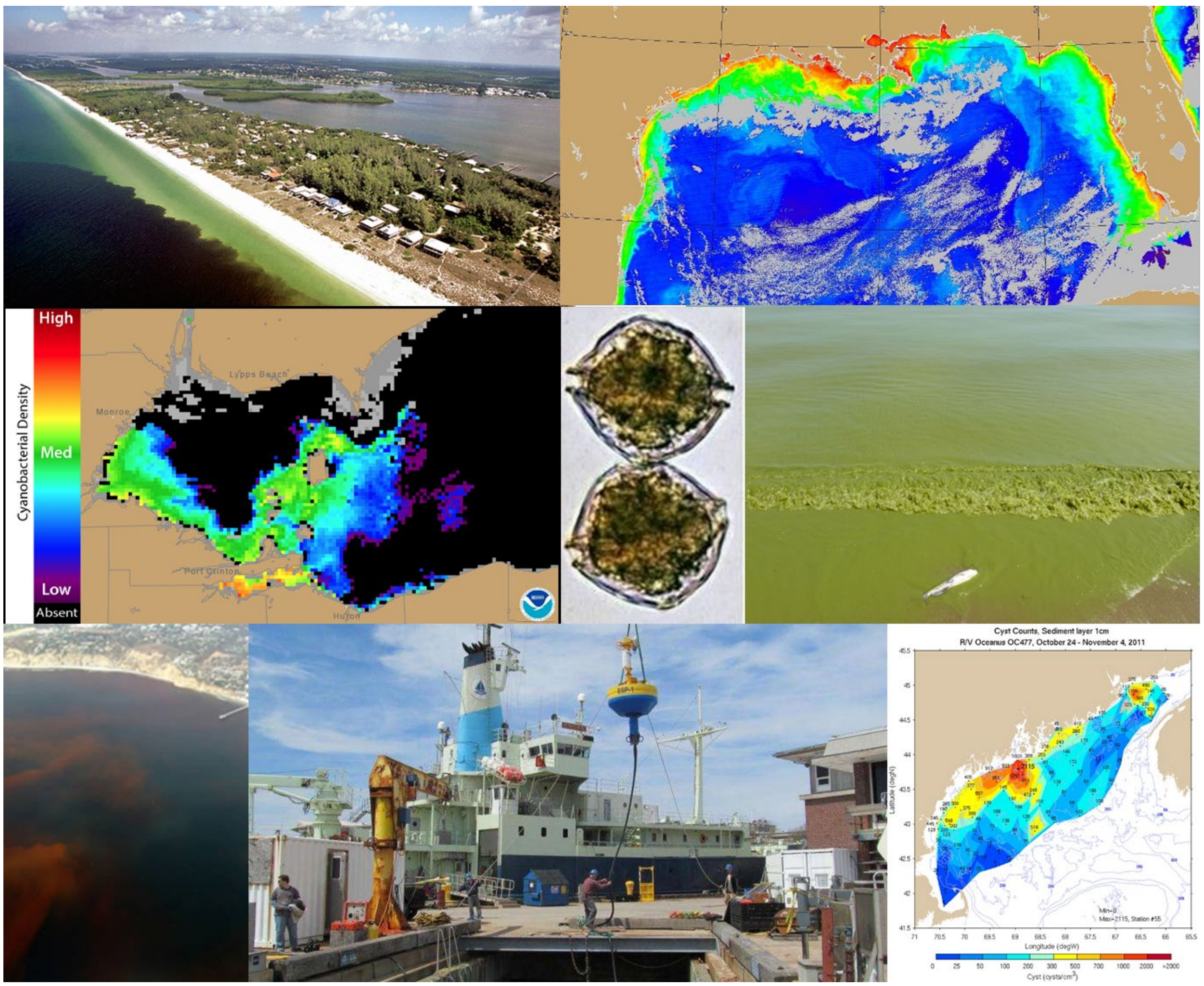
Framework for the National Harmful Algal Bloom Observing Network: A Workshop Report



National Centers for Coastal Ocean Science and
U.S. Integrated Ocean Observing System
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Acknowledgements for cover photos: Top: *Karenia brevis* "red tide" bloom in the Gulf of Mexico (NOAA); Satellite imagery of a *Karenia brevis* bloom (NOAA); Middle: Cyanobacterial density in Lake Erie using satellite imagery (NOAA); *Alexandrium* spp. (Donald Anderson, WHOI); Cyanobacterial bloom in Lake Erie (NOAA); Bottom: *Pseudo-nitzschia* spp. bloom off the U.S. West Coast (NOAA); Ship getting an ESP ready for deployment (WHOI); *Alexandrium* spp. cysts counts (WHOI).

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Executive Summary

Harmful algal blooms (HABs) occur in marine and freshwater environments across the nation. Blooms can be noxious, producing a foul smell or discoloring water, and disrupt ecosystems by shading seagrasses or corals and causing oxygen depletion in bottom waters. By far the most severe impacts are caused by HABs that produce toxins, resulting in sickness and even the death of humans and animals. HABs are estimated to result in annual economic losses totaling at least 100 million dollars. However, a single major HAB event can cost coastal economies tens of millions of dollars, indicating that the nationwide economic impact of HABs is much larger. In recent years, the frequency and duration of HABs, along with the number of species responsible, have all increased. In addition, the geographic range of some HAB species is expanding.

Observations and measurements of HAB species and toxins are critical to support early warning and forecasting. These data also have intrinsic value in assessing bloom toxicity, identifying potential drivers of HAB growth and toxin production, initializing models, and validating airborne/satellite observations and model outputs. Many new HAB observing technologies are now being used as part of regional research efforts and some are deployed with the intent to become part of operational forecast systems. Currently, HAB sensors have been deployed in the Gulf of Maine, Gulf of Mexico, Pacific Northwest, California, and the Great Lakes (Lake Erie). Many of these assets are funded through research projects that have a finite lifespan. When project funding ends, critical observing and data acquisition infrastructure relied upon by forecasters and decision makers can be lost. Additionally, regional HAB observing assets are operated independently of each other so that full integration and leveraging of regional HAB observations are not achieved.

A National HAB Observing Network (NHABON) is needed to efficiently and effectively integrate local, state, regional, and Federal HAB observing capabilities and deliver products operationally. Implementation of the NHABON will achieve the following benefits: enable HAB forecasting and early warning; leverage economies of scale and enhance information transfer between regions; determine algal community baselines and discern patterns/trends to help assess the impacts of climate change, eutrophication, and other environmental forcings; and provide observations to support the National Oceanic and Atmospheric Administration's (NOAA) mission of understanding and predicting changes in our oceans.

This NHABON Framework is the product of an internal NOAA workshop convened at the National Centers for Coastal Ocean Science (NCCOS) and Integrated Ocean Observing System (IOOS) Headquarters in Silver Spring, MD (August 29-30, 2017) (Appendix 1). Representatives from the following NOAA Line Offices participated in the workshop: National Ocean Service; National Marine Fisheries Service; Office of Oceanic and Atmospheric Research; National Weather Service; and National Environmental Satellite, Data, and Information Service. This document offers a high-level regional analysis of existing efforts to monitor and forecast HABs and identifies gaps in observing capabilities that can best be addressed with a national network. The regional context of this network aligns with the IOOS structure that comprises 11 distinct regions, each with a corresponding Regional Association (RA). All the IOOS regions have significant HAB-related issues, but some RAs are further advanced in their monitoring efforts and their ability to detect and/or forecast HAB events is more mature. In addition, each region faces a unique set of HAB-related threats in terms of species presence, environmental conditions, and type and scale of impacts, which necessitates customized, region-specific approaches that are outlined in this document. Herein, the regional capabilities needed to achieve a sustainable national network of HAB-specific monitoring infrastructure are identified and prioritized, and the potential societal benefits and estimated costs of establishing the NHABON are discussed.

This Framework is the first step in developing an NHABON that can ultimately integrate the respective regional HAB observing systems into a single, nationwide network. The next steps to achieve a sustainable NHABON are:

1. Develop an implementation plan
2. Determine a governance strategy
3. Identify and obtain stakeholder support
4. Integrate with the annual budget process
5. Make information publicly available

By executing these next steps towards establishing the NHABON and fully integrating this effort with other environmental observing systems and networks, NOAA can improve resource management, mitigate risks to ecosystem health, ensure the safety of wildlife and humans, protect property and the environment, and expand science and information about HABs.

Framework Vision, Goals, and Geographic Scope

The **vision** for the NHABON is a sustainable[1] national network of HAB-specific monitoring infrastructure, integrated with other environmental observing systems, focused on monitoring HAB organisms and their toxins, with integration of ancillary measurements to build an effective nationwide HAB forecasting system. Monitoring tools can range from fully automated *in situ* HAB cell or toxin monitoring instruments, to cell counts from water samples taken manually from a beach or pier.

The **goals** of the NHABON Framework (this document) are to:

- ➢ Describe current[2] observing capacities at the regional level, including funded and unfunded components
- ➢ Identify and prioritize capabilities needed to achieve an optimized NHABON infrastructure
- ➢ Initiate development of a plan to implement integration of the NHABON into established Regional Associations (RAs) of the U.S. Integrated Observing System (IOOS)

The **geographic scope** of the NHABON is constrained to coastal regions of the United States and its territories, including the area from the high tide line to the edge of the U.S. Exclusive Economic Zone. It also includes that portion of the Great Lakes within U.S. jurisdiction.

Some NHABON observing assets will be purchased or operated with funding provided by the Federal government. Other NHABON assets will be purchased or operated by other entities, such as:

- ➢ state, tribal, and local government public health and/or resource management agencies
- ➢ fish and shellfish industry, i.e. finfish and shellfish aquaculture businesses
- ➢ non-governmental organizations, including IOOS Regional Associations
- ➢ academic institutions

For non-Federal entities, participation will require sharing of data, optimization of asset locations, and coordination of protocols, all of which can be facilitated through

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[1] Sustained observations defined as measurements taken routinely on an ongoing basis, for seven years or more, usually for public services or for Earth-system research in the public interest (NSTC 2014).
[2] Reflects the understanding of participants in the 2017 workshop and those who have subsequently contributed to the development and publication of this document in 2020.

collaboration with IOOS RAs. The more comprehensive the coordination and cooperation, the more cost-effective the collective observing networks will be.

Framework Rationale

There is a critical need for establishment of the NHABON to help coastal communities adapt to the impacts of HABs. This will be achieved by expanding upon the relatively small-scale monitoring programs that have been established with limited, competitive research funds. This expanded program will enable scientists conducting similar types of monitoring to leverage efficiencies of scale by deploying HAB sensors in multiple regions, which could result in more affordable pricing of sensors. Sustained funding for dedicated HAB monitoring is needed to increase the duration, frequency, and/or quantity of sensor deployments. The NHABON will also foster new partnerships through sharing of equipment, data, methods, and troubleshooting capabilities. Having a sustained monitoring presence on our coastal beaches, the Great Lakes, and oceans will form the basis for an optimized early warning and observing network for HABs, thereby increasing the awareness of stakeholders and the public of the scientific effort being invested to mitigate HAB-related human health and environmental concerns.

Background

Harmful algal blooms (HABs) are one of the most scientifically complex and economically damaging coastal issues challenging our ability to safeguard public health and coastal ecosystems. Almost every state in the U.S. has experienced some kind of HAB event (Figure 1). There are many different kinds of HABs caused by a variety of algal species (Figure 2) with diverse impacts and unique responses to changing environmental conditions. For example, three recent blooms with severe impacts illustrate the diversity of HABs, their toxins, and associated impacts.

- 2014 *Microcystis* bloom in Lake Erie (Box 14) caused the city of Toledo to shut down its drinking water plants and supply bottled water for 2 days;
- 2015 *Pseudo-nitzschia* bloom on the West Coast of the U.S. (Box 9) closed Dungeness and rock crab commercial fisheries, razor clam subsistence and recreational harvesting, and forage fish harvesting for months; and
- 2018 *Karenia* bloom in Florida (Box 10) caused respiratory irritation in humans at beaches, mass mortalities of fish, turtles, birds, and marine mammals, and depleted bottom waters of oxygen.

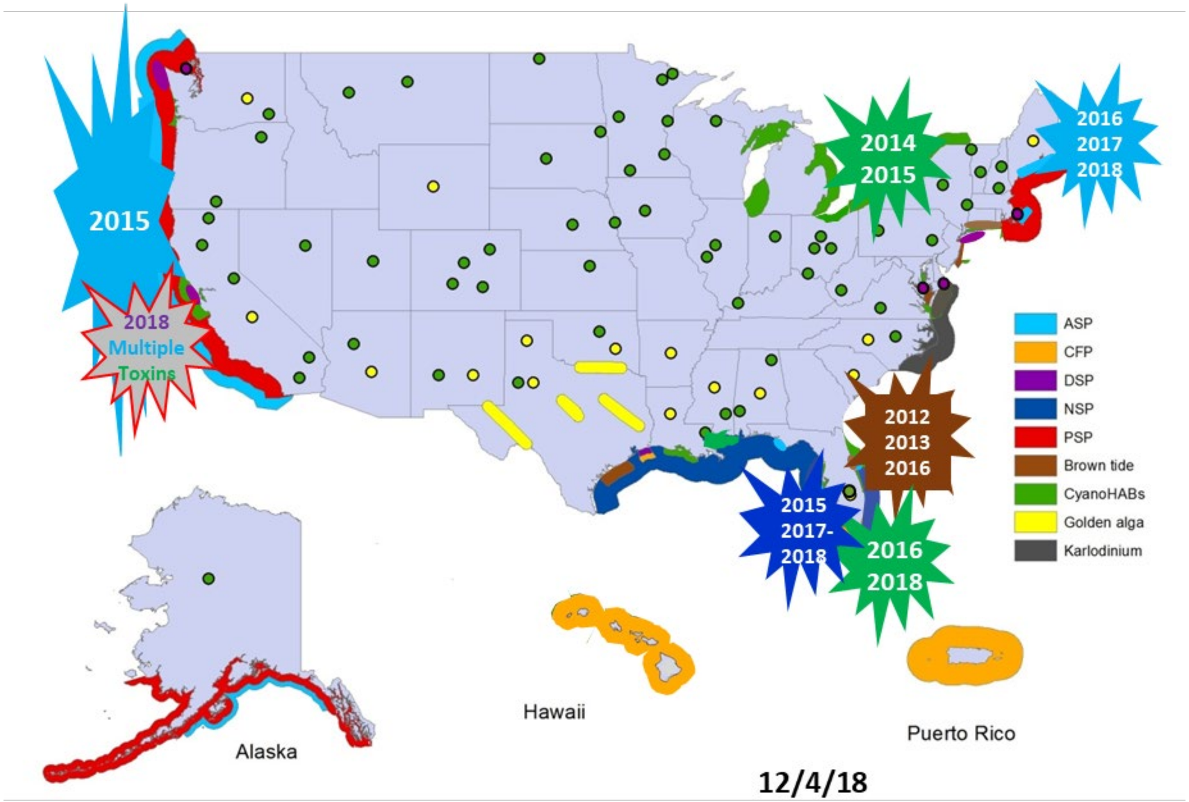


Figure 1. Recent newsworthy harmful algal bloom events across the nation.

Since each region of the U.S. has a complex and often unique suite of HABs and environmental regulators, approaches to monitoring and mitigating HAB impacts must be regionally specific (see regional sections under 'Current HAB Observing Capability' for more details). In 1998, Congress recognized the severity of these threats and authorized the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA 1998; embedded in Public Law 105-383). It was reauthorized in 2004 (Public Law 108-456), 2014 (Public Law 113–124), and most recently in 2017 (Public Law 115-423), reaffirming and expanding the mandate for NOAA to advance the scientific understanding and ability to detect, monitor, assess, and predict HAB and hypoxia events.

The HABHRCA legislation authorized funding for both intramural research and competitive research programs on HABs and hypoxia. Although it mentions HAB observing and forecasting as important activities, it does not provide the authorization to sustain operational HAB observing and forecasting. To fill that gap, NOAA developed an [Ecological Forecasting Roadmap] with operational HAB forecasting identified as a high priority. The NHABON Framework is intended to enable this priority by implementing

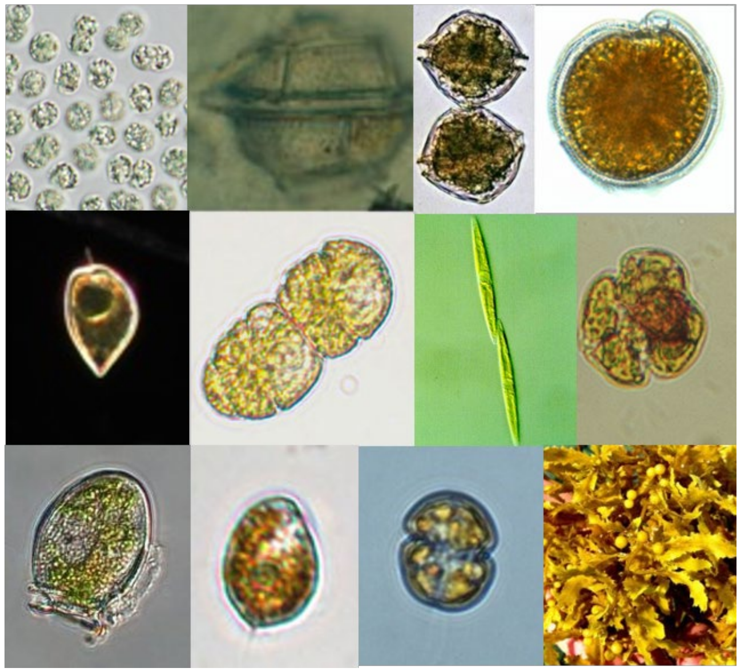


Figure 2. Major HAB genera/species from left to right, top row: *Microcystis* (Barry H. Rosen, USGS)*, Pyrodinium bahamense* (Gárate-Lizárraga and González-Armas 2011)*, Alexandrium* (Donald Anderson, WHOI)*, Gambierdiscus* (Mindy Richlen, WHOI). Middle row: *Prorocentrum, Margalefidinium* (Raphael Kudela, UCSC), *Pseudo-nitzschia* (Greg Doucette, NCCOS)*, Karenia brevis* (MML)*. Bottom row: Dinophysis, Heterosigma akashiwo* (Raphael Kudela, UCSC)*, Karlodinium* (King County, WA)*, Sargassum fluitans* (Gulf Coast Research Laboratory).

operational HAB observing required to support complex forecasts, as well as addressing other early warning needs of resource managers and public health officials.

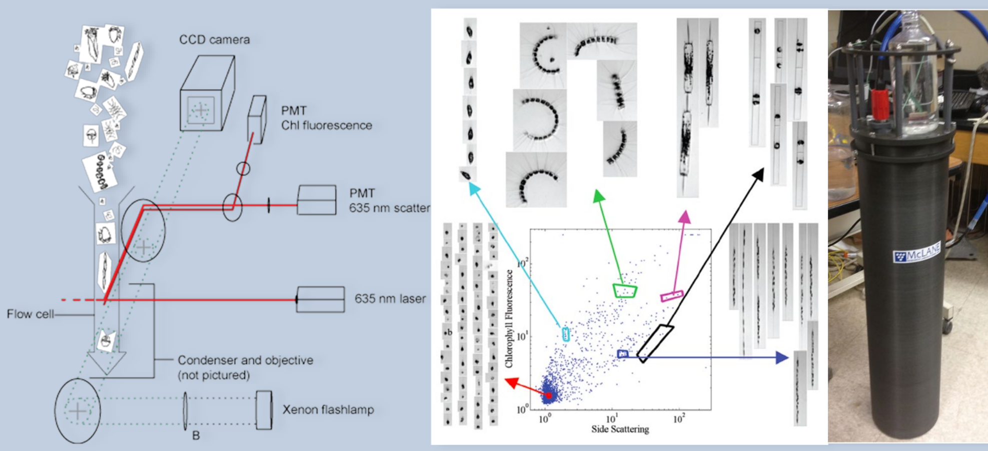
In October 2016, scientists in NOAA's National Centers for Coastal Ocean Science (NCCOS) identified the need for a sustainable observing network for HABs. Scientists in NCCOS and IOOS organized an internal NOAA workshop in August 2017 with participation across many NOAA line offices, including: the National Marine Fisheries Service; National Weather Service; National Ocean Service; National Environmental Satellite, Data; and Information Service, and Office of Oceanic and Atmospheric Research, to initiate broader discussion of the NHABON concept (Appendix 1). This document is informed by discussions with NOAA scientists involved in HAB observing and forecasting during and after the NOAA workshop and with members of the IOOS Association.

HAB Observing Tools and Technologies

Identifying the most appropriate HAB observing tool(s) for a given purpose involves consideration of many factors, including equipment cost, maturity, required data types and frequency, availability of a technique for the target species or toxin, and necessary

Box 1. Imaging FlowCytobot

The Imaging FlowCytobot (IFCB; McLane Research Laboratories), also known as a "microscope-in-a-can," continuously sips ambient water through a very narrow tube. The thin stream flows past a laser with a detector that determines whether or not a cell contains chlorophyll. If it does, a picture is taken and stored. Image analysis software, including classifiers trained to recognize multiple HAB species (and other phytoplankton), identifies and counts cells of HAB taxa. IFCBs can be configured to transmit data in real time, even from remote locations. State public health managers and other users of the data can receive alerts when cell counts exceed a pre-established threshold. All pictures are archived and can be examined later in more detail for taxonomic confirmation or identification (see Box 11 for a HAB example in Texas). IFCBs can be deployed on piers, moorings or autonomous vehicles, installed on ship flow-through seawater systems, or used in the lab.



Pictures. Left: Schematic diagram of the IFCB showing pathway of sample acquisition and analysis. Middle: Plot of chlorophyll fluorescence vs. side scattering, including images of cells corresponding to individual data points (Sosik and Olson 2007). Right: IFCB in laboratory prior to deployment (credit: M. Brosnahan, WHOI).

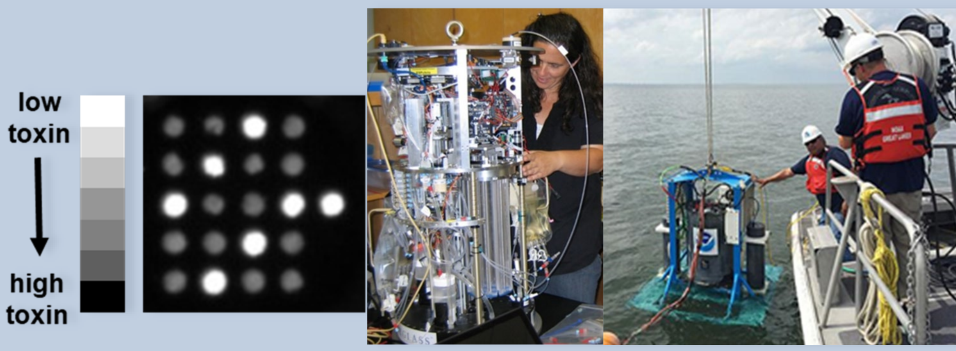
infrastructure. In response to these diverse requirements, developers have designed multiple observing tools and technologies that now allow for HAB species and toxin detection and quantification with speed and accuracy, often under extreme conditions. A few examples are provided below for context, but many more tools and technologies exist or are currently under development (see Doucette and Kudela 2018).

In situ and field-portable cell/toxin detection technologies

The ability to rapidly detect harmful algal species and assess their toxicity is essential for early warning and forecasting of HABs. Technology currently exists for remote, *in situ*[3] detection, identification, and measurement of harmful algal cells and toxins. Examples of such autonomous instruments include the Environmental Sample Processor (ESP),

Box 2: Environmental Sample Processor

The Environmental Sample Processor (ESP; McLane Research Laboratories), or "lab-in-a-can," is an autonomous, robotic instrument capable of remotely determining in-water concentrations of HAB cells and/or toxins. Deployable on a mooring beneath the surface or on a pier, the ESP filters particles from a water sample, extracts the target genetic material or toxin from any captured HAB cells, conducts a molecular biological assay using either genetic (species detection) or antibody (toxin detection) probes, and transmits the results to the operator in near-real time. The ESP's measurements of *in situ* cell or toxin concentrations provide resource managers with early warning of HAB events or are used to inform/validate HAB forecast products for that location. Multiple ESPs have been deployed numerous times in marine (WA and CA coast, Gulf of Maine) and freshwater (Lake Erie) systems.



Pictures. Left: Image of ESP toxin array showing chemistry control features (7 bright spots) and toxin features (14 dimmer spots), along with a grayscale showing that toxin concentration in the assay is inversely proportional to signal intensity. Middle: Core ESP unit on the laboratory bench. Right: ESP contained in pressure housing (large gray can in middle) and integrated with bottom lander (blue frame structure) being deployed in Lake Erie to detect and measure microcystin levels (credits: G. Doucette, NOAA/NCCOS; T. Davis, NOAA/GLERL).

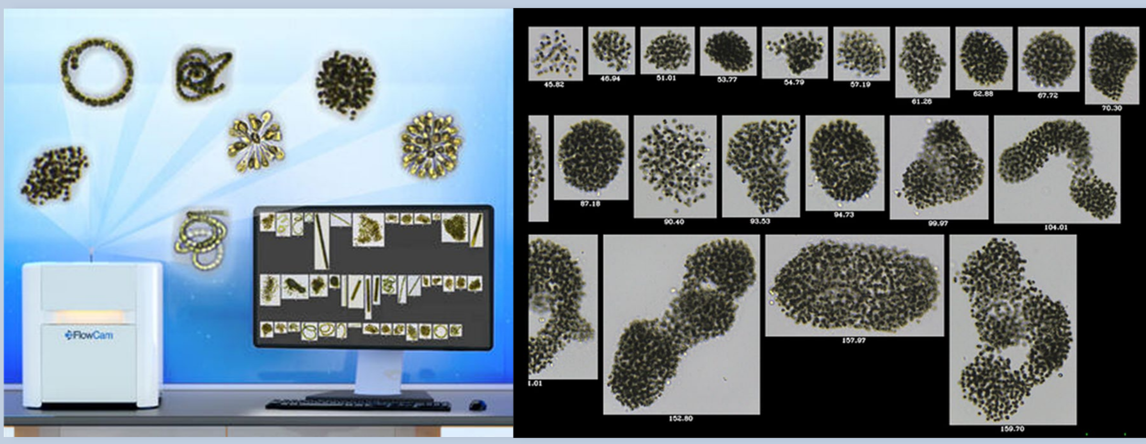
which can identify and report concentrations of cells, toxins, or both, and the Imaging FlowCytobot (IFCB), which collects and identifies images of cells in water to determine the presence and concentration of harmful algal species (see Boxes 1 and 2). The ESP and IFCB, along with the other *in situ* tools listed in Table 1 and in Boxes 3 and 4, have

[3] Detection that is situated in the original, natural, or existing place or position

been deployed in many U.S. coastal regions and, in several cases, have provided data to support resource management decisions.

Box 3: FlowCam

The FlowCam (Yokogawa Fluid Imaging Technologies) is an instrument that combines flow cytometry with light microscope-like optics and is used to obtain images of phytoplankton cells, including those of HAB taxa. The unit is generally employed in the laboratory, but both dockside and shipboard applications have been demonstrated, and material for analysis can be accepted as discrete (live or preserved) water samples or via a flow-through pumping system. The FlowCam has been used to detect and quantify freshwater and marine HAB species, and reasonable correlations with identification and enumeration by standard light microscopy (see Box6) have been reported. Cells of cyanobacteria can be discriminated based on fluorescence of pigments specific to this group and the FlowCam is being used to rapidly screen lake samples for developing blooms. Although image recognition software is available for classifying organisms, a certain level of taxonomic expertise is needed to ensure accurate identification at the genus/species level.



Pictures. Left. The FlowCam Cyano distinguishes cyanobacteria from other algae and particles in samples; software can be used to further characterize specific types of algae in the sample. Right. Images of *Microcystis* captured from a samples taken in the St. Lucie River, FL (2016) using a 10X objective lens and 100 µm flow cell. Credits: Yokogawa Fluid Imaging Technologies, Inc.

Box 4: Optical Phytoplankton Discriminator

The Optical Phytoplankton Discriminator (OPD; Mote Marine Laboratory (MML)), aka the 'BreveBuster', uses the spectral characteristics of photosynthetic pigments in the water to produce a 'fingerprint' of the phytoplankton community present. The OPD references a database of group-specific algal pigment signatures to interrogate the composition of the total phytoplankton community. A unique taxon-specific pigment (gyroxanthindiester), considered a 'biomarker' for *Karenia brevis,* allows the instrument to generate data on its abundance in mixed species assemblages; however, the validity of these data relies on the operator being familiar with the local phytoplankton composition and understanding the potential for co-occurrence of other species containing this (or a similar) pigment. Genus-level identification of cyanobacterial HAB events has also been executed successfully by the OPD. The core unit is a highly flexible instrument that has been deployed in a wide range of configurations, including piers, vessels, subsurface stationary moorings, and autonomous mobile platforms such as gliders.

Pictures. Left: OPD configured for payload of WRC Slocum electric glider. Middle: Slocum gliders carrying OPD payload being prepared in the laboratory for field deployment. Right: Deployment of Slocum glider with OPD payload in west Florida shelf waters (credit: G. Kirkpatrick, MML).

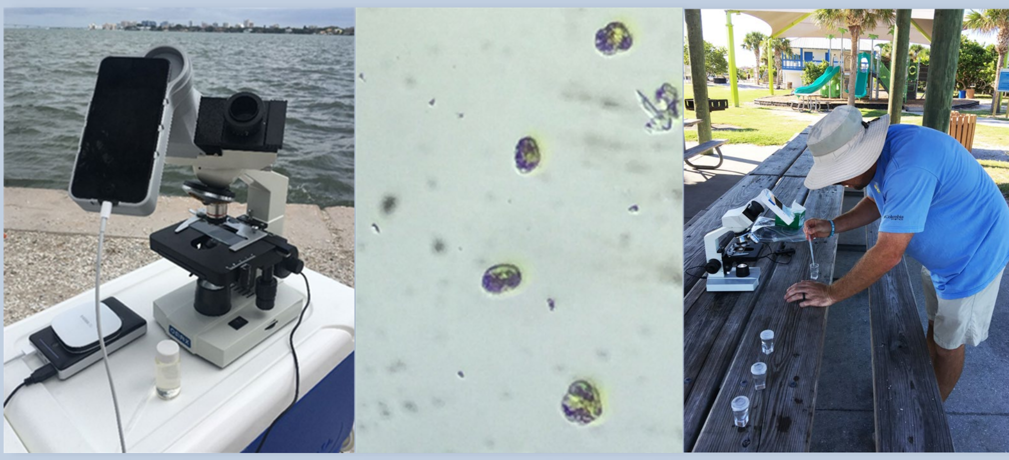
In some cases, human-assisted, field-portable detection of HABs is desired and/or needed. These technologies enable users to bring traditional laboratory-based equipment and methods to field locations, which typically results in a faster turnaround time for generating and disseminating HAB data. An example of a field-portable detection tool is the HABscope (see Box 5), which uses a cell phone attached to a low-cost microscope to capture digital video of cells in a water sample. These videos are then uploaded to a cloud server and an algorithm[4] is used to estimate the concentration of HAB cells in the sample. The HABscope is currently used to detect and enumerate cells of the Florida red tide dinoflagellate, *Karenia brevis*, with recognition of this organism based on its unique swimming behavior. Many of these detection tools also

[4] A process or set of rules to be followed in calculations or other problem-solving operations, especially by a computer.

are designed to be used by people with minimal training or background in HAB science or detection techniques. This then allows for reliable data to be collected across a wide geographic sampling range, while maintaining a relatively low operating cost.

Box 5: HABscope

The HABscope is a new approach to rapid, field-portable identification and enumeration of a specific algal taxon (i.e., *Karenia brevis*), developed recently by NOAA and partners. A water sample is placed in a chamber under a relatively cheap, field-portable microscope. A cell phone with special software monitors the cells' characteristic swimming behavior and automatically counts the number of cells with that behavior and sends those data to a central cloud-based repository. Developed for use by volunteer networks, volunteer network coordinators and data managers are needed to oversee the network and ensure data quality. Testing against known quantities of *K. brevis* cells has shown that the HABscope consistently provides cell counts within 20% of manual microscope counts. Data from the HABscope are being used to inform an experimental respiratory forecast developed under a partnership between NOAA/NCCOS and GCOOS.



Pictures. Left. Image of the HABscope comprising a field-portable microscope, a cell phone, and data storage device (credit: C. Holland, NOAA/NCCOS). Center. Photo of *Karenia brevis* cells as viewed via the attached cell phone (credit: C. Holland, NOAA/NCCOS). Right. Volunteer prepares a water sample for viewing under the HABscope in the field (credit: R. Hardison, NOAA/NCCOS).

Table 1. *In situ* and field-portable HAB detection, including commercial products, available for operational use.

Tool	Detection Method	Species/Toxins	Information Outcome	Find Out More
		In situ		
FlowCam	Discrete samples or flow through; images	Species for which it is trained	Cell concentration	www.fluidimaging.com
IFCB	Discrete sample or flow through; images	Species for which it is trained	Cell concentration	www.mclanelabs.com/imaging-flowcytobot
ESP	Molecular probes, sandwich hybridization; or antibody probes, competitive ELISA	*Pseudo-nitzschia*/ domoic acid; *Alexandrium*/ saxitoxins; *Microcystis*/ microcystins-nodularin; *Heterosigma*	Cell and toxin concentration	www.mclanelabs.com/environmental-sample-processor
CytoSense	Flow through; images	Species for which it is trained	Cell concentration	www.cytobuoy.com/products/benchtop
Optical Plankton Discriminator (OPD)	Pigment absorption profile; spectrophotometer	*Karenia*	Probability that chlorophyll is *Karenia*	www.mote.org/research/program/ocean-technology-research
		Field-Portable/Rapid Test Methods		
LightDeck® System	Antibody probes; fluorescence	Toxins for which antibodies are included	Toxin concentration	mbiodx.com/partners/environmental/
Freedom4 (qPCR)	Molecular probes; real time qPCR	Species for which probes are included	Cell concentration	www.ubiquitomebio.com/environment
AmpliFire	Molecular probes; NASBA/isothermal amplification	*Karenia*	Cell concentration	www.puremolecular.com/products

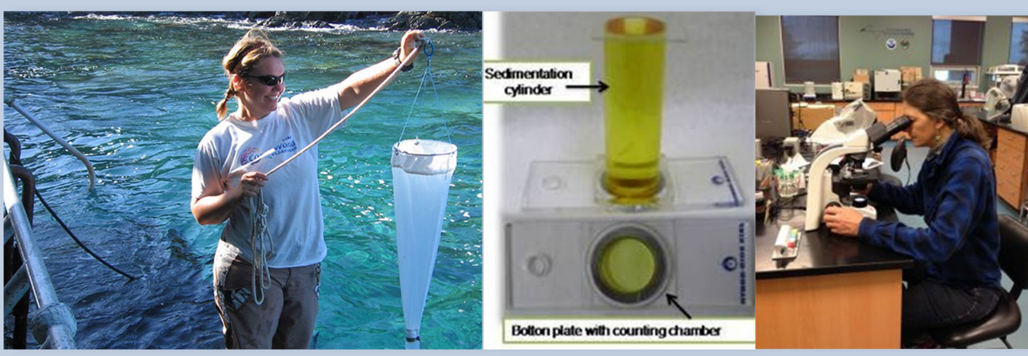
HABscope	Images and swimming behavior	*Karenia*	Cell concentration	www.habscope.gcoos.org/about
SPIRIT	Molecular or antibody probes; refractive index changes	*Alexandrium*; saxitoxin, domoic acid, microcystin	Cell and toxin concentration	www.seattlesensors.com
CyanoDTec and DinoDTec	Molecular probes; real time qPCR	Cyanobacteria and toxin producing genes (microcystin, cylindrospermopsin, nodularin, saxitoxin) and toxin genes (saxitoxin)	Quantify toxin producing gene	www.phytoxigene.com/products
Scotia Rapid Test Kits	Antibody probes; colorimetric test strip	Toxins for which antibodies are included	Toxin presence	www.jellett.ca
Reveal 2.0	Antibody probes; colorimetric plate ELISA	Toxins for which antibodies are included	Toxin presence	www.foodsafety.neogen.com/en/reveal-2
Abraxis Fresh Water Strip Tests	Antibody probes; colorimetric test strip	Microcystins, cylindrospermopsin, anatoxin-a	Toxin presence	www.abraxiskits.com/products/algal-toxins/#dipsticks
Abraxis Shipboard ELISA	Antibody probes; colorimetric test strip	Saxitoxins/PSP	Toxin presence	www.abraxiskits.com/products/algal-toxins/#sxt%20marine
Mercury Science, Inc.	Antibody probes; colorimetric plate ELISA	Domoic acid	Toxin concentration	http://www.mercuryscience.com/DA.html
MARBIONIC Test Kit	Antibody probes; colorimetric plate ELISA	Brevetoxins	Toxin concentration	http://www.marbionc.org/gallery/detail.aspx?id=343974

Laboratory detection

Many monitoring programs collect water or tissue samples in the field and bring them back to the laboratory for analyses. Although not as fast as *in situ* or field-portable techniques, a wide range of these methods is available to detect or quantify cells, toxins, or both (Doucette et al. 2018). These laboratory methods are typically less expensive, but more labor-intensive, than *in situ* and field-portable methods. Some identification techniques, such as standard microscopy (see Box 6), can be used to rapidly determine the presence or absence of cells responsible for HABs or, alternatively, to generate more time consuming, quantitative cell concentration data. Techniques including the enzyme-linked immunosorbent assay (ELISA) and the quantitative polymerase chain reaction (qPCR) can quantify toxins, toxin genes, and/or cells in the laboratory; however, both approaches have been or are currently being adapted for use in the

Box 6. Standard Microscopy

Microscopic cell counts are the standard approach for monitoring cell concentrations. Usually, a water sample is collected, preserved, concentrated, and examined microscopically by a person trained to identify phytoplankton taxa. General or species-specific stains/probes may be used to make cells easier to identify and count. Since a plankton sample from any one region can contain hundreds of algal species, the person analyzing the material must have considerable taxonomic expertise and, depending on how many taxa are identified and how many cells are enumerated, it can take minutes to hours to identify and count the phytoplankton of interest, i.e., only HAB taxa or all taxa. Several days may elapse between collecting samples at multiple locations, transporting samples to a lab that may be far from the sampling site, preparing samples for counting, and then identifying and counting the HAB taxa. However, several monitoring programs have trained personnel and labs set up near the sites of sample collection, allowing for rapid sample analysis.



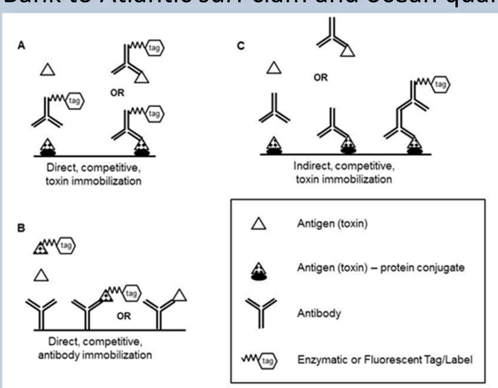
Pictures. Left: Phytoplankton net tow used to obtain qualitative samples for microscopic analysis (credit: NOAA PMN). Chamber used to sediment cells from a known volume of water to obtain quantitative phytoplankton counts (credit: Nitroalboran Project, Spain). Right: Researcher uses a light microscope to analyze samples collected from Kachemak Bay, AK (credit: AK HAB Network).

field (see Box 7). Other more expensive, technically demanding analytical instrumentation (e.g., mass spectrometers) can be used in the laboratory to confirm and quantify algal toxins in complex mixtures.

All states and tribes with commercial shellfish industries must monitor or have a plan for monitoring shellfish toxicity according to the National Shellfish Sanitation Program Guide for the Control of Molluscan Shellfish. This guide specifies methods for analyzing shellfish tissues

Box 7: Rapid toxin testing

A large number of commercial, immunoassay (i.e. antibody)-based toxin test kits are currently available. These kits generally employ an ELISA method that is formatted for use in a 96-well plate, test strip, or cartridge format. The former is configured predominantly for laboratory use and requires a colorimetric or fluorescence-based plate reader to generate results (although portable, hand-held readers are available), whereas output of the latter two, more rapid test types is evaluated visually or via portable reader, making these methods considerably easier to use from a technical perspective and more amenable to field-portable applications. ELISA-based methods are available for use with water samples and extracts of cells or shellfish tissues and cover a wide range of freshwater and marine algal toxins. Preparation of tissue samples for ELISA, especially in the field, can be challenging, and manufacturers have developed several novel approaches to effectively extract toxins from tissues using field-portable equipment and supplies. Two field-portable methods for PSP toxins (one plate or well-based, one lateral flow test strip) were evaluated successfully in a pilot study of the Onboard Screening Dockside Testing Protocol (DeGrasse et al. 2014), resulting in the subsequent reopening of a portion of Georges Bank to Atlantic surf clam and ocean quahog harvesting with use of the Protocol.



Pictures. Left: Schematic showing direct and indirect immunoassay configurations generally used in plated-based ELISA formats (from Doucette et al. 2018). Center: Lateral flow immunoassay test strips for visual PSP toxin detection in shellfish (credit: Scotia Rapid Testing). Right: MBio Diagnostics waveguide-based LightDeck technology with single-use immunoassay cartridge (multiplexed toxin detection capable) and field-portable reader (credit: M. Lochhead, MBio).

for toxins, and the state and tribal regulatory agencies must use these data to close shellfish beds to harvesting for public health protection and when to reopen. While regulatory agencies can use cell counts and particulate toxin measurements to provide early warnings to guide monitoring strategies, regulatory actions and decisions must be based on approved regulatory methods for measuring toxins in seafood.

Sampling platforms

Many different platforms exist to enable sample collection. Small and large boats are used conventionally for nearshore and offshore sampling operations, respectively, for both research and monitoring applications. Citizen science volunteer networks, such as NOAA's Phytoplankton Monitoring Network (PMN), SoundToxins, and the Olympic Region HAB (ORHAB) partnerships can be employed to collect samples at multiple, geographically distributed, shore-based (or nearshore) sampling sites. HAB sensors mounted on buoys, moorings, or piers allow for autonomous sample collection and analysis at fixed locations that are strategically selected using knowledge of local or regional bloom dynamics. Some HAB sensors, such as the ESP and IFCB, have been integrated with autonomous underwater or surface vehicles, to remotely collect and analyze samples across a broad range of temporal and spatial scales under challenging field conditions.

Existing Ancillary Monitoring

There are a variety of monitoring assets already in place that can generate data to inform or predict HAB dynamics. First, multiple satellite-based sensors are used by NOAA's CoastWatch program and by the National Aeronautics and Space Administration (NASA) to routinely collect images of our nation's freshwater and marine environments for a range of applications. These can provide information on the size, intensity, and distribution of algal blooms based on detection of chlorophyll from space, and, in some cases, even specific HABs, when these blooms comprise a large percentage of the overall phytoplankton community.

Second, the National Data Buoy Center (NDBC), as well as the US IOOS, and many states[5] maintain networks of moorings, buoys, and in some places, autonomous underwater vehicles (AUVs) that routinely collect physical, chemical, and biological oceanographic information (e.g., currents, wind, sea-surface temperature, salinity, and nutrient and chlorophyll concentrations). This information can be used to inform physical and biological models of HAB dynamics to create nowcasts and forecasts. These assets also represent physical platforms available for mounting HAB-specific sensors, although siting of buoys does not always target locations based

[5] For example, Maryland (Eyes on the Bay) and Texas (Texas Automated Buoy System)

on optimization for HAB observing. The ancillary physicochemical data from other sensors will provide data on the environmental factors controlling or influencing bloom growth and toxicity to complement data from HAB-specific sensors. Recently, IOOS and NDBC developed a National Strategy for a Sustained Network of Coastal Moorings (IOOS and NDBC 2017) that called out the need for moorings with substantial ecosystem monitoring capabilities aimed at enhancing biological sampling at moorings and buoys around the nation (see McManus et al. 2018).

Third, surveys and cruises designed to collect physical and biological information in marine and freshwater environments provide information about offshore initiation and transport of HABs. For example, cruises along NOAA's hydrographic line off Newport, OR have enabled measurements of conductivity, temperature, depth, surface water transparency, chlorophyll, nutrients, plankton, fluorometry, and oxygen since the 1990s at Heceta Bank, a critical HAB initiation site.

Socioeconomic Costs of HABs across the Nation

The socioeconomic costs of HABs can be significant when direct and indirect effects are considered. Closures of fisheries to commercial, tribal, and recreational harvest, mortalities of fish, and illnesses in humans are all examples of direct costs associated with HABs. However, HABs can also result in decreased seafood purchases by consumers, reductions in recreation and tourism in the affected area, limited aquaculture development or investment in areas affected by HABs, and reduced property values near impacted water bodies. These and other direct and indirect costs are difficult to quantify and there are many gaps in our understanding of factors that influence the socioeconomic costs of HABs (Adams et al. 2018).

Scatasta and Hoagland (2006) estimated the annual economic cost of HABs in the US from 1987-2000 at $103M (in 2018 dollars). The analysis included four impact categories: public health, commercial fishery, recreation/tourism, and monitoring/management; public health costs accounting for about half of the total. The authors also noted that these figures are underestimates because they do not include economic multipliers, the value of untapped or unexploited resources that are closed to harvest, or the effects of delayed harvesting. In addition, the frequency and duration, geographic scope, and the number of HAB-causing species has increased over the years (NCCOS 2018). Hitting us where it hurts: The untold story of harmful algal blooms, is a story map that lays out the impacts of individual events in different geographic locations, which illustrates why the $103M is likely an underestimate. Lastly, certain individual HAB events cause severe economic impacts that equal or exceed the annual averages for the selected study interval in Scatasta and Hoagland (2006). Several recent examples are described below.

The city of Toledo, Ohio draws its drinking water from western Lake Erie. In August of 2014, a toxic cyanobacterial HAB caused the city's water treatment plant to advise against using the drinking water supplied to approximately 500,000 residents for two days. During the event, water usage by restaurants, food facilities (including breweries), and swimming pools was suspended. Bottled water distribution centers were established until the ban on drinking water was lifted (Carmichael and Boyer 2016). An assessment of the economic impacts of this event estimated a loss of $65M in property value, tourism, recreation, and water treatment (Bingham et al. 2015).

In 2015, the Pacific Northwest saw the largest ever-recorded HAB event in the region, which resulted in the closure of the Dungeness crab and razor clam fisheries for many months. These closures prevented human illness but cost the commercial Dungeness crab fishery $97M in landings compared to the previous year (NMFS 2016) and resulted in Federal disaster declarations. Razor clam fisheries attract tens of thousands of recreational fishers to West Coast communities each year (Dyson et al. 2010). Because of the closure, coastal communities in the state of Washington lost about $40M in tourism spending (NCCOS 2018).

Off the southwest Florida Coast, another HAB event began in October 2017 and finally dissipated in February 2019. This greatly impacted the economics of Lee County, one of the five counties affected by the bloom, where an estimated $34M in lost revenue occurred to date. The county's estimates are based on surveys of local businesses involved in paid accommodations, food and beverage, retail, real estate, and other smaller business segments, such as fishing guides, boat rentals, wedding planners, and photographers (ISCCC 2018).

Benefits of the NHABON

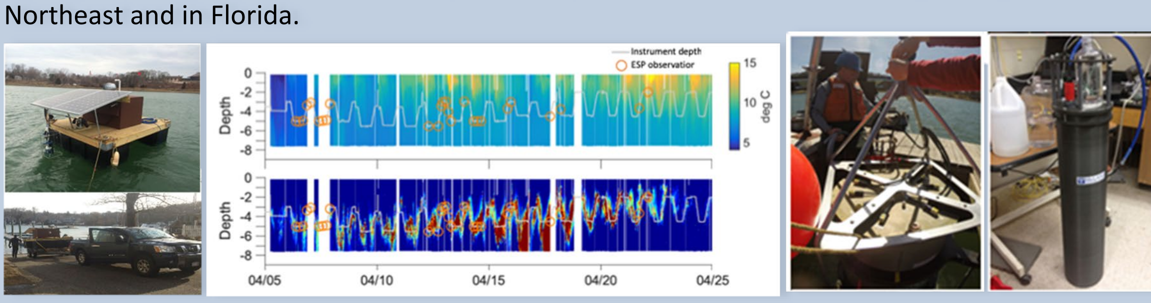
Information from a national observing network of HAB-specific sensors will provide multiple societal benefits on interconnected local, regional, national, and global scales. The economies of scale associated with the NHABON reduces the cost of information transfer between regions. More importantly, the NHABON reduces costs associated with unnecessary or insufficient HAB responses by enabling delivery of more accurate/precise forecasts and other information. Examples include the following:

- Guide decisions by state, local, and tribal resource and public health managers
    - help target shellfish/fish harvesting closures to specific locations
    - enable early harvest of shellfish/fish prior to HAB arrival
    - determine when it is necessary to increase drinking water contamination checks or plan for applying chemical treatments that may be expensive

    - post advisories or close recreational waters only when conditions warrant
- ➢ Allow shellfish/fish industries to make decisions about where and when to fish or harvest (see Box 8)

Box 8. PhytO-ARM: applying high-tech sensors to aquaculture, shellfish harvests, and event response.

As sophisticated HAB sensor technologies become commercially available, it is important to make it easy for a broad range of users to deploy these instruments and harness their data streams to address their many surveillance and monitoring needs. One approach being developed by researchers at the Woods Hole Oceanographic Institution and their colleagues is the PhytO-ARM (Phytoplankton Observing for Automated Real-time Management) platform, which aims to provide aquaculturists and resource managers with detailed, real-time information about HABs and their toxins through a web-based, user-friendly dashboard. PhytO-ARM can be configured in multiple ways, depending on a user's requirements. For example, an IFCB can be deployed with a profiling conductivity-temperature-depth (CTD) to assess the vertical distribution of HAB cells and detect invasive species near aquaculture sites and shellfish beds. These data will inform management actions, as well as the design of aquaculture infrastructure, to mitigate negative impacts. A more sophisticated version of the platform adds a new high-capacity ESP that, when coupled with an IFCB, can provide real-time measurements of dangerous HAB biotoxins and alert aquaculture operators and managers to the potential for shellfish contamination. PhytO-ARMs are integrated with trailered barges that can be deployed quickly in response to unanticipated bloom events. These units will be tested in various configurations over the next several years at aquaculture sites and shellfish growing areas in the Northeast and in Florida.



Pictures. Left top: A PhytO-ARM platform installed in the Nauset Marsh, a HAB "hot spot" on Cape Cod, MA. Left bottom: PhytO-ARM being deployed from a bunk trailer. Middle left: PhytO-ARM data display showing changes in temperature and HAB cell abundance through the full depth of a deployment site. Middle right: Top of an ESP housing as it is deployed on the PhytO-ARM. Right: IFCB shown in the laboratory. On the PhytO-ARM raft the IFCB is deployed adjacent to the ESP (credit: M. Brosnahan, WHOI).

- ➢ Assist the aquaculture industry in building and operating facilities in locations that minimize exposure to HABs
- ➢ Improve public awareness and knowledge about HABs for informed decisions about beach usage, seafood consumption, and tourism choices

- ➢ Track the introduction of HABs to new regions and emergence of new HABs
- ➢ Provide sustained support to existing operational HAB forecasts and drive advancements to models and early warning capabilities
- ➢ Deepen our scientific understanding of the environmental factors driving HAB growth and toxicity, ultimately contributing to better forecast accuracy and methods for prevention and control

NCCOS and IOOS partners and stakeholders critical to a successful NHABON effort include the IOOS Association and its eleven Regional Associations, NOAA's Ocean Acidification Observing Program, and the NSF Ocean Observatories Initiative. Engagement with a wide-range of additional partners will also be important, including Federal agencies, such as the U.S. Environmental Protection Agency, the U.S. Food and Drug Administration, National Aeronautics and Space Administration, the U.S. Geological Survey, the Centers for Disease Control and Protection, as well as state and tribal agencies, fishing and tourism industries and interest groups, drinking/recreational water managers, and various academic and private research institutions.

Costs of the NHABON

Currently, HAB sensors and ancillary measurements are funded entirely through research grants and cooperative agreements (e.g., Texas IFCBs, Gulf of Maine ESPs and nitrate sensors, Lake Erie ESPs, coastal Washington ESP), by private donations, and non-profit, non-governmental organizations (e.g., the Monterey Bay (California) Aquarium Research Institute ESPs, Virginia Institute of Marine Science IFCB). In addition, considerable routine HAB monitoring is being conducted by research programs and state, local, and tribal governments. Thus, monitoring coverage is fragmented and often not sustainable. Although research has demonstrated the value of having HAB sensors for early warning and validating models, it is now time to move the new technology to a sustainable operational status and develop infrastructure for data analysis, display, and management/storage that can incorporate information from diverse sources.

Components of the NHABON could take many forms depending on the local conditions, the type of HAB, the impact of concern, and the interests of the user community and stakeholders. Minimally, it would include sensors at sentinel sites and a data portal that could collect and display data from a variety of sources in near-real time. Stakeholder groups would provide additional data and also contribute to decisions on the data display formats.

The start-up capital, operations, and maintenance costs for several of the technologies or approaches are estimated in Table 2, including the costs of standard microscopy. Initial costs of developing the NHABON can be reduced by phasing in new technologies that offer higher throughput and near-real time data availability. Additional research into improving existing and developing new technologies will provide new, more efficient and cost-effective options. Furthermore, infrastructure (methods of deployment, data management and display) developed by a region for one HAB and sensor type may be adapted to other regions, resulting in cost-savings for these validated systems. Finally, there are likely to be economies of scale and ways to combine technologies to increase efficiencies.

To fully understand the net benefit, new asset acquisition, operation and maintenance, and infrastructure costs must be compared with the cost of current monitoring efforts. The ability of new sensor arrays to reduce HAB impacts should be quantified to help justify the cost of these new assets. For example, if early warning of a HAB event, made possible by a new ESP deployment, allows shellfish to be harvested early and sold or the recreational catch or bag limit to be increased, this may compensate for the cost of the ESP used to inform this management decision. Many states are already using HAB cell counts and in-water toxin measurements to provide early warning and guidance for when and where to sample toxins in shellfish to protect human health.

Furthermore, early warning and forecasting may be able to prevent human illness by offering resource managers and public health officials advance notice of when a toxic HAB may be present at a certain beach, or in a source of drinking water. Although it is difficult to quantify the total cost of human illness in emotional and social terms (Ritzman et al. 2018), prevention of human health effects is likely to be highly valued. This is akin to the National Weather Service's ability to predict major weather events, such as hurricanes and tornadoes, where the health and safety of people justify the cost of weather monitoring and prediction. This type of economic valuation analysis has not yet been done yet for HABs, and is an important next step in justifying and creating the NHABON. There is an NCCOS-supported economic valuation study underway for Lake Erie and the Gulf of Mexico HAB forecasts, with an estimated completion date of January 2021 that should provide more socioeconomic context going forward.

It is likely that funding to support and sustain the NHABON will come from a variety of sources. These will certainly include federal agencies, such as NOAA and the Environmental Protection Agency. Major potential stakeholders, including coastal states and the shellfish industry, especially the growing aquaculture sector, would likely be willing to contribute to the acquisition, operation, and maintenance of observing assets. As an example, Washington State supports the ORHAB monitoring program through a surcharge on recreational shellfish licenses, resulting in sustained cell- and toxin-based monitoring that protect public health and coastal economic interests.

Table 2. Cost details (from 2018) for several HAB observing technologies (see Table 1 for websites).

Technology	Initial purchase	Deployment (if autonomous)	Annual operations, and maintenance	Throughput
ESP	$400,000[1]	$90,000[2]	$40,000	44 analyses/ESP/ deployment
IFCB	$135,000	$50,000	$65,000	30,000 images/hour
HABscope	$500/volunteer	Not applicable	$140,000 (coordinator)	Depends on # of volunteers
FlowCam	$95,000	Not applicable	$2,000	1 sample/ 6 minutes
Standard Microscopy	$35,000[3]	Not applicable	$125,000[4]	10 samples/day

[1] Includes estimated mooring hardware costs
[2] Includes estimated ship time and personnel for offshore deployment
[3] Includes boats, vehicles and microscope
[4] Includes one full-time and one part-time employee

Current HAB Observing Capability

In the following sections, HAB issues, current HAB observing assets and monitoring, and future needs required to address gaps in observations (based on current state of the science) are described for each of the 11 U.S. IOOS regions (Figure 3). Although not all HAB observing capabilities are currently integrated within the relevant IOOS regions, the IOOS regional distinctions are a useful way to highlight capabilities and gaps in existing HAB monitoring efforts in a geographic context.

Our recommended approach for prioritizing capabilities is to address the most tractable problems first, namely those for which technology has already been tested, infrastructure is established, and the human health and economic consequences are most severe. For reference, Figure 4 shows the regions with recent or current HAB monitoring and forecasting. Some of these solutions will also serve as a template for how to address HAB problems in other regions. Smaller investments will then allow expansion of the NHABON into other regions and for additional HAB species. Thus, we propose starting with a basic, but adequate HAB observing system to demonstrate the

Figure 3. Integrated Ocean Observing System (IOOS) Regions.

concept. This system will be built-out and optimized as knowledge, funding, and improved or more cost-effective technologies become available.

Pacific Northwest

The Northwest Association of Networked Ocean Observing Systems (NANOOS) extends from Washington to the Oregon/California border, and includes Puget Sound. Along the coast, and to a lesser extent, in Puget Sound, blooms of *Pseudo-nitzschia* spp., the diatoms that can produce the neurotoxin domoic acid, have caused recurring closures of tribal, recreational, and commercial razor clam and Dungeness crab harvests[6]. The reason for these closures is that domoic acid can bio-accumulate in shellfish, crustaceans, and finfish and be transferred to humans and wildlife through consumption of contaminated seafood. The human illness caused by domoic acid is termed amnesic shellfish poisoning (ASP) due to the distinctive symptom of short-term memory loss, although other symptoms are possible (e.g., nausea, diarrhea, dizziness, seizures, coma). These blooms have had a devastating economic effect on coastal communities, with possible disproportionate impacts on relatively remote coastal tribal communities

[6] https://ioos.noaa.gov/project/detecting-harmful-algal-blooms-pacific-northwest/

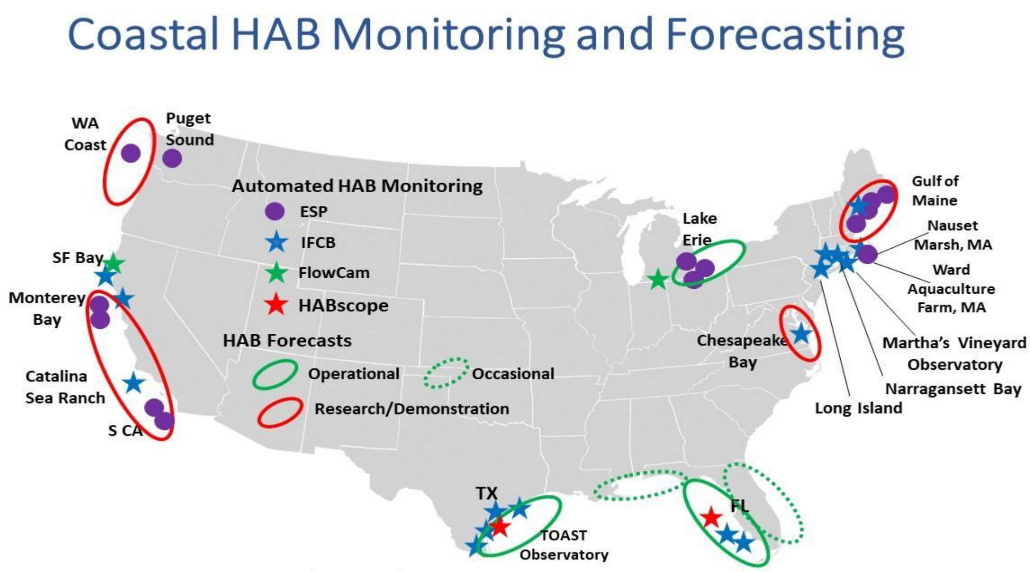


Figure 4. Regions with HAB monitoring and forecasting. These efforts are supported primarily with research funding. Operational forecasts are those that are consistently conducted. Occasional forecasts are those that may be conducted sporadically in response to bloom dynamics. The Environmental Sample Processor (ESP) uses molecular or antibody probes to detect HAB cells or toxins, while the Imaging FlowCytobot (IFCB), FlowCam, and HABscope are automated or semi-automated microscopes that capture images of HAB cells.

because shellfish are an integral part of their culture and a significant source of food and income.

The dinoflagellate *Alexandrium catenella* has caused issues for the shellfish industry, especially in Puget Sound. *A. catenella* produces saxitoxin and many of its derivatives that, upon ingestion of contaminated shellfish, causes paralytic shellfish poisoning (PSP) in humans. Symptoms of PSP include, but are not limited to, loss of coordination, slurred speech, nausea, shortness of breath, and tingling or burning sensations throughout the body. Exposure to sufficient toxin levels may be fatal. Shellfish harvesting closures to prevent PSP occur on a regular basis in Puget Sound. Similar to the Northeast region, where *Alexandrium* blooms are also common, mapping the distribution and abundance of seed-like cysts (Greengrove et al. 2014, Moore et al. 2015) may help predict the location and severity of future outbreaks.

Another dinoflagellate, *Dinophysis,* occurs in coastal waters of WA and OR, and in Puget Sound. It produces both okadaic acid and dinophysis toxins, which can cause diarrhetic shellfish poisoning (DSP) in humans, characterized by symptoms such as diarrhea, nausea, vomiting and abdominal pain. The first DSP outbreak in the U.S. occurred in 2011, when three people became ill from eating shellfish harvested recreationally from closed waters in Sequim Bay, WA (Trainer et al. 2013).

The raphidophyte *Heterosigma akashiwo* can also cause significant impacts in this region, primarily for the aquaculture industry within Puget Sound. Although not toxic to humans, *H. akashiwo* has caused large-scale mortalities of both farmed and wild-caught fish, with costs to the aquaculture industry alone reaching $2-6M per event[7] and concern is growing that it may adversely impact salmon recruitment (Rensel et al. 2010).

HAB-specific monitoring

Current monitoring for HABs and their toxins in this region consists of nearshore water sampling, shellfish sampling, airborne remote sensing of chlorophyll, and an offshore autonomous ESP (see Box 9). Water samples are collected by the Makah Tribe and the ORHAB partnership on the outer coast of Washington State, and by SoundToxins within Puget Sound. Laboratory-based analyses of water samples are used to detect and measure concentrations of cells and toxins. Shellfish sampling is conducted by WA and OR along the coast and in estuaries. Chlorophyll-based remote sensing also occurs in Puget Sound via aircraft by the WA Department of Ecology. Because of frequent cloud cover, satellite imagery is often not available for this region. An ESP has been deployed off La Push, WA multiple times through a research project led by the Northwest Fisheries Science Center and University of Washington, in partnership with NCCOS. The ESP, outfitted with *Pseudo-nitzschia* and domoic acid detection capabilities, was located within a known 'transport pathway' for potential delivery of toxic bloom populations from the Juan de Fuca eddy, a known HAB "hotspot", to coastal beaches that support recreational shellfish harvesting.

Future Needs

Open Coast

Heceta Bank, OR, has been identified as a key location driving coastal HAB dynamics in the Pacific Northwest region. Thus, a second ESP mooring deployed near Heceta Bank would improve forecasting of bloom development to the south. Optimally, a third ESP would eliminate data gaps by providing continued monitoring when either of the other two ESPs was recovered for routine maintenance and/or repair.

[7] https://hab.whoi.edu/impacts/impacts-wildlife/fish-kills/

A limitation of the ESP's utility is the relatively small number of samples (i.e., 44) that can be analyzed before needing to recover the instrument and replenish reagents/ supplies; however, recent engineering modifications have increased its capacity by 50% to 66 samples. A major advantage of the ESP is its ability to measure toxin, as well as cell concentrations, which is critical since the same *Pseudo-nitzschia* species can range from highly toxic to non-toxic. Pairing an IFCB for continuous monitoring of *Pseudo-nitzschia* cells with an ESP to measure toxicity only when *Pseudo-nitzschia* cells are present, would greatly enhance the efficiency of operation and further extend the ESP's deployment duration.

Use of an ESP or ESP/IFCB combination on an autonomous surface vehicle, autonomous underwater vehicle, or glider would allow surveys of cells and toxicity under most conditions. A recent trial was conducted with the Ocean Aero Submaran, a remotely guided surface/subsurface vehicle capable of discrete water sample collection in its ballast tanks. In this spring 2018 trial, water was collected by the Submaran and brought back to the Makah tribal lab for toxin and cell analysis. This remotely operated vehicle will prove useful especially at times when sea conditions are too extreme for small boat sampling of HAB hotspots, such as the Juan de Fuca eddy.

Puget Sound

Although the WA coast can experience different kinds of HABs, Puget Sound and the Strait of Juan de Fuca more frequently experience a wide variety of the HAB organisms described above. SoundToxins provides weekly data, but there is a strong desire to add IFCBs with their high frequency sampling resolution. Sentinel stations for IFCB deployment would be selected based on SoundToxins and historical shellfish monitoring data, and maps of *Alexandrium* cyst abundance in sediments.

California

The Central and Northern California Ocean Observing System (CeNCOOS) extends south from the California/Oregon border to Point Conception. The Southern California Coastal Ocean Observing System (SCCOOS) extends south from Point Conception to the Mexican border. The genus *Pseudo-nitzschia*, a major HAB issue in these regions, has widely distributed blooms occurring on an annual basis (See Box 9). Not only are these blooms problematic for human health, they also can have pronounced effects on marine mammals, including stranding and death (IWC 2017). The economic impacts of these HABs on CA coastal communities can be enormous in some years, such as in 2015, with a prolonged closure of the Dungeness crab fishery (see Socioeconomics). *Alexandrium* blooms are responsible for annual blanket closures of shellfish harvesting in areas inaccessible to routine monitoring, due to the threat of PSP.

California has experienced a variety of other blooms (e.g., *Akashiwo, Margalefidinium* (formerly *Cochlodinium*)), with impacts on wildlife, such as abalone, sea otters, and migratory birds (Curtiss et al. 2008, White et al. 2014), as well as causing water discoloration and bioluminescence (e.g., *Lingulodinium, Ceratium*). Recently, toxin

Box 9. 2015 West Coast *Pseudo-nitzschia* event: A Sign of Blooms to Come?
Blooms of the diatom *Pseudo-nitzschia (PN)* are common on the U.S. West Coast. Some *PN* species produce the potent neurotoxin domoic acid (DA) under certain environmental conditions. However, in 2015, the largest ever-recorded *PN* bloom occurred throughout this region, resulting in mammal strandings and multiple fishery closures from British Columbia, Canada to San Diego, CA. The ability of a particular species of *PN*, *P. australis*, to survive in unusually warm, nutrient-poor waters and its presence along the entire coast prior to upwelling in the spring contributed to the massive scale of the 2015 bloom compared to previous years. Long-term records of DA in razor clams are correlated with warmer years, such as El Niño or the 2015 northeast Pacific marine heatwave, and more frequent DA contamination of shellfish (McCabe et al. 2016, McKibben et al. 2017). The predicted increases in sea surface temperature due to climate change in future years may allow for more frequent blooms with higher toxicity over larger geographic areas (McCabe et al. 2016). Recently, an ESP, capable of rapid, *in situ* measurement of *PN* species abundance and DA concentrations, has been deployed in the transport pathway of phytoplankton from the Juan de Fuca eddy, a "hot spot" where many *PN* blooms originate. Knowing the concentration of cells and toxicity offshore can greatly improve the lead time for model predictions. Providing sustainable funding for an ESP south of the Juan de Fuca eddy and several other hot spots along the coast will greatly improve early warning of DA events.

Pictures. Left: Razor clam diggers on the Washington coast; Middle: Processing razor clams for commerce, (credit: Quinault Indian Nation); Right: Deployment of ESP near La Push, WA and south of the Juan de Fuca eddy, for remote, near-real time detection of *PN* and DA (credit: S. Moore, NWFSC).

measurements in San Francisco Bay have shown that individual shellfish there can contain as many as four HAB toxins, with some above regulatory limits. Although San Francisco Bay is closed to commercial shellfish harvesting, urban subsistence harvesting is common in the area (Peacock et al. 2018). Together, the presence of multiple toxins and harvesting shellfish from closed areas justify the need for implementing routine monitoring.

HAB-specific monitoring

Along the California coast, HAB cell concentrations are measured weekly by collecting water samples at eight shore stations as part of the California HAB Monitoring and Alert Program (CalHABMAP). Every two weeks, the CA Department of Public Health (CDPH), Marine Biotoxin Monitoring and Control Program, collects shellfish tissue from approximately 100 sites coast-wide to monitor for HAB toxin presence and concentration. The CDPH Phytoplankton Monitoring Program also collects weekly water samples from approximately 160 sites coast-wide to determine the relative cell abundance of HAB taxa. The University of California-Santa Cruz monitors HAB cell concentrations weekly at the Santa Cruz Wharf and the Monterey Municipal Wharf. A photometer (i.e., NASA's seaPRISM) has also been installed near Catalina Island to help validate satellite chlorophyll data. In addition to these monitoring programs, SCCOOS publishes a monthly CA HAB Bulletin, and produces the daily CA-Harmful Algae Risk Mapping nowcast and three-day forecasts for *Pseudo-nitzschia* and domoic acid risk along the CA and southern OR coasts. This system is currently in the process of transitioning to a NOAA operational forecast.

Both ESPs and IFCBs are being deployed in California waters. The ESP was initially designed and developed at the Monterey Bay Aquarium Research Institute to monitor *Pseudo-nitzschia* and other phytoplankton and microbial taxa. The ability to monitor HAB toxins, including domoic acid, was added to the ESP through a collaboration with NOAA/NCCOS scientists (Doucette et al. 2009). ESPs have been deployed during multiple high-technology field campaigns in Monterey Bay and off San Diego, but none are deployed routinely. IFCBs are in use at several coastal stations, at the offshore aquaculture facility, Catalina Sea Ranch, and as part of a USGS ship-based mapping program in San Francisco Bay.

Future Needs

Monitoring in these regions has focused largely on nearshore waters, with minimal effort to developing offshore sampling. Further, a potential new offshore HAB hotspot near Trinidad, CA has been identified, which may be another source of toxic blooms affecting OR and WA (McCabe et al. 2016). Results of a U.S. West Coast case study (Frolov et al. 2013) suggested that a combination of shore-based and several (5-10) offshore moorings would provide an effective HAB observing network for the region. As offshore aquaculture expands, use of these sites in combination with AUVs as observing platforms might also help address the need for offshore data. In addition, incorporating recent advances in autonomous HAB sensors (e.g., ESP, IFCB), which can detect cells and toxins at offshore sites, along with satellite optical water mass characterization and modeling efforts, could further improve early warning and forecasting capabilities.

Gulf of Mexico

The Gulf of Mexico Coastal Ocean Observing System (GCOOS) extends from the Florida Keys westward to the southern tip of Texas. The major HAB issue in this region is the dinoflagellate *Karenia brevis* (see Box 10), which produces a suite of toxins called brevetoxins. Ingestion of these toxins, which bio-accumulate in shellfish, can lead to neurotoxic shellfish poisoning (NSP), with symptoms that last for several days, including, but not limited to, tingling, reversal of hot-cold temperature sensation, muscle pain, vertigo, loss of coordination, nausea and diarrhea. An additional route of exposure is from aerosolized toxins released by cells broken apart in wave action at beaches and carried by onshore winds, resulting in respiratory irritation in healthy populations and more severe illness in those with pre-existing respiratory conditions, such as asthma. Brevetoxins can also kill fish, sea turtles, birds, and marine mammals, including protected species. *K. brevis* blooms, which occur almost annually in the late summer and

Box 10. Monitoring for *Karenia brevis:* the Role of Sensors

The IFCB and HABscope (Boxes 1 and 5) are two new sensor technologies for detecting the dinoflagellate *Karenia brevis*, the Florida red tide organism, that could be combined with existing satellite-based red tide and cyanobacterial HAB monitoring to protect public health, recreation, and aquaculture in the Gulf of Mexico. At present, these technologies have been tested in a few locations with funding from research programs.

Implementation of a Gulf-wide HAB observing system that incorporated these two technologies, as appropriate, would vastly improve HAB monitoring and early warning, protecting the public from threats of shellfish toxicity. It would also feed into the existing satellite red tide forecasting (FL, AL, TX) so that it would be possible to predict respiratory impacts on every beach, every day. Finally, improved HAB monitoring and prediction will support development of the Gulf aquaculture industry. Without these tools, Florida is limited to daily (or less frequent) shore-based sampling and a few offshore cruises per year.

early fall, can extend into early spring or even last for several years. Because of the frequency, duration, and highly visible red discoloration of the bloom, as well as associated fish kills and human respiratory impacts, the coastal tourism and recreation industries can suffer large economic losses when blooms occur.

The Gulf of Mexico region also experiences blooms caused by a species of the dinoflagellate genus *Dinophysis*. The DSP toxins produced by this HAB organism have been responsible for multiple shellfish harvesting closures along the Texas coast (see Box 11). In addition, the diatom genus *Pseudo-nitszchia*, which resulted in Florida's first shellfish harvesting closure due to domoic acid contamination in 2017, is an emerging concern in the region. A number of Florida coastal embayments also experience blooms of the PSP toxin-producing dinoflagellate *Pyrodinium bahamense*. Recreational fishing for puffer fish, which can accumulate PSP toxins, has been closed in some areas since 2004[8] to safeguard human health.

Box 11. The Emergence of *Dinophysis* in Texas
In 2008, an IFCB (Box 1) was deployed on a pier at the entrance to the Mission-Aransas Estuary in the Gulf of Mexico to continuously monitor for *Karenia brevis* abundance. No *Karenia brevis* blooms occurred in Texas in 2008; however, the IFCB did allow for detection of *Dinophysis*, another potentially harmful dinoflagellate associated with DSP, from mid-February through March. The IFCB's detection of *Dinophysis* gave resource managers early warning of a bloom and informed decisions to close oyster harvests and recall product to prevent DSP illnesses, a first in the U.S. This alert and regulatory action occurred just before the annual Fullerton/Rockport Oysterfest (~30,000 attendees) and thus prevented many people from becoming sick (Campbell et al. 2010). Since its deployment, the IFCB has provided seven additional early warnings of HABs and no cases of human illness have been reported (L. Campbell, TAMU; pers. comm.).

Several areas in the Gulf of Mexico have had recurrent cyanobacterial blooms in low salinity estuaries, mostly microcystin-producing *Microcystis*, with potentially toxic *Dolichospermum* (formerly *Anabaena*) and *Cylindrospermopsis* also being abundant. Most notable were the toxic blooms that occurred in Lake Okeechobee in 2016 and 2018, which were transported during planned water releases into rivers and flowed to the Atlantic coast (2016) or the Gulf coast (2018), where they affected a number of communities. In Louisiana, Lake Pontchartrain and several other estuaries, at times, have had large, and sometimes toxic, cyanobacterial blooms and, coupled with freshwater diversions, there is an increasing likelihood of these blooms being

[8] https://myfwc.com/fishing/saltwater/recreational/puffer/

transported into the coastal zone (Bargu et al. 2019). The recently established accumulation of cyanobacterial toxins in marine shellfish (Gibble et al. 2016) may necessitate monitoring for cyanobacterial cells and toxins in low-salinity coastal waters.

HAB-specific monitoring

The states of Florida and Alabama routinely collect coastal water samples to assess the presence and concentration of harmful algal cells. In Florida, the FWC/FWRI-Mote Marine Laboratory (MML) Cooperative Red Tide Program conducts periodic offshore transects to assess offshore blooms of *Karenia* that can initiate and feed the coastal blooms. In Texas, IFCBs funded almost entirely by research programs, are located at sentinel sites in Port Aransas, Surfside, and Galveston Bay. When early warning indicators, such as IFCB cell counts or increases in fish kills and respiratory irritation are reported (GOMA 2014), the state obtains samples by calling out the Red Tide Rangers or Texas state employees. In Florida and Texas, NOAA is testing the HABscope with volunteer networks that can provide more extensive temporal and spatial sampling coverage. A photometer (i.e., seaPRISM), which detects wavelengths of light reflected by surface water, has also been installed in the Gulf of Mexico to help validate satellite data.

Louisiana and Mississippi, which rarely experience marine HABs, have contingency plans for responding when blooms approach from neighboring states. For *K. brevis*, shellfish harvesting closures are based initially on cell counts, but reopening harvesting requires shellfish toxicity testing after cells counts have receded to below the regulatory limit. For other species and toxins, regulation of shellfish harvesting is based exclusively on measuring toxin levels in shellfish.

In addition, the MML owns several OPDs (see Box 4), deployed at fixed locations and on autonomous vehicles, to provide real-time information on phytoplankton species present in the water (with a focus on *K. brevis* detection). The MML also conducts daily monitoring to determine the level of respiratory irritation during *K. brevis* bloom events. The survey results are combined with information on the presence/absence of dead fish, wind direction, water color, and any lifeguard flags that may be flying, and shared with the public. This information is available for 26 beaches and is updated twice daily year round.

Besides providing early warning, the observations described above are used, along with remote sensing data and oceanographic models, by multiple HAB forecasts. NOAA provides operational forecasts of respiratory irritation and bloom movement along the coasts of Florida, the northern Gulf of Mexico, and Texas[9]. With funding from NOAA, the state of Florida and the University of South Florida are also working on short-term and seasonal forecasts for *K. brevis*[10]. *Karenia* observations from the Gulf States are also compiled, displayed, and archived through NOAA's Harmful Algal Blooms Observing System (HABSOS).

Future Needs

The most promising technologies, IFCBs, OPDs, and HABscopes, which have already been tested in this region, need to be transitioned from research to operations. In addition, enough cell count data exist for Florida and, possibly Alabama, to choose sentinel sites for locating additional IFCBs at HAB hot spots for early warning, thereby forming a multi-state observing network. Since blooms in this region can originate below the sea surface, developing a profiling or subsurface monitoring capability will be important. Although the main focus would be on *Karenia*, strategically located IFCBs would provide early warning about *Dinophysis*, *Pyrodinium*, and *Pseudo-nitzschia* blooms as well. Deployment of ESPs equipped with toxin sensors in areas where HABs have caused shellfish harvesting closures would be beneficial, and may also be useful for predicting human respiratory irritation.

Volunteer networks, using HABscopes or other easy-to-use technologies, should continue to be expanded to additional areas with frequent *Karenia* blooms and a large tourism industry. Expanded use of gliders, making routine transects of physical properties, chlorophyll, and *Karenia* abundance, would provide valuable water column data for models predicting short-term and long-term *Karenia* blooms.

Southeast

The Southeast Coastal Ocean Observing Regional Association (SECOORA) spans the coastal ocean from NC to the west coast of FL. As mentioned above in the Gulf of Mexico section, the major HAB concern in Florida is *K. brevis*, which is predominantly an issue along the Gulf coast. However, *K. brevis* cells can be entrained in the Gulf Stream and delivered to the Atlantic coast of Florida and as far north as NC (e.g., Tester et al. 1991), with potentially severe impacts to shellfish growing and harvesting areas in that region. On the Florida East Coast, the Indian River lagoon has suffered devastating blooms of the *Aureoumbra lagunensis* (Texas Brown Tide), *Pyrodinium bahamensis*, and

[9] https://tidesandcurrents.noaa.gov/hab_info.html
[10] http://ocgweb.marine.usf.edu/hab_tracking/

cyanobacteria and estuarine cyanobacterial blooms have been a common problem in other areas. Other HAB organisms of concern in the southeast region that were not already mentioned in the Gulf of Mexico section include several fish killing genera, such as *Margalefidinium* and *Karlodinium*. Coastal stormwater retention ponds are replete with fish-killing HAB species.

HAB-specific monitoring

Monitoring for HAB species in this region relies predominantly on the manual collection of water samples. In the South Atlantic Bight, the South Carolina Department of Natural Resources collects water samples from 30 sites once each summer to assess chlorophyll concentration. On the Florida Atlantic coast, the Florida Fish and Wildlife Conservation Commission's Florida Fish and Wildlife Research Institute collects and analyzes semi-weekly, shore-based water samples to determine the presence and concentration of harmful algal cells. This information is used to inform the operational *K. brevis* HAB forecast for Florida. NOAA's PMN also collects water from multiple sites in this region to assess the presence of harmful algal cells. SECOORA funds buoy and coastal station operations on the West Florida Shelf, collectively known as the USF Coastal Ocean Monitoring and Prediction System, which provides data input to support USF HAB forecasts. In addition, SECOORA hosts a webpage that pulls together various Florida red tide resources, ranging from the FWC status updates to modeling and forecasting outputs, as well as web camera feeds.

Future Needs

In addition to the recommendations made in the Gulf of Mexico section, the use of IFCBs placed in a few key onshore locations throughout this region from NC to GA, perhaps in association with those planned by MARACOOS and recommended for GCOOS, is likely to improve HAB early warning. The information generated by the IFCBs could be used to develop routine HAB nowcasts and forecasts for this region, as well as improve the understanding of HAB and general phytoplankton population dynamics.

Northeast

The Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS) extends from the Canadian Maritime Provinces south to the New York Bight. The major algal genera responsible for HABs in this region are the same as those occurring in the Pacific Northwest: *Alexandrium* and *Pseudo-nitzschia*. *Alexandrium* has been responsible for annual blooms and PSP-related shellfish harvesting closures in this region since a massive and widespread event in 1972. There is considerable inter-annual variation in the distribution and severity of impacts across the region, including periodic offshore blooms on Georges Bank. Some marine mammal mortality events (Geraci et al. 1989) and, perhaps, sub-lethal effects may result from exposure to PSP toxins, as well as domoic acid (Doucette et al. 2006, 2012; Leandro et al. 2010).

Pseudo-nitzschia, historically present in New England waters, emerged as a public health threat in 2016, when domoic acid levels exceeded regulatory limits for safe human consumption of shellfish, resulting in shellfish harvesting closures and significant product recalls. Although the environmental drivers of these blooms remain uncertain, the presence of highly toxic cells of *P. australis*, a species typically reported only on the U.S. West Coast (see Box 10), was an unexpected finding.

An emerging HAB genus in the region is *Margalefidinium*. This dinoflagellate has been present on the east coast of North America for many decades, but the frequency and the geographic scale of events has increased in recent years. Although not known to affect human health, the toxins released by this genus can be toxic to fish, shellfish, and many other marine organisms (Kudela and Gobler 2012). Since 1985, some coastal bays have experienced blooms of *Aureococcus anophagefferens*, the Long Island Brown Tide organism, which has caused the decline of local shellfish fisheries and submerged aquatic vegetation (Gobler et al. 2005). These organisms have delayed shellfish restoration efforts and may be a threat to the growing aquaculture industry.

HAB-specific monitoring

Monitoring for HABs in this region includes water and shellfish samples, as well as the use of both IFCBs and ESPs. Each of the six states in this region (ME, NH, MA, RI, CT, NY) routinely collect shellfish samples to assess toxin levels during the bloom season. If toxin concentrations exceed action levels established by the 2017 National Shellfish Sanitation Program Guide, sampling may become more frequent. In order to provide early warning of bloom events, nearshore water samples for cells counts and toxin analysis are also collected in most states using state-supported and volunteer networks.

Researchers at the Woods Hole Oceanographic Institution (WHOI) own multiple ESPs and IFCBs, originally purchased with funding from NSF, EPA, and NOAA. The ESPs have been configured to detect and estimate cell concentrations of multiple HAB species, especially *Alexandrium* and *Pseudo-nitzschia* and, sometimes, to detect PSP toxins using an NCCOS-developed toxin sensor. These instruments have been deployed in the Gulf of

Maine as part of NOAA, NSF, and National Institute of Environmental Health Sciences funded projects to test their use as part of an early warning network, to validate the Gulf of Maine HAB forecast, and to support model development for predicting shellfish toxicity. These projects successfully deployed ESPs in onshore and nearshore locations, at several NERACOOS buoys, and even in the Bay of Fundy, where huge tidal ranges result in extremely strong currents. Nitrate sensors, deployed at the same time on NERACOOS moorings, have added critical contextual data to help better understand environmental drivers of HABs.

Box 12. An Autonomous, Monitoring Network in the Gulf of Maine
The coastal Gulf of Maine region supports extensive bivalve shellfish resources, which can become toxic for human consumption by ingesting cells of toxin-producing algal cells. Harvesting closures vary considerably each year and can cause severe economic losses exceeding $10M's in some years. NOAA and its partners seek to sustain an autonomous monitoring network in the region, comprised of ESPs and IFCBs, in both fixed and mobile formats. Pilot networks provide real-time data to resource managers on cell concentrations, as well as bloom toxicity (ESP). The ESP network of HAB sensors is also being used to better understand the origins of PSP toxicity, and the life cycle rates and behavioral patterns in natural phytoplankton populations to improve our assessment and prediction of phytoplankton community dynamics in the Gulf of Maine. Overall, these observations will contribute to early warning and to the development of accurate forecasts of these potentially devastating toxic blooms, which are priorities for NOAA as well as diverse stakeholders in the region.

Picture. Left: Monitoring network in the Gulf of Maine. Right: ESP mooring configuration as deployed in the Gulf of Maine. Credit: D. Anderson, WHOI.

Seasonal and weekly forecasts of *Alexandrium* blooms in the Gulf of Maine are being transitioned to operations. Regional *Alexandrium* cyst maps initiate the forecast models. Sustained deployment of ESPs, now only available as part of short-term research projects, could provide cell count data to supplement limited cell counts from later in the bloom season and be used to compare with model outputs in order to improve the accuracy of forecasted bloom movement and intensity. Deployment of ESPs near shore would improve model coverage of more inshore waters, which has been requested by state shellfish managers.

With funding from Massachusetts Sea Grant, IFCBs and ESPs have been deployed simultaneously in Salt Pond, MA, in the Nauset Marsh System, where an *Alexandrium* bloom occurs every spring. These deployments tested the feasibility of using the IFCB to identify and count cells, and the ESP to measure PSP toxins to better understand and predict *Alexandrium* blooms. In one year, a *Dinophysis* bloom occurred instead of an *Alexandrium* bloom, with the IFCB providing early warning to local shellfish managers that prevented human illness. Expanding this work, an NCCOS funded WHOI HAB Observing Network-New England (HABON-NE) pilot project is deploying the ESP and IFCB at several locations along the New England coast, and one IFCB will be deployed from an autonomous boat enabling adaptive sampling of offshore blooms (see Box 12). This extensive network of advanced sensors will enable year-round monitoring of *Alexandrium,* as well as emergent HAB species like *Pseudo-nitzschia* and *Dinophysis*. Data on HAB cells and their toxins, model outputs, and management actions will be shared with resource managers and through the web-based WHOI HAB Hub, an open source platform readily adaptable to other regions of the country.

Future Needs

Research funding in this region will maintain the deployment of HAB sensors for a few more years, with the aim of optimizing a monitoring network based primarily on ESPs deployed in the Gulf of Maine. Efforts are being made to link *Alexandrium* cell counts, obtained using onshore and nearshore ESPs, to PSP toxin levels in shellfish, thus demonstrating their utility to shellfish managers. Once this research is completed, there is a need for sustained funding to deploy ESPs in the appropriate locations.

Using coupled IFCBs and ESPs would be more effective, although expensive up front. The IFCB would sample continuously until the organism of interest exceeded a threshold, then the ESP could conduct *in situ* analyses to determine toxicity, and in the case of *Pseudo-nitzschia*, determine the species present using molecular probe technology. This adaptive approach would allow the ESP to sample more strategically during the bloom and facilitate extended deployments. It may be beneficial to add ESPs and IFCBs at more coastal sites south of the Gulf of Maine, where toxic blooms can also impact shellfish resources. The offshore clam fishery would also benefit from remote HAB monitoring (e.g., by ESP) on Georges Bank.

At present, the understanding of *Pseudo-nitzschia* blooms in the Northeast is not adequate enough to assess the observing needs for domoic acid. Once the best sentinel sites have been identified, deployment of ESPs with toxin analysis capability is required because *Pseudo-nitzschia* cells can be present and with highly variable toxin levels (including non-toxic).

Mid-Atlantic

The Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) covers the region from Cape Cod, MA, to Cape Hatteras, NC. The algal taxa responsible for HABs in the northern part of this region include the same toxin producing genera as seen in the Pacific Northwest and the Northeast (i.e., *Alexandrium catenella*, *Pseudo-nitzschia*, and *Dinophysis*). Toxic *Karenia* outbreaks, while less common, are also a concern. There are also growing problems with a variety of HABs that do not threaten human health, but can have significant impacts on commercially valuable shellfish and finfish (i.e., *Margalefidinium*, *Alexandrium monilatum*, Long Island Brown Tide or *Aureococcus anophagefferens*, *Karlodinium venificum*).

Box 13. Sensors in the Mid-Atlantic Provide Early Warning of Emerging HAB Species
Numerous HAB species of concern occur in the mid-Atlantic region. *Microcystis aeruginosa*, *Pseudo-nitzschia*, *Prorocentrum minimum*, *Karlodinium venficum*, *Margalefidinium polykrikoides*, and *Aureococcus anophagefferens* are the focus of monitoring programs that utilize a range of HAB detection technologies, including satellite and aerial-drone remote sensing, molecular assays, and traditional microscopy. More recently, several species have emerged as concerns for regional seafood producers. These include *Chattonella subsalsa*, which has been associated with fish kills and can produce brevetoxin-like compounds, and *Dinophysis* species, whose toxins have been linked to outbreaks of diarrhetic shellfish poisoning (DSP) in humans elsewhere in the U.S. Another species, *Alexandrium monilatum* threatens rapidly expanding shellfish aquaculture interests, which in VA alone is worth $54M. In VA's lower Chesapeake Bay region, recurrent blooms can produce a toxin lethal to fish and shellfish. Active research efforts are assessing HAB risks to oyster stocks, blue crabs, and striped bass, while evaluating the use of new HAB sensors, like the IFCB and passive in situ toxin samplers, for integration with existing monitoring to provide for HAB early warning.

HAB-specific monitoring

Mid-Atlantic coastal states routinely collect shellfish samples to assess toxin levels during the bloom season and increase sampling frequency if toxin levels exceed the regulatory threshold in order to ensure safe shellfish harvest and compliance with the National Shellfish Sanitation Program (NSSP). States also operate and maintain various types of HAB early warning and surveillance programs using satellite, airplane, and aerial-drone remote sensing to locate and track potential blooms (VA and NJ). They help guide the collection and analysis of water samples for phytoplankton cell counts and measurement of dissolved toxin levels. Investigations of fish kills are also conducted by state agencies, universities, and volunteer networks[11]. Examples of HAB sensor use in this region include an IFCB deployed by the Long Island Sound Observatory, and the installation of a seaPRISM photometer on Long Island Sound. An IFCB located at the Virginia Institute of Marine Science is also helping to monitor HABs in the lower Chesapeake Bay and to detect *Dinophysis* spp. for DSP early warning (see Box 13).

Future Needs

Advancing development of HAB sensors for deployment on autonomous underwater vehicles will add value to existing gliders used to monitor water quality in the region. Continued development of HAB autonomous remote sensing methods that yield greater spatial resolution (e.g., use of autonomous surface vehicles as HAB sensor deployment platforms) is needed in order to better capture HAB patchiness and extend surveillance of blooms into shallow bays and tributaries. Networks of IFCBs, especially in the Chesapeake and coastal bays, will also enhance regional HAB monitoring capabilities.

MARACOOS has been working towards developing a HAB data network that would include output from the five IFCBs already planned for the region. Information generated by the IFCBs could be used to develop routine nowcasts and forecasts for this region.

Alaska

The Alaska Ocean Observing System (AOOS) region includes the area within the US Exclusive Economic Zone encompassing four large marine ecosystems: the Gulf of Alaska and the Bering, Chukchi, and Beaufort Seas. The major HAB issues in Alaska are PSP caused by saxitoxins produced by the genus *Alexandrium,* and ASP caused by domoic acid produced by the genus *Pseudo-nitzschia*. Non-toxic HABs are also a concern. For example, hatchery managers routinely monitor the abundance of the spiny diatom genus *Chaetoceros* in order to avoid releasing young fish when their gills are susceptible to damage by the spines. As documented elsewhere, *Pseudo-nitzschia* blooms in Alaskan waters do not always produce toxins and to date there have been no documented amnesic shellfish poisoning cases. However, domoic acid does occur in marine mammals harvested for cultural and subsistence use. Moreover, broader health

[11] HAB monitoring programs in Virginia, Maryland (Department of Natural Resources, and Department of the Environment), the Chesapeake Bay, New Jersey, and Delaware.

impacts are a concern, given that toxic algal blooms may expand and increase in intensity as ocean temperatures rise due to climate change[13]. Due to the widespread occurrence of PSP events and a lack of routine testing of shellfish harvested for recreational, subsistence, or ceremonial use, the AK Department of Health and Social Services advises Alaskans to consider all non-commercially certified shellfish to be toxic at all times and refrain from consumption.

HAB-specific monitoring

In Alaska, manual water and shellfish sampling are the predominant methods of HAB monitoring. Some programs utilize volunteer networks to conduct qualitative cell counts, whereas others (e.g., NOAA's Kasitsna Bay Lab) utilize quantitative measures. The State of Alaska Department of Environmental Conservation (DEC) analyzes PSP toxins in shellfish from areas with commercial wild harvest or aquaculture according to NSSP guidelines. A partnership between NOAA's PMN and the University of Alaska, Anchorage supports water sampling at 12 sites in Kachemak Bay throughout the summer to determine HAB cell presence and abundance. A link between *Alexandrium* abundance and temperature was recently documented by this group, which may facilitate early warning of PSP-causing blooms (Vandersea et al. 2018).

In southeast Alaska, the PMN and the Southeast Alaska Tribal Toxins Partnership (SEATT), under the SE Alaska Tribal Ocean Research (SEATOR) project, collect water samples at 37 sites weekly, testing for HAB species and toxins and other environmental parameters. The SEATT also tests shellfish tissue toxin levels from key monitoring locations. In addition, the Sitka Tribe of Alaska Environmental Research lab was established with assistance from NCCOS to provide a 48-hour turnaround on shellfish PSP toxin testing results, using a high-throughput receptor binding assay. Data and associated advisories are available immediately to shellfish harvesters and researchers via the SEATOR website. This testing capability has enabled tribes to establish their own effective subsistence management plans. The Aleutian Pribilof Islands Association conducts monthly shellfish bed sampling at 10 sites to determine toxin presence[12]. Unique to the southeast sub-region, *Alexandrium* cyst mapping is conducted by the SEATT and the University of Alaska, Fairbanks to understand PSP toxicity in geoducks.

[12] https://www.aoos.org/alaska-HAB-network/

Future Needs

This region is oceanographically very complex and there is little understanding of the causes of HABs. Thus, at present, it is difficult to identify appropriate sentinel sites and or develop predictive models. These would provide commercial, recreational, and subsidence harvesters with badly needed information about when and where it would be safe to harvest shellfish. The establishment of the Alaska HAB Observing Network builds on the strengths of existing monitoring programs in the Southeast and Southcentral Alaska and the Aleutian Islands, and creates an opportunity to increase the visibility of HAB problems, research gaps, and needed investments that will advance HAB observation in the state.

Great Lakes

The Great Lakes Observing System (GLOS) region covers the five Great Lakes, including Superior, Michigan, Huron, Erie, and Ontario, which hold 95 percent of our nation's surface freshwater supply, and 20 percent of the world's surface freshwater. The major HAB issues in this region are caused by blooms of cyanobacteria, also referred to as blue-green algae. Besides turning the water various shades of green, causing taste and odor problems in drinking water and fish, and being responsible for bottom water hypoxia[13], as well as fish kills, these organisms often produce suites of liver and neurological toxins. The dominant cyanobacteria in this region are *Microcystis* spp., which sometimes, but not always, produce microcystins, a group of hepatotoxins. Symptoms of microcystin poisoning include, but are not limited to, abdominal cramps, nausea, vomiting, fever and sore throat. Other cyanobacterial genera also occur and can sometimes be abundant, including *Dolichospermum* (formerly *Anabaena*), *Cylindrospermopsis,*and *Lyngbya*. They can also produce hepatotoxins and neurotoxins, some of which can be lethal to humans, pets, livestock, and wildlife. Since the Great Lakes are a source of drinking water for millions of people and support a large recreational/tourism-based regional economic sector, cyanobacterial blooms are a threat to both drinking and recreational water use, thereby posing a major human health risk (see Box 14).

[13] https://www.epa.gov/nutrient-policy-data/health-and-ecological-effects

HAB-specific monitoring

NOAA's Great Lakes Environmental Research Laboratory (GLERL) conducts water sampling in Lake Erie, Lake Huron, and Lake St. Clair to monitor for HAB cells and toxins. This sampling takes place weekly from the spring through fall at mooring locations in western Lake Erie that comprise part of GLERL's Real-time Coastal Observing Network (ReCON). In Lake Huron, five fixed stations are sampled every two weeks in Saginaw Bay. In Lake St. Claire, there are nine fixed stations, with five sampled every two weeks, and four sampled monthly. In western Lake Erie, there are also four GLERL buoy stations with physico-chemical sensors and fluorometric sensors that measure chlorophyll and phycocyanin concentrations continuously throughout the spring and fall. NOAA's PMN also routinely collects water samples in this region to assess the presence/absence of HAB cells.

Box 14. Cyanobacteria in Lake Erie: Beyond Cell Counts

Cyanobacterial blooms occur annually in Lake Erie, and their magnitude and toxicity vary considerably from year to year. While the magnitude of the bloom is correlated with nutrient loading from the Maumee River, the factors affecting bloom toxicity are not yet fully understood. Biomass is easily measured with satellite remote sensing and, in combination with models of bloom transport, is used by NOAA to forecast bloom location and movement several days in advance. In 2014, the bloom moved over the Toledo, OH water intake pipe, but this bloom was not nearly as severe in terms of cell concentration as the one that occurred in 2017. However, because the 2014 bloom contained high levels of microcystin, a liver toxin, the City of Toledo was forced to issue a "Do Not Drink" order and provide bottled water for 48 hours. To address the non-predictive nature of cell concentration for toxin levels, NOAA has been testing the use of ESPs to remotely measure microcystins in the water (see Box 2). The intent is to couple remote sensing, toxin and cell detection, and models to predict bloom biomass and toxicity, and provide that information to stakeholders, including water utility operators, charter boat captains, and beach goers, to inform mitigation strategies and decision making.

Picture. Left, Center: Cyanobacterial bloom in Lake Erie. Right: ESP carrying microcystin toxin sensor deployed in western Lake Erie on (blue) bottom lander (credits: NOAA GLERL).

The various states, such as Ohio and Pennsylvania[14] that border the Great Lakes, work in conjunction with NOAA, the EPA, and other entities to collect water samples for cyanobacterial detection and tracking during suspected or confirmed blooms. Remote sensing data for cyanobacterial biomass and hydrographic models allow for a currently operational nowcast and five-day forecast to provide more precise bloom location, projected direction, intensity, and toxicity[15]. A photometer (i.e., seaPRISM) has also been installed on the shore of western Lake Erie to help validate satellite data.

One of the main concerns in this region is that the toxicity of cyanobacterial blooms cannot be predicted from biomass alone. Thus, knowing the bloom location is not sufficient as current information on bloom toxicity is also required in order to accurately assess the risk of toxic impacts to drinking and recreational waters. One ESP has been deployed each summer since 2016, upstream of the Toledo, OH water intake in western Lake Erie, providing near-real time data on microcystin concentrations at surface and bottom (i.e., drinking water intake) depths. Two additional ESPs were available in summer 2019 and deployed sequentially in order to maintain continuous coverage at the water intake site over the entire bloom season. NCCOS and partners are working to transition the LightDeck field-portable multi-toxin detection platform (see Box 7) to managers, communities, and individual users in the region for targeted field-based cyanotoxin detection and surveillance applications.

Future Needs

Since the 2014 Toledo, OH water crisis, monitoring for HABs and their toxins in this region has increased. An ESP integrated with a long-range autonomous underwater vehicle, adding mobility and bloom tracking capabilities to near-real time microcystin measurements, was successfully field-trialed in summer 2018 and in 2019. Although still at the research and development prototype stage, this technology will provide improved spatiotemporal resolution of bloom toxicity to support a toxicity forecast currently under development through NOAA-funded research. Additional research is also being conducted to develop a field-portable version of the Phytoxigene assay for near real-time detection in water samples of toxin genes, which will effectively complement the ESP's toxin measurements. Ultimately, these observing assets and capabilities will contribute to developing a plan for HAB observing that will provide early warning and support forecasting of HAB toxicity.

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[14] OH HAB response strategy; PA HAB response strategy

[15] https://tidesandcurrents.noaa.gov/hab/lakeerie.html

Pacific Islands and Caribbean Sea

The Pacific Islands Ocean Observing System (PacIOOS) region includes the U.S. Pacific (Hawaii, Guam, American Samoa, Commonwealth of the Northern Mariana Islands), the Pacific nations in Free Association with the U.S. (Republic of the Marshall Islands, Federated States of Micronesia, Republic of Palau), and the U.S. Pacific Remote Island Areas (Howland, Baker, Johnston, Jarvis, Kingman, Palmyra, Midway, Wake). The Caribbean Coastal Ocean Observing System (CARICOOS) region includes the coastal areas of Puerto Rico, the U.S. Virgin Islands, and Navassa Island.

One major harmful algal genus of concern in both regions is the dinoflagellate *Gambierdiscus*, of which many species produce toxins that cause Ciguatera Poisoning (CP) in humans. Other potentially toxic benthic dinoflagellate genera, including *Coolia*, *Ostreopsis*, and *Prorocentrum*, are also suspected to contribute to the symptoms of CP.

Gambierdiscus cells are found on various surfaces (e.g., macroalgae, mangroves, etc.) in the reef environment and are grazed by herbivorous fish that are, in turn, consumed by larger omnivorous and/or carnivorous fish and other seafood. The toxin can bio-accumulate to high levels (i.e., biomagnification) in the flesh of upper-level predatory fish species (e.g., barracuda, grouper, snapper, amberjack) that are primary targets of subsistence, recreational, and commercial fishers. More than 400 fish species are known to carry CP toxins. Ingestion of sufficiently contaminated seafood can cause CP symptoms, such as nausea, vomiting, diarrhea, as well as a range of neurologic effects, including, but not limited to, painful sensations, dizziness, vertigo, and reversal of hot/cold temperature sensation.

Another major HAB genus in the Caribbean is the macroalga *Sargassum*, also known as "Sargasso." Since 2011, the arrival of massive Sargasso mats has become a major economic and ecological issue in this area (see Box 15). Seasonal occurrence of these mats has resulted in region-wide closure of hotels and beaches due to the decomposition of large quantities of Sargasso. Sargasso also accumulates in mangroves and lagoons, resulting in fish kills, alterations to benthic flora, and most probably negates the mangrove roots as nurseries for various important fish species. Propeller fouling by Sargasso mats has also been reported to affect marine operations (Quintrell 2017).

HAB-specific monitoring

Nearshore water samples are collected through NOAA's PMN and analyzed to determine the presence/absence of harmful algal cells at a few locations across the various islands. A NOAA-funded research project from 2011-2015 allowed for sampling of coral, seaweed, and reef fish throughout the greater Caribbean region over five years to document *Gambierdiscus* diversity, distribution, physiology, and toxicity. Intensive monitoring occurred at field sites in St. Thomas and the Florida Keys, while less frequent sampling occurred on Gulf of Mexico oil rigs, in the Flower Garden Banks National Marine Sanctuary, along the Mexican coast, and in the Bahamas[16]. A second NOAA-funded project is evaluating screening methods for CP cells to determine if these cells can be used to identify regions most at risk and if a CP warning system can be developed[17].

NOAA and partners are also developing methods to detect ciguatoxins in fish, examining the factors that contribute to increased toxin production to predict CP outbreaks, and predicting how changes in climate will impact the incidence of CP. Recent advances include: new ciguatoxin detection lab capabilities, predictive models and maps showing how ocean warming will impact growth and distribution of Caribbean *Gambierdiscus* strains, describing how ciguatoxins may impact development of commercial fisheries for lionfish, improved monitoring via the PMN, and training Catholic University of Puerto Rico students to monitor twenty sites in southern Puerto Rico.

Future Needs

Because *Gambierdiscus* spp. are benthic algae normally associated with, or attached to, various substrates, sampling for this genus can be difficult and their presence may not be detectable in the water column using the autonomous technologies identified previously (e.g., IFCB, ESP). Thus, sampling usually requires collection of macroalgae, with *Gambierdiscus* spp. attached (Berdalet et al. 2012). This type of sampling conducted periodically where the genus is known to occur, coupled with toxin detection, will likely contribute to early warning of any HAB events. However, fish contaminated with CP toxins are highly mobile and may be caught in areas where *Gambierdiscus* spp. cells are absent or in low abundance, which is why an effort is being made to develop rapid tests for detecting these toxins in fish flesh. Also, as with other HAB species, climate change may be associated with expansion in the geographic areas affected by CP, and thus require broadening of surveillance efforts (see Friedman et al. 2017).

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[16] https://coastalscience.noaa.gov/project/tools-managing-ciguatera-poisoning-risks-caribbean/
[17] https://coastalscience.noaa.gov/project/ciguatera-fish-poisoning-identifying-toxic-species/

Box 15. New methods for predicting *Sargassum* spp. blooms
In recent years, the accumulation of *Sargassum* spp. on shorelines throughout the Caribbean has prompted the need for better monitoring and forecasting of these macroalgal blooms. The University of South Florida Optical Oceanography Laboratory (USF-OOL) has developed an approach to forecast *Sargassum* spp. blooms based on measurements from satellite imagery (i.e., Floating Algae Index) and models of *Sargassum* growth and transport. This product, termed the "*Sargassum* Outlook," can predict bloom occurrence from May through August based on conditions in the Atlantic Ocean in February (Wang and Hu 2017). Another group of researchers in Puerto Rico has proposed an approach for monitoring *Sargassum* spp. around Puerto Rico using the satellite imagery provided by the USF-OOL, combined with an algorithm to identify dense algal patches, and then applying models of ocean current movement to determine transport of the algae (Prakash et al. 2018). The ability to forecast bloom events allows coastal communities to prepare for the consequences of these types of blooms by implementing management actions, such as collection of marine resources prior to the bloom or planning and mobilizing personnel for algae removal.

Picture. *Sargassum* spp. bloom on the east coast of Barbados (credit: H. Oxenford, University of the West Indies).

Next Steps

The following recommendations are offered as next steps to enhance the current network components and develop a more complete and sustainable network.

1. **Develop an implementation plan**

   The NHABON Implementation Plan will be critical for delineating the specific monitoring requirements and prioritization within each region, and to serve as a guide for program execution and funding to ensure sustainability. Certain elements within each region may be phased in at different times, given that not all regions have similarly mature assets and infrastructure. NOAA can work with each

IOOS Regional Association to develop a detailed plan documenting current observing components that will be transitioned from research to sustained operational monitoring and forecasting applications. In addition, the plan would detail how and when to implement each of the elements outlined in the future needs section for each region above, including:

- Data management, display, and sharing processes
- Coordinate with NOAA's CoastWatch and Ecological Forecasting Roadmap
- Region-specific costs

2. Develop a governance strategy

Fully integrating each region into a national network will require an advisory committee and/or network coordinator to decide how to prioritize spending as funds become available from various sources, and how to most effectively and efficiently share data and resources (e.g., sensors) among regions. NOAA's Ecological Forecasting Roadmap or Ocean Acidification Program could serve as examples of internal coordination, and then the IOOS RA's would be the implementing body. The advisory committee could include subject matter experts from IOOS, NCCOS, CO-OPS, other NOAA line offices with HAB expertise, as well as individuals representing the IOOS Regional Associations who have direct connections with stakeholder groups (see below). Appropriate agency mechanisms, such as the NOAA Observing Systems Council, can be engaged to ensure coordination with other interested observing programs

3. Identify and obtain stakeholder support

Stakeholders should be integrally involved in the development of the NHABON Implementation Plan to ensure that their specific requirements are identified and addressed. Socioeconomics should be considered early in the planning of each regional observing network, and continue through its maintenance phase, to ensure that networks meet stakeholder requirements and to prioritize upgrades as technologies advance and needs evolve. The IOOS Regional Associations should be engaged to provide a critical link to some of the more regionally based stakeholders, such as states, tribes, private institutions, fishing and aquaculture industries, drinking water facility managers, tourism industries, and recreational users. NOAA can facilitate or be responsible for soliciting and sharing feedback from other Federal agencies, national stakeholders such as advocacy groups, and global and regional international partners (e.g., the Great Lakes Water Quality Agreement with Canada, GlobalHAB, the Intergovernmental Panel on HABs, and the North Pacific Marine Science Organization). Consultation with developers and manufacturers of new HAB monitoring and surveillance technologies will be vital to guide future innovations and improve the overall cost-effectiveness of, as well as accessibility to, HAB detection tools. The Alliance for Coastal Technologies, which is dedicated to fostering the development and adoption of effective and reliable sensors and platforms for use in coastal, freshwater and ocean environments, can also be an important contributor.

4. **Integrate with the annual budget process**

   To ensure sustainability, a long-term funding commitment is needed. Thus, it will be necessary to integrate funding for the NHABON into the federal budget process; a cost-benefit analysis should be conducted to demonstrate the value of this investment to taxpayers. In 1998, Congress authorized HABHRCA, and reaffirmed and expanded the mandate for NOAA to advance the scientific understanding and ability to detect, monitor, assess, and predict HAB and hypoxia events in 2004, 2014, and 2018. Guaranteed funding for the NHABON from Congress would further ensure this legislative mandate is carried out as intended.

5. **Make report publicly available**

   The purpose of holding the workshop and writing a report was to help NOAA plan to address future HAB observing needs. Making this report publicly available will initiate discussions in the broader HAB monitoring and response community, enabling the collaboration needed to optimize deployment locations of observing assets, identify potential contextual data being delivered that will support other needs, and potentially aid in defraying the cost of operations and maintenance (e.g., ship time) by co-locating buoys or moorings with other interested programs. Other entities with involvement in ocean or Great Lakes observing systems will be able to leverage the NHABON's assets and infrastructure for other applications.

Acronyms

Acronym	Definition
ASP	Amnesic Shellfish Poisoning
AOOS	Alaska Ocean Observing System
CariCOOS	Caribbean Coastal Ocean Observing System
CeNCOOS	Central and Northern California Ocean Observing System
CalHABMAP	California HAB Monitoring and Alert Program
DSP	Diarrhetic Shellfish Poisoning
ELISA	Enzyme-Linked Immunosorbent Assay
ESP	Environmental Sample Processor
GCOOS	Gulf of Mexico Coastal Ocean Observing System
GLERL	Great Lakes Environmental Research Laboratory
GLOS	Great Lakes Observing System
HAB	Harmful Algal Bloom
HABHRCA	Harmful Algal Bloom and Hypoxia Research and Control Act
IFCB	Imaging FlowCytobot
IOOS	Integrated Ocean Observing System
MARACOOS	Mid-Atlantic Regional Association Ocean Observing System
MERHAB	Monitoring and Event Response for Harmful Algal Blooms Program
MML	Mote Marine Laboratory
NANOOS	Northwest Association of Networked Ocean Observing Systems
NASA	National Aeronautics and Space Administration
NCCOS	National Centers For Coastal Ocean Science
NDBC	National Data Buoy Center
NERACOOS	Northeastern Regional Association of Coastal Ocean Observing Systems
NHABON	National Harmful Algal Bloom Observing Network
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSP	Neurotoxic Shellfish Poisoning
NWFSC	Northwest Fisheries Science Center
ORHAB	Olympic Region HAB Monitoring Program
PacIOOS	Pacific Islands Ocean Observing System
PCMHAB	Prevention, Control, and Mitigation of Harmful Algal Blooms Program
PMN	Phytoplankton Monitoring Network
PSP	Paralytic Shellfish Poisoning
qPCR	Quantitative Polymerase Chain Reaction
SCCOOS	Southern California Coastal Ocean Observing System
SEATT	Southeast Alaska Tribal Toxins Partnership
SECOORA	Southeast Coastal Ocean Observing Regional Association
TAMU	Texas A&M University
UCSC	University of California-Santa Cruz
WHOI	Woods Hole Oceanographic Institution

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Appendix 1: Summary of NHABON workshop activities and conclusions

The following is a summary of the activities and conclusions of a National Harmful Algal Bloom Observing Workshop convened at NOAA NCCOS and IOOS Headquarters in Silver Spring, MD from August 29-30, 2017.

Workshop Vision:

To initiate development of a framework for National HAB Observing capability.

Workshop Purpose:

- Take critical first step toward planning a *National Harmful Algal Bloom (HAB) Observing* capability in direct support of NOAA's EFR priorities, HABHRCA and ICOOS Act mandates, and other NOAA line offices involved in HAB observations
- Discuss design and development of a National HAB Observing capability using an across-NOAA Working Group (WG) to document current HAB observing capabilities and identify requirements and/or gaps
- Develop strategy for NOAA to work with Federal, regional, local, non-Federal and academic partners to describe requirements to develop, integrate, and transition regional HAB observing infrastructure into a sustained national observing capability

Workshop Aims:

- develop regional inventories of current HAB observing assets/capabilities
- identify requirements for regional observing networks ranging from the 'minimum yet sufficient' to 'optimum' configurations
- assess the status of regional observing networks based on user community, socioeconomic benefits, partnerships/ collaborations, synergism/ integration, and costs to develop/sustain/improve the network

Workshop Conclusions:

- *Observations and measurements of HAB species and toxins are critical to support early warning and forecasting.* These data also have intrinsic value in assessing bloom toxicity, identifying potential drivers of HAB growth and toxin production, initializing models, and validating airborne/satellite observations and model outputs.
- *HAB observing technologies are being applied in a research mode at the regional level (e.g., Gulf of Maine, Gulf of Mexico, Pacific Northwest, California, and the Great Lakes)*

and some are deployed quasi-operationally. Many of these assets are funded through research projects that will end in the near future, resulting in the loss of critical observing and data acquisition infrastructure used by forecasters and decision makers.

- *NOAA has reaffirmed its commitment to the Ecological Forecasting Roadmap and the transition to operations of additional HAB forecasts is at the forefront of this effort.* Establishing sustained regional HAB observing systems and integrating these into a coordinated National network will play a vital role in operationalizing forecasts as well as improving their accuracy and usefulness to our stakeholders.
- *A national HAB observing capability is needed to efficiently and effectively integrate local, state, regional, and Federal HAB observing capabilities and deliver early warning and forecast products operationally.* Implementing a national HAB observing capability will: leverage efficiencies of scale and information transfer between regions, ensure uniformity of data and data management, and provide observations to support NOAA's mission of understanding and predicting change in our oceans.
- *This cross-NOAA workshop served to initiate development of a design for a national HAB observing capability.* Participants focused on identifying requirements for six priority regions (i.e., Pacific Northwest, Florida, Lake Erie, California, Gulf of Maine, and Texas), and assessing the current status of these regional networks for transition to operations.
- *Emphasis in the near-future will be on coordination with external partners/stakeholders and NOAA leadership to advance the discussions and planning process initiated during the workshop.* The primary aims of this effort will be to fully describe, in a wider context, diverse user needs and to complete the design for a national HAB observing capability.

Post-Workshop Priority:

WG will communicate directly with partners/stakeholders internal and external to NOAA (e.g., EFR HAB Team, NOAA-NOSC, HABHRCA-IWG, IOOS RAs, National HAB Committee) to ensure that the design and implementation of this National HAB Observing Network (NHABON) design meets observing requirements at local, regional, and national levels.

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