Governments
- Economic and Trade

    - Tourism boards
    - Trade commissions
    - City managers
- Educational and Awareness Institutions
    - Academic institutions
    - NGO outreach
    - National marine sanctuaries
    - Sea Grant
    - CA Ocean Protection Council

General needs of the stakeholders/user groups:

- Seafood safety
- Seafood product quality assurance
- Needs of water quality managers (stakeholder group): 1) local pollution impact assessment (air or water managers) 2) biological impairment assessment
- Improved/faster/more accessible toxin testing
- More information about a wide range of toxins - domoic acid (DA), paralytic shellfish toxins (PSTs) and less common/emerging toxins: azaspiracids (AZA), yessotoxins (YTX), diarrhetic shellfish poisoning (DSP) toxins, freshwater toxins in the coastal environment, etc. These are not well monitored and not addressed by current modeling products.
- Risk/Hazards assessments
    - Information about DA and emerging toxins under OA conditions
    - Better spatial and temporal understanding of OA conditions and impacts
- Vulnerability assessments
    - The classic definition is that a hazard is the problem (toxins, for example), vulnerability is how likely a hazard is to impact a population, and risk is the overlap of the two. When risk is manifested it becomes exposure.
    - Managers and other stakeholders need to understand resource interactions with HABs/OA and which species are adversely affected.
- Education/engagement/communication
    - Need for two way communications between stakeholders and the research community.
    - Need a clear conduit of information from scientists to stakeholders (Suggestion: IOOS RAs, Sea Grant offices).
    - Avoid stakeholder fatigue. Researchers need to engage stakeholders in a coordinated manner (through agencies as suggested above).
- Need to "connect the dots" on multi stressor issues for stakeholders.
- Agency managers want interpreted data. They don't usually want raw data they have to interpret. Something like the NOAA Climate Prediction Center's El Nino Watch bulletin that is distributed to those who sign up for it.
- Need for funding for the academics to help with management descriptions – and the issue of freedom of information acts (FOIA) when data are requested for management decisions.
- Models and information products that have attribution – local short term sources and climate (HAB and OA)

Products to meet stakeholder needs:

- Bulletins, real time data --> OA-HAB overlap - bulletin/condition evaluation for HABs, OAH, temperature. These should be “spoon fed” directly to users, with combined HAB/OAH real-time information in one place. Products must be adaptable to save time, money, and resources and meet the evolving needs of stakeholders.
- Statistical/empirical products to predict impacts of HABs and OA. Aim for 10 year modeling goal to predict conditions AND impacts.
- Interpreted data and model output (i.e., NOAA Climate Prediction Center's El Nino Watch bulletin), including biological impacts information.
- Prediction of HABs/OAH at a number of time scales: 3 day, weekly, seasonal, decadal. HABs are more difficult to predict over the long term than OAH.
- Regional-level information that captures larger-scale processes
- Evaluation of resource recovery or other "living solutions"
- Source attribution of HAB and OA events.
- Integrated metric of duration and severity of OA-HAB event.
- Rapid response mechanisms to (unusual) events, including incident response and communication.

The brainstorm lists above were collated, mapped to our objective, and presented at the plenary session. The breakout and plenary session discussions revealed substantial overlap among the stakeholders served and the research needs/gaps that are addressed by various products. In some cases (e.g., source attribution of HABs and OA), the research need/gap was also defined as an eventual product.

<table>
<tr><th>STAKEHOLDER +</th><th>PRODUCT →</th><th>RESEARCH NEED/GAP</th></tr>
<tr><td rowspan="3">Public health
Resource managers
Industry
Education/Awareness</td><td>Bulletins / real-time data</td><td rowspan="3">Risk assessment
Communication</td></tr>
<tr><td>Products to predict impacts of HABs and OAH</td></tr>
<tr><td>Interpreted data and model output</td></tr>
<tr><td>Public health
Industry</td><td>Prediction of HABs and OA at relevant time scales</td><td>Seafood safety
Seafood product quality assurance
Risk assessment</td></tr>
<tr><td>Resource managers and research community</td><td>Regional-level information that captures larger scale processes</td><td>Multi-stressor evaluation
Source attribution</td></tr>
<tr><td>Resource managers</td><td>Evaluation of resource recovery or living solutions</td><td>Vulnerability/risk assessment</td></tr>
</table>

Resource managers and research community	Source attribution for HABs and OA	Risk assessment Multi-stressor evaluation
Public health Resource managers Industry Economic/trade Education/Awareness	Integrated metric of duration and severity of HAB and OA "events"	Seafood safety Risk assessment Communication
Public health Resource managers Industry Economic/trade	Rapid response mechanism for unusual events	Seafood safety Improved toxin testing Risk assessment

Alaska Breakout: Research Products

The objective of the second breakout session was to complete a roadmap exercise to identify regional stakeholders and potential products to address some of the research needs or gaps identified from the previous day. The breakout session began by summarizing and discussing the main points from the stakeholder panel and relating them to potential products. For the roadmap, we first identified the following list of stakeholders for the region, divided primarily between industry, state, and tribal governments.

1. Subsistence harvesters
2. Oyster and/or geoduck farmers
3. State managers
    a. Alaska Department of Fish and Game: Aquatic Farming; Sportfish Division
4. Alaska Department of Environmental Conservation (ADEC)
5. Alaska Department of Health and Social Services
6. Tribal Governments
7. Alaska Fisheries Development Foundation and the Mariculture Task Force
8. NOAA Fisheries Marine Mammal
9. Protected Resource Managers
10. Village Environmental Monitors
11. Researchers

After finalizing the list of stakeholders, the attendees sought to connect research needs/gaps to stakeholders based on the prior conversation and stakeholder panel. Overall, there was a consensus that the identified products would apply in some capacity to the entire list of stakeholders, except for Researchers, who fell under the last product recommendation (see Table below) for increased observations.

The products identified for our group fell into one of four topic areas:

1. ***Vulnerability Assessment:*** There is a need for completing and/or updating vulnerability assessments for HABs and OA within the state of Alaska. The need for parallel vs. independent timelines is something to be discussed as it relates to monitoring and data collection. Further, the assessment should be community based to ensure collaboration, inclusion, and include multi-stressors as they relate to HABs, OA, and climate variability.
2. ***Statewide HAB Monitoring Plan:*** A Monitoring and Response Plan with a statewide scope would assist with current gaps identified for Western and Northern Alaska. Further, this plan would optimize and prioritize HAB monitoring and test kits for saxitoxin field testing capability.
3. ***Data Aggregation and Integration:*** Our group identified that steps need to be taken to assure that community sampled data is being collected and ingested for monitoring and future forecast efforts. To address this concern, the group discussed the generation of an integrated data portal for real-time needs. This would aim to provide forecasts and risk assessment products to local communities. A sustainable service delivery framework is essential. An additional product that could be ingested and displayed within the data portal could be a summary of ongoing efforts and outreach to assist with future collaborations between local communities.
4. ***Co-locating Sensors for Monitoring and Testing:*** Presented here as more of a solution that a research product, our group discussed the need for increased monitoring and sampling efforts. Part of this discussion included the potential for co-locating new technology and sensors alongside existing platforms to provide continuous, high temporal data. This would leverage existing platforms, cut costs for deployment, and allow for testing in a few key locations that would be beneficial to stakeholders.

After connecting the four proposed products/solutions to our stakeholders, the following roadmap was presented during the plenary that provided a bridge from stakeholders to products and listed the research needs and/or gaps that were being addressed.

Stakeholders	**Research Needs/Gaps**	**Product(s)**
Subsistence Harvesters, Oyster/Geoduck Farmers, managers (Alaska Dept. of Fish and Game: Aquatic Farming, Sportfish Division; Alaska Department of Environmental Conservation	Vulnerability Assessment: Integrate new information for community vulnerability for local groups/industries for HABs/OA/climate variability. This would integrate data from more recent coastal	We need to complete/update vulnerability assessments for HABs and OA. The need for parallel vs. independent timelines is something to be discussed as it relates to

(ADEC); Alaska Department of Health and Social Services; Tribal Governments; Alaska Fisheries Development Foundation and the Mariculture Task Force; NOAA Fisheries Marine Mammal Protected Resource Managers; Village Environmental Monitors	environmental and species sensitivity to OA-HAB species relationships to environmental changes. This could further implement or direct aquaculture development.	monitoring and data collection. A community focused vulnerability assessment that takes into account OA, HABs, and climate change (multi-stressors).
Subsistence Harvesters, Oyster/Geoduck Farmers, managers (Alaska Dept. of Fish and Game: Aquatic Farming, Sportfish Division; Alaska Department of Environmental Conservation (ADEC); Alaska Department of Health and Social Services; Tribal Governments; Alaska Fisheries Development Foundation and the Mariculture Task Force; NOAA Fisheries Marine Mammal Protected Resource Managers; Village Environmental Monitors	Statewide HAB and OA coordination and monitoring plans, with first priority on HAB monitoring and response plan for western AK, Bering Strait, North Slope communities. Would include data management plan and standardization/ QA/QC methods for monitoring. First priority on monitoring needs is robust saxitoxin field testing capacity - accurate and cost-effective field test kits.	A Statewide HAB Monitoring and Response Plan (This would address the current needs of Western and Northern Alaska, for example).

Subsistence Harvesters, Oyster/Geoduck Farmers, managers (Alaska Dept. of Fish and Game: Aquatic Farming, Sportfish Division; Alaska Department of Environmental Conservation (ADEC); Alaska Department of Health and Social Services; Tribal Governments; Alaska Fisheries Development Foundation and the Mariculture Task Force; NOAA Fisheries Marine Mammal Protected Resource Managers; Village Environmental Monitors	There is a need to aggregate/integrate HAB and OA data across research, continuous monitoring and community efforts and sampling to ensure they are being combined, interpreted, published, etc. **Sampling and Analysis Protocols:** There is a current overlap with sampling/collection techniques, but varying QA/QC procedures. A Standardization protocol would address this and work to identify current sampling techniques/metadata standards/ and data report outs/communication across Alaskan communities. Quantifying uncertainties across lab testing is a priority.	Developing and making available a Monitoring, Collection, and QA/QC Protocol / Standards Develop integrated data portal to share data for both real-time needs and to help in developing forecast and risk assessment products going forward. Develop information dashboards/Risk assessment tools and ensure sustained service delivery over time. A summary or outreach document to summarize monitoring and analytical techniques that is summarized for general OA-HAB audiences.

Researchers, Stake Agencies, Subsistence Harvesters, Oyster/Geoduck Farmers, managers (Alaska Dept. of Fish and Game: Aquatic Farming, Sportfish Division; Alaska Department of Environmental Conservation (ADEC); Alaska Department of Health and Social Services; Tribal Governments; Alaska Fisheries Development Foundation and the Mariculture Task Force; NOAA Fisheries Marine Mammal Protected Resource Managers; Village Environmental Monitors	Continuous high-temporal resolution measurements to understand relationships between temp/salinity/carbonate chemistry/HABs. Shore station obs -Burk-o-laters, Flow cytobot (Auke Bay Lab, Alutiiq Pride Shellfish Hatchery). Add ecosystem monitoring buoys in a few places (Sitka, PWS, Kachemak Bay?). Can also leverage community monitoring, for example collecting phytoplankton samples with known water volume and temp/salinity and using qPCR to analyze for cell abundance - one way to build up info on relationships over time across multiple areas.	Use the output from the vulnerability assessment and current data collection to identify next steps/gaps/improvements Testing new technology capabilities/utility Coupling new sensors (e.g., cytobots) with existing equipment to provide the mechanistic information for factors driving blooms to apply to distributed community sampling.