GlobalHAB

A New Program to Promote International Research, Observations, and Modeling of Harmful Algal Blooms in Aquatic Systems

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ABSTRACT. From 1998 to 2013, the international community of scientists researching harmful algal blooms (HABs) in marine systems worked through the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the Scientific Committee on Oceanic Research (SCOR) to better understand the ecological and oceanographic controls on these natural events that cause harm to humans and ecosystems. During this period, IOC and SCOR cosponsored the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) program to facilitate progress in HAB research, observations, and modeling. In 2016, building on the foundation provided by GEOHAB, IOC and SCOR launched a new HAB project design to extend research into freshwater systems and address several topics related to the effects of HABs on human society now and in a rapidly changing world.

GENESIS OF GlobalHAB

As described by Kudela et al. (2017, in this issue), GlobalHAB was conceived during the final Open Science Meeting (OSM) of the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) program, held in Paris in April 2013 (GEOHAB, 2014). The main purpose of the OSM was to evaluate and synthesize the outcomes of GEOHAB. Meeting participants agreed that international coordination of HAB science was still needed in order to advance understanding of factors controlling HABs and how they affect humans and aquatic ecosystems. While GEOHAB focused on marine HABs, and more narrowly on their ecological and oceanographic aspects, meeting participants agreed that broadening international coordination to other aspects of HABs would be valuable. The two sponsors of GEOHAB—the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the Scientific Committee on Oceanic Research (SCOR)—agreed to help the HAB science community move in the new directions proposed. In 2015, IOC and SCOR appointed a Scientific Steering Committee (SSC) for the new GlobalHAB program, and it met for the first time in March 2016.

FACING PAGE. Sampling benthic harmful dinoflagellates from coral rubble overgrown by macroalgae in a degraded tropical coral reef ecosystem. *Photo credit: P.T. Lim, University of Malaya*

VALUE ADDED BY INTERNATIONAL ACTIVITIES LIKE GlobalHAB

It is worthwhile to consider the value of the international approach used by GEOHAB and now by GlobalHAB. The new program has many potential benefits:

1. GlobalHAB will serve as a focal point to bring together a larger number of scientists to help address the priority questions identified as part of the program, to develop promising approaches to answering these questions, and to continue developing new questions as the field evolves. GlobalHAB will bridge parts of the HAB science field that are not currently well connected (e.g., marine and freshwater scientists, natural and social scientists).
2. GlobalHAB will provide a mechanism for bringing together a critical mass of resources (expertise, equipment, finances) over an extended period to address difficult observational, modeling, and research challenges.
3. GlobalHAB will provide support for international standardization and intercalibrations for better comparison of the results of observations, modeling, and research worldwide.
4. GlobalHAB will demonstrate the importance of a better understanding of HABs to the public, managers, and policymakers.
5. GlobalHAB will attract financial resources and staffing that will provide critical infrastructure to support meeting planning, communication, development of scientific publications, and capacity building.
6. GlobalHAB will offer a mechanism for interaction with other national and international organizations and projects, building on the successful collaborations established by GEOHAB.
7. GlobalHAB will endorse and provide an international framework for scientific projects and activities that, by addressing HAB research at national or regional levels, contribute to the implementation of GlobalHAB objectives.

GlobalHAB recognizes that much remains to be learned about HABs in order to help protect marine ecosystems and human health and that there are advantages to bringing marine and freshwater HAB scientists together to work on issues of common interest. Therefore, following on from GEOHAB, the general mission of GlobalHAB is to foster international cooperative research on HABs; its overall goal is to improve understanding and prediction of HABs in aquatic ecosystems and also to improve management and mitigation of their impacts. To achieve this goal, GlobalHAB will:

- Address the scientific and societal challenges of HABs, including their environmental, human health, and economic impacts, in a rapidly changing world.
- Consolidate linkages with broader scientific fields and regional and international initiatives relevant to HABs.
- Foster the development and adoption of advanced, cost-effective technologies.
- Promote training, capacity building, and communication of HAB research to society.
- Serve as a liaison between the HAB-related scientific community, stakeholders, and policymakers toward informing science-based decision-making.

The following sections provide brief descriptions of topics to be addressed by GlobalHAB. More information about GlobalHAB may be found in the *GlobalHAB Science and Implementation Plan*, which will be available in mid-2017 through IOC and SCOR.

CONTINUATION OF GEOHAB PROGRAM ELEMENTS IN GlobalHAB

The GlobalHAB SSC acknowledged the important foundation laid by GEOHAB through its five program elements (Figure 1). Significant progress made on these program elements (see Kudela et al., 2017, in this issue) provides a sound and useful scientific framework that will be incorporated into and continued under GlobalHAB.

Program Element 1: Biodiversity and Biogeography

The overall objective of this program element was to identify the factors that determine the changing biogeographic distribution of HAB species, including potential trends associated with climate change; their genetic variability; and the biodiversity of HAB communities, including diversity of toxins. Achievement of this objective depends in part on correct taxonomic identification of harmful species. New molecular technologies with progressively reduced cost (e.g., qPCR, fluorescent in situ hybridization, high throughput sequencing metabarcoding) are helping to refine species descriptions and to identify cryptic and pseudo-cryptic diversity among HAB species formerly defined based on morphological characters (Lelong et al., 2012; Kremp et al., 2014).

At present, GlobalHAB objectives include establishing reference sequences for interpreting molecular data and achieving identifications at the species level, educating a new generation of taxonomists worldwide who will bridge the morphological and molecular techniques, conducting research and training to improve species delimitation using integrated approaches (e.g., morphology and molecular characterization, toxin composition, physiology, life history), and defining standardized protocols for physiological investigations. Program participants are also working toward identifying trends in HAB occurrence, enabling prediction of HABs, and designing plans for management and, when possible, mitigation of their impacts.

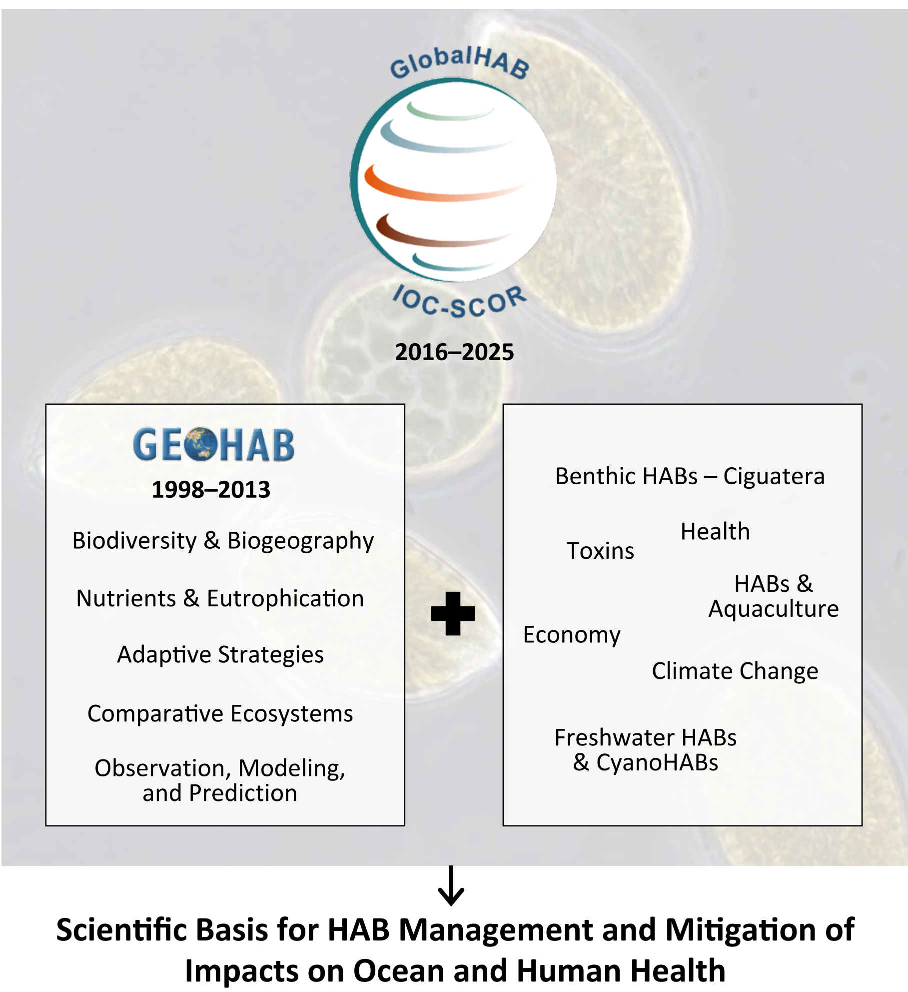

FIGURE 1. Topics integrated into GlobalHAB, including the five program elements of GEOHAB.

Program Element 2: Nutrients and Eutrophication

This program element aimed to determine the influences of eutrophication on the occurrence of HABs and their harmful effects. Important advances (see Glibert and Burford, 2017, in this issue) contributed, for instance, to the implementation of policies limiting nutrient input and proved useful for preventing HABs in certain coastal areas.

New challenges include understanding the role of organic nutrient availability and ratios in some HAB events as well as in the modulation of HAB toxin production. Changes in nutrients that may accompany climate change and other anthropogenic forcing factors are likely to affect planktonic (e.g., *Pseudo-nitzschia*, *Alexandrium*) and benthic (*Gambierdiscus, Ostreopsis*) HAB taxa, macroalgal (e.g., *Sargassum*, *Enteromorpha*) blooms, freshwater HABs (FHABs), and cyanobacterial HABs (cHABs). GlobalHAB will also investigate the links between aquaculture-related nutrients and HAB occurrence and toxicity as well as deoxygenation and anoxia that result from high-biomass HABs.

Program Element 3: Adaptive Strategies

The overall objective of this program element was to determine the unique adaptations of HAB species and how these adaptations help to explain their proliferation or harmful effects. Detecting unique characteristics and adaptations of HAB species in particular environments could contribute in the development of predictive models.

The studies conducted during the GEOHAB program were not able to identify harmful species uniquely associated with upwelling systems (Smayda, 2010) or with fjords and coastal embayments (Roy et al., in press), with the possible exception of the pelagophytes *Aureococcus* and *Aureoumbra* that have caused persistent brown tides in coastal eutrophied embayments. However, intensive studies facilitated by technological progress (e.g., Berdalet et al., 2017a, in this issue) clarified the important role of particular life history strategies (e.g., encystment and excystment processes, sexual reproduction), production of allelopathic compounds (biologically active substances that elicit specific responses in competitors or predators), and intrinsic defense against parasites (virus, protists) in the capacity to proliferate exhibited by harmful organisms. There is still a need to gain more knowledge about these strategies used by many harmful organisms and especially under natural conditions. These challenges have been incorporated in GlobalHAB.

Further research considered in GlobalHAB will address the role of particular adaptations of benthic HABs (flattened shapes, production of mucus to attach to surfaces) in the colonization of substrates and the development of the blooms. There is also a need to investigate the life histories and the floating and dispersion strategies of macrophytes (e.g., *Sargassum*, *Enteromorpha*) and cHABs to understand their bloom dynamics. The new studies should include assessments of adaptive biological traits and intra-specific interactions (e.g., physiology, toxin production, allelochemical properties, life histories) of HAB species and populations in different environments. The new cutting-edge methodologies (e.g., metabolomics, proteomics) offer new possibilities for progress. Still, a main challenge is to estimate biological rates and other parameters at the cellular level that could be incorporated in models to understand and predict HAB events.

Program Element 4: Comparative Ecosystems

The overall objective of this program element was to determine the extent to which HAB species, their population dynamics, and their community interactions respond similarly within comparable ecosystem types. The GEOHAB program adopted the comparative approach, working from the cellular level to the ecosystem level (upwelling and stratified systems, embayments and fjords; Berdalet et al., 2017a; Kudela et al., 2017; Pitcher et al., 2017, all in this issue). This approach is based on the view that the ecology and oceanography of HABs can best be understood through study of the causative organisms and affected systems in relation to comparable organisms and systems. Improved generalizations about the causes and consequences of HABs would be particularly applicable to modeling them, and to managing and mitigating their effects.

It is useful to continue using the comparative approach in GlobalHAB, and extend it to comparisons not only among specific marine ecosystem types but also comparisons among aquatic systems that have different salinity regimes (freshwater, brackish, and open-ocean environments). GlobalHAB will bring together scientists who study these different salinity regimes. Other examples of the potential use of the comparative approach in GlobalHAB include comparisons of *Gambierdiscus* dynamics in the main affected areas (the Pacific Ocean and the Caribbean Sea), dynamics of the main benthic HAB taxa (*Ostreopsis* and *Gambierdiscus*), and blooms of *Pseudochattonella* species that have caused fish mortalities in northern Europe, Japan, and South America.

Program Element 5: Observation, Modeling, and Prediction

The overall objective of this program element was to improve the detection and prediction of HABs by developing new capabilities in observation and modeling. GEOHAB highlighted the need for specialized and highly resolved observations to describe the biological, chemical, and physical conditions that influence the population dynamics of individual species in natural communities. Long-term, coordinated observation systems are crucial to enabling early warning and prediction of HABs, and to supporting decision-making for the protection and management of coastal resources. During the lifetime of GEOHAB, technical advances improved our ability to observe HABs (e.g., see HABWATCH, 2004; GEOHAB, 2013; Berdalet et al., 2014). Observations can feed into models, which are essential tools for HAB prediction and management. The modeling workshop held in Galway, Ireland, in 2009 (GEOHAB, 2011) was a major GEOHAB activity.

GlobalHAB will foster new steps and challenges in observation and modeling. In general, the empirical site- and population-specific statistical HAB models that give the most predictive power in particular cases are the hardest to scale up in order to gain general biological insight, suggesting that long-term or large-scale projections (see Climate Change below) may require different strategies from short-term, regional forecasting. Improvements needed in modeling HABs include better parameterization of the biological, physical, and chemical processes affecting HABs, as well as model validation. These improvements require high-resolution sampling of the appropriate parameters, resolving small scales (e.g., thin layers in stratified systems, rheological processes at the micrometer-length scale) such as using automated equipment like the Imaging Flow Cytobot (Figure 2; Brosnahan et al., 2015), and sustaining long time series of observations. GlobalHAB will work with other organizations, for example, the Global Ocean Observing System (GOOS), the International Council for the Exploration of the Sea (ICES), and the International Ocean-Colour Coordination Group (IOCCG), to identify and provide justification for long-term HAB sentinel sites and encourage their inclusion in GOOS.

NEW TOPICS IN GlobalHAB

The international HAB science community proposed a number of new topics during the final GEOHAB OSM (GEOHAB, 2014). When added to the GEOHAB program elements, significant funding would be required to address this large number of topics. The GlobalHAB SSC will seek such funding and will determine priorities for implementation of activities on an annual basis. In some cases, GlobalHAB's involvement in the following topics will mainly be participation in activities led by other organizations.

Benthic HABs (BHABs)

The overall objective of this topic will be to achieve a better understanding of BHABs and to provide tools to manage and mitigate the impacts of these events on human health and the environment. The GEOHAB Core Research Project (CRP) on "HABs in Benthic Systems," launched in 2010, was the last of the program's CRPs (GEOHAB, 2012). It was established because of more frequent events and geographic expansion of BHABs. Tropical regions have long been threatened by ciguatera fish poisoning (CFP) associated with blooms of the toxic benthic dinoflagellate *Gambierdiscus*, whose ciguatoxins are bioaccumulated in reef fishes. CFP is the most frequent HAB-related illness in the world, often resulting in significant long-term health effects. Globally, there are as many as 50–280 CFP cases per 10,000 people per year in affected areas, although the true incidence is difficult to ascertain due to under-reporting and other challenges (Friedman et al., 2017). The broad importance of CFP is reflected in the 2015 adoption of a "Global Ciguatera Strategy" by the IOC, the World Heath Organization (WHO), the Food and Agriculture Organization (FAO), and the International Atomic Energy Agency (IAEA) (http://hab.ioc-unesco.org), and in initiatives launched by other international as well as national agencies. GlobalHAB will be directly involved in these initiatives, especially in the most affected tropical and subtropical areas.

Blooms of another toxic dinoflagellate, *Ostreopsis*, have become more frequent and intense, especially in temperate waters (Figure 3). *Ostreopsis* produces palytoxins and analogues, and some outbreaks have been associated with sporadic acute respiratory irritations in humans exposed to marine aerosols and with massive benthic faunal damage. Significant progress was achieved in a relatively short time on the objectives identified in the BHAB Science Plan (GEOHAB, 2012), as reviewed in this issue by Berdalet et al. (2017b). The objectives and questions formulated in GEOHAB (2012) are still valid, and continued research efforts will benefit from cooperative international research. In particular, studies will address improving knowledge of BHAB species ecology, physiology, and marine food web toxin-transfer mechanisms, and also determining fundamental parameters needed for modeling their dynamics. Direct collaboration with public health experts and people affected by BHABs is fundamental for progress. Attention to other BHAB species should also be addressed within GlobalHAB. Finally, the roles of BHABs in marine ecosystems, such as their effects on other marine organisms, should be investigated, as well as the impacts of climate change on BHAB dynamics.

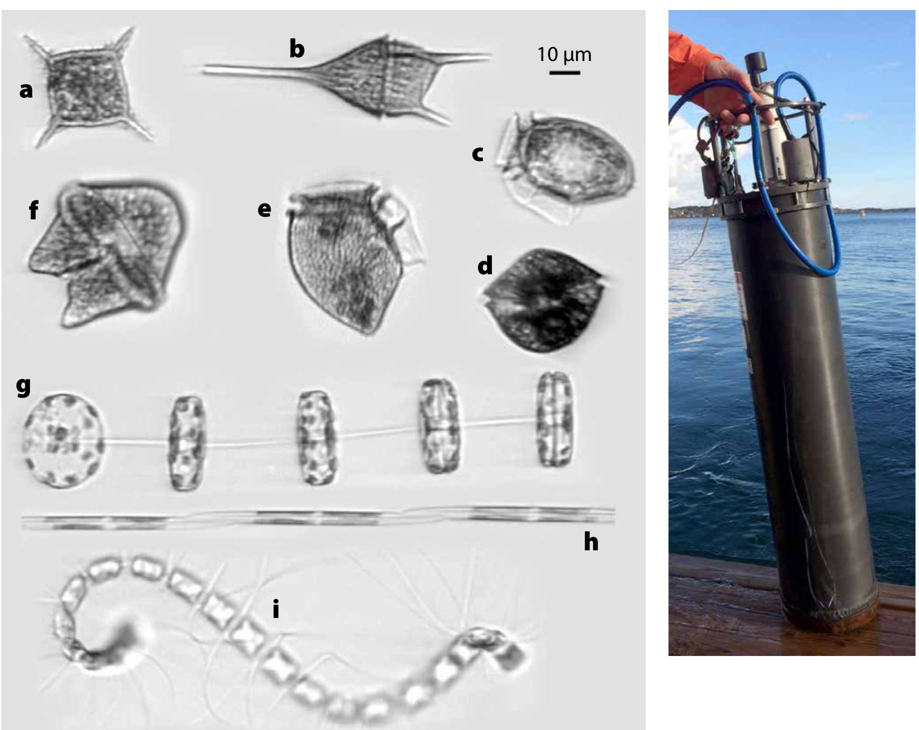

FIGURE 2. Images of plankton (left) obtained with the Imaging Flow Cytobot (right), acquired at Tångesund, Swedish Skagerrak coast. (a) *Dictyocha fibula*, (b) *Tripos lineatus* (syn. *Ceratium lineatum*), (c) *Dinophysis acuminata*, (d) *Alexandrium pseudogonyaulax*, (e) *Dinophysis norvegica*, (f) *Akashiwo sanguinea*, (g) *Thalassiosira* sp., (h) *Pseudo-nitzschia* sp. (i) *Chaetoceros* sp. *Photo credits: Bengt Karlson and Michael Brosnahan*

Cyanobacterial HABs and Freshwater HABs: From Marine to Freshwater Systems

The overall objective of this theme is to develop a global perspective in the science and management of freshwater HABs, as well as cyanobacterial HABs, in marine, brackish (Figure 4), and freshwater habitats (Figure 5). Freshwater HABs include a range of cyanobacterial species and some eukaryotic groups. Historically, much of the research has focused on toxic planktonic cyanobacteria genera (including *Microcystis*, *Cylindrospermopsis*, *Dolichospermum*, *Aphanizomenon*, *Planktothrix*, and *Lyngbya*), but new harmful taxa have recently been described in benthic habitats (e.g., *Phormidium*, *Didymosphenia*). Cyanobacterial HABs can pose problems in freshwater and brackish areas (e.g., *Nodularia* in the Baltic Sea) and in marine ecosystems, especially in tropical regions where toxic filamentous cyanobacteria such as *Lyngbya* and *Moorea* proliferate. These species produce a wide range of toxins, including microcystins, cylindrospermopsins, anatoxins, nodularins, saxitoxins, aplysiatoxins, and lyngbyatoxins.

This is an important new theme for GlobalHAB because FHABs and cHABs have major economic, social, and environmental impacts. Worldwide, water authorities spend millions of dollars annually testing water supplies and mitigating the effects of cHABs (Figure 5). GlobalHAB's unique role will be to bridge the gaps between freshwater and marine HAB researchers to share knowledge, techniques, and approaches. Additionally, there is the need to communicate more effectively with policymakers internationally about the current state of knowledge and potential approaches to managing, mitigating, and predicting cHAB outbreaks. One of the first objectives of GlobalHAB in relation to this theme will be to synthesize and share existing information on mitigation strategies with environmental and resource managers. An important additional task will be to identify emerging issues for cHABs across freshwater, brackish, and marine habitats, both benthic and pelagic.

HABs and Marine Aquaculture

The objectives of this theme are to determine the links between marine aquaculture and HAB occurrence in different regions and to find efficient methods for protecting farmed seafood products from HAB impacts. Shellfish and finfish aquaculture has many benefits, including the creation of nutritious, high-protein food; reducing pressure on natural resources; and supporting sustainable economic development and employment. However, because of the improved awareness and identification of HAB events that have occurred alongside increases in aquaculture developments, it is important to determine whether aquaculture may cause and/or increase the intensity of HAB occurrences. Through focused studies and improved observational methods, this theme will seek to provide fresh perspectives for assessing the potential effects of nutrients, shifting nutrient ratios, and/or organic matter produced by aquaculture in the promotion

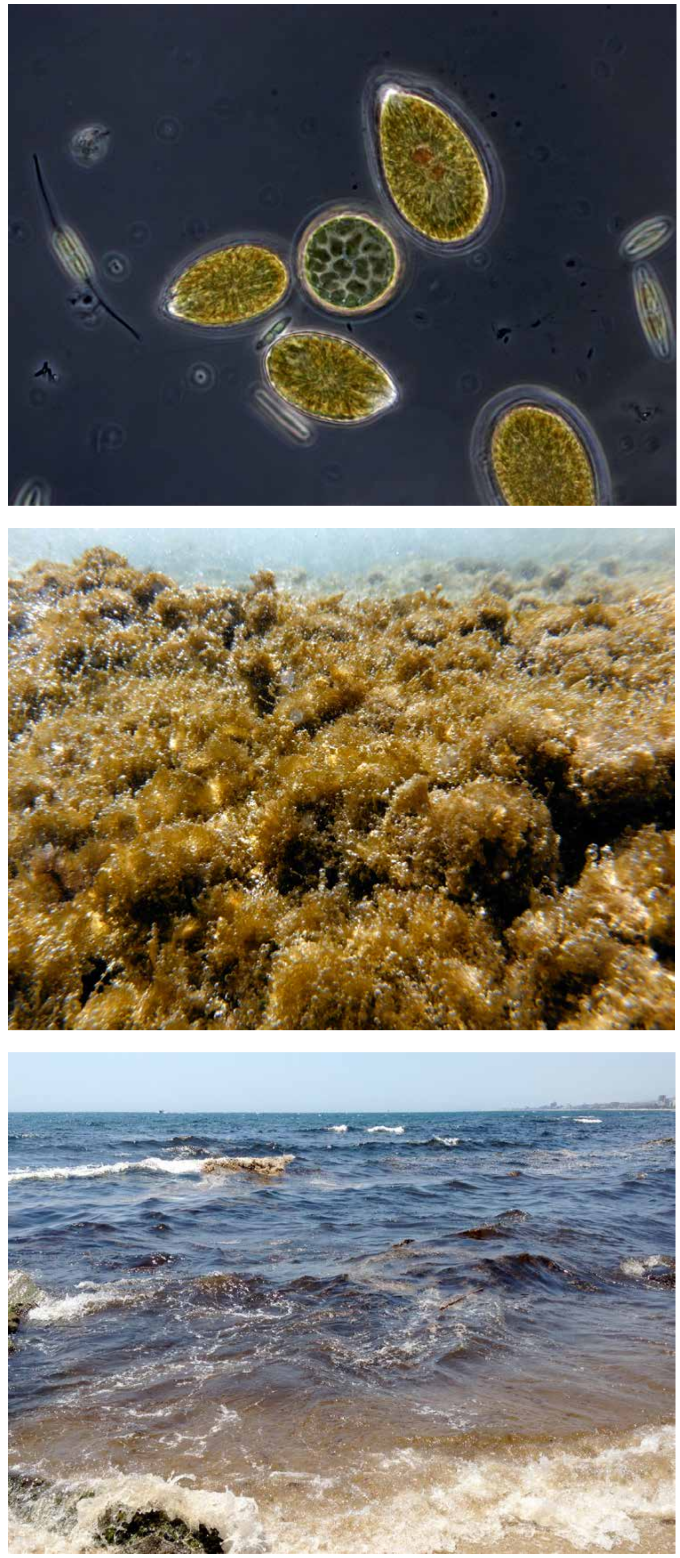

FIGURE 3. (top) Light micrograph of a natural sample of the benthic harmful dinoflagellate *Ostreopsis* cf. *ovata* from the Gulf of Naples (Mediterranean Sea). *Photo credit: Laura Escalera, SZN* (middle) Dense mucous carpet containing high densities of *Ostreopsis* cells covers the macroalgal community. *Photo credit: Magda Vila, ICM-CSIC* (bottom) Water motion and internal life processes release cell aggregates that can be found at surface. *Photo credit: E. Berdalet*

of HABs. Conversely, algal-toxin contamination and mass mortalities of cultured animals caused by HABs can have devastating impacts on aquaculture operations (Figure 6). Blooms of a variety of microalgae (raphidophytes, dictyochophytes, haptophytes, dinophytes) continue to cause substantial losses to sea-cage fish-culture operations.

Progress in modeling (hydrodynamic and coupled biogeochemical models) and technology can notably contribute to improve early warning and mitigation methods. High-tech, autonomous, in situ molecular and imaging flow cytometry methods have proved capable of real-time sensing of impending blooms, although they require further refinement and field trials. Rapid-test kits using a variety of technologies for the detection of organisms and toxins in waters and in shellfish are becoming increasingly available, although further development of methods, a wider range of targets, and validation studies are needed. These applied research fields are important and require continued effort to provide reliable, mature, cost-effective solutions that can be used to prevent and mitigate the impacts of HABs on aquaculture.

HAB Toxins

The overall objective of this theme is to characterize the genetic and environmental aspects of HAB toxin production, determine the mode of action of selected toxins, and address several limitations in toxin analysis. Toxins are a crosscutting subject and a common concern through all the GlobalHAB research topics.

A first challenge and fundamental task is to obtain better understanding of toxin biosynthesis pathways and of the genes involved. Knowledge of the genetic basis of toxin production could reveal if there are suitable target genes for the identification of toxic species. Additionally, such knowledge will lead to a better understanding of environmental controls on toxin production and to better prediction of the probable impacts of changes in marine habitats on the toxicity of HAB species. In this regard, significant progress has been made in understanding paralytic shellfish poisoning (PSP) toxins (saxitoxins; see review in Krüger et al., 2010). Such success stimulates analogous research on other well-known phycotoxins such as domoic acid (e.g., Jeffery et al., 2004), ciguatoxins, and okadaic acid, as well as on emerging toxins.

After decades of research, the modes of action of most microalgal toxins on mammalian systems are fairly well understood, but the picture is much less clear in the case of fish-killing species such as *Cochlodinium polykrikoides, Chattonella* spp., *Heterosigma akashiwo,* and *Karlodinium australe* (e.g., Wagoner et al., 2008; Lim et al., 2014), and of cytotoxic species affecting marine cultured organisms such as shrimp. Information on modes of action is crucial in the development of countermeasures to be applied by the marine aquaculture industry in dealing with massive mortality events due to different microalgal blooms.

Sensitive, accurate, and cost-effective means of microalgal toxin analysis are also essential for sustainability of marine aquaculture (as explained above), food security, and the protection of public health. Progress has been made in the detection and characterization of several microalgal toxins due to advances in analytical techniques and in cell-based and functional assays. However, official and reliable methods that are recognized in health regulations are not yet available for some toxins, with ciguatoxin being the most notable.

HABs and Human and Animal Health

The overall objective of this topic is to increase collaboration among HAB scientists with medical, veterinary, public health, and social science expertise to help minimize the risk of HAB impacts to human and animal health. This theme aligns with other initiatives in the United States and Europe that highlight the need for integrated understanding of the health and environmental

FIGURE 4. Surface accumulations of cyanobacteria in the southern Baltic Sea in 2013. *Photo credit: Bengt Karlson*

FIGURE 5. Bloom of the toxic cyanobacterium *Microcystis* in a New Zealand lake. *Photo credit: David Hamilton, University of Waikato*

characteristics of the ocean, including HABs. In June 2016, the US Centers for Disease Control and Prevention (CDC) launched the "One Health Harmful Algal Bloom System" (OHHABS) to collect information on HAB-related illnesses in animals and people, and on certain environmental characteristics of the blooms (http://www.cdc.gov/habs/ohhabs.html). The CDC also developed a module within the National Outbreak Reporting System (NORS) to compile information about HAB-related illnesses (https://www.cdc.gov/nors). Other recent examples in Europe include position papers (Moore et al., 2013), the 2014 Oceans and Human Health Workshop in Cornwall, UK (http://www.ecehh.org/events/oceans-human-health), and a dedicated Session on Oceans and Human Health at the EurOcean 2014 Conference in Rome. More recently, Grattan et al. (2016) emphasized the need for transdisciplinary research on efficient illness prevention. They also recommended close communication and collaboration regarding this issue among HAB scientists, public health researchers, and local, state, and tribal health departments at academic, community outreach, and policy levels. GlobalHAB will begin its work on this theme by focusing on CFP, due to the high incidence worldwide of this human illness caused by marine microalgae. GlobalHAB's initial focus on CFP will be followed by the longer-term aim of developing analogous transdisciplinary research initiatives for prevention of diarrhetic shellfish poisoning (DSP) and PSP incidence in the most affected areas.

Economy

The overall objective of this topic is to develop cross-community understanding of the economic impacts of HABs and to define methods and criteria capable of robustly assessing the economic costs of HABs at both regional and national levels, as well as the costs of methods for predicting and mitigating HABs. The main contribution of GlobalHAB will be to bring together natural scientists with economists. Many past economic studies have been led by or had significant contributions from natural scientists who study HABs, and many studies on the negative economic impacts of HABs have employed relatively crude measures and methodologies whose results are difficult to compare (Davidson et al., 2014). The economic effects of HABs arise from public health costs, commercial fishery and aquaculture operation closures and fish kills, possible medium- and long-term declines in coastal and marine recreation and tourism, and the costs of insurance, monitoring, management, and mitigation (Morgan et al., 2010). Aggregating economic effects—both within and across these categories—can also be problematic with available data and currently used methodologies (Hoagland et al., 2002). An example of an economic evaluation of HABs at a national level is given by Anderson et al. (2000), who estimated the economic effects of HABs in the United States to be $100 million per year (as later translated into 2012 dollars), broken down as follows: 45% for public health costs, 37% for the costs of closures and losses experienced by commercial fisheries, 13% from the impact on lost recreation and tourism opportunities, and 4% from

FIGURE 6. Massive fish mortalities in Jakarta, Indonesia. *Photo credits: Tumpak Sidabutar (HAN53)*

monitoring and management costs. The increasing magnitude of macroalgal HABs is dramatically impacting the economy of countries that depend on tourism and coastal fisheries (e.g., Smetacek and Zingone, 2013). Revision of regional estimates with more modern environmental economic methodologies is required, as are more local evaluations in regions of particular concern or economic value. Moreover, many parts of the world report, at best, only ad hoc estimates of impacts stemming from extraordinary HAB events and hence lack even basic data on HAB costs. Improved economic evaluations of the costs of HABs will allow for more robust management decisions among the aquaculture industry, their insurers, and coastal zone managers, and will facilitate better decision-making on scientific priorities.

> "Built upon the legacy of GEOHAB, GlobalHAB aims to serve the international community working on HABs by providing a scientific framework for the integration and coordination of research and expertise of many individual scientists in the study of HABs."

Climate Change and HABs

This theme was initiated at the end of GEOHAB in cooperation with ICES and the North Pacific Marine Science Organization (PICES). The overall objective of this topic is to understand global patterns in HAB responses to common drivers (thermal windows, stratification, changing levels of CO_2). There is increasing concern that global change may stimulate geographic expansion and greater incidence of severe impacts of HABs (e.g., Hallegraeff, 2010; Wells et al., 2015). There is ample evidence that the main factors controlling microalgal populations (surface water temperature, ocean stratification, wind and water circulation patterns, precipitation-linked nutrient inputs) are changing in ways that could stimulate HABs. Surface water acidification and alteration of marine habitats are other global changes that could affect the prevalence of HABs. A fundamental question is whether the environmental windows of opportunity for HAB species are expanding (e.g., Moore et al., 2015) or simply shifting geographically and seasonally.

Specific objectives of GlobalHAB in relation to this topic begin with understanding global and regional patterns in HAB responses to the most common factors affecting phytoplankton populations. GlobalHAB will encourage and facilitate the use of long time series of meteorological and hydrographic physicochemical parameters and HAB occurrences as a base for predictions of climate effects on HABs. Experimental work on the effects of climate on HABs should also be carried out, for example, laboratory and mesocosm experiments, as a base for predictions of climate change effects on HABs. GlobalHAB will encourage the development of comprehensive, region-specific studies that integrate biological process data with downscaled climate projections. GlobalHAB will also develop activities to promote the adoption of best practices in laboratory and field approaches to investigate HAB responses to climate-linked drivers (see Wells et al., 2015). GlobalHAB will cooperate with other international groups (particularly the Global Ocean Oxygen Network, GO_2NE) to examine ocean deoxygenation in response to climate change and eutrophication, with a specific focus on HABs. GlobalHAB will work with partner organizations to complete the list of existing time-series locations relevant for addressing the effects of climate change on HABs. The program will identify the best sites for time-series observations of HABs and related oceanographic parameters (essential ocean variables, or EOVs) to track the potential impact of climate change on HABs, in coordination with GOOS.

CONTEXT OF GlobalHAB WITHIN THE HAB COMMUNITY

Despite GlobalHAB's unique role, it is not the only international activity related to HABs; there are several regional organizations and many national HAB research projects relevant to GlobalHAB. To be successful, GlobalHAB will need to find its niche within the international community and form strategic partnerships among organizations and projects with similar interests. At the initiation of the GlobalHAB SSC, some of these entities were already identified, due to past links with GEOHAB (see Kudela et al., 2017, in this issue). The representatives of some partner organizations are contributing to the development of the *GlobalHAB Science and Implementation Plan*. Some of the organizations with which GlobalHAB intends to continue to build or establish new partnerships and synergies are listed below.

Global Organizations and Projects

GlobalHAB is building partnerships with several other global organizations and projects, including the Intergovernmental Panel on Harmful Algal Blooms (IPHAB), the GOOS Biology and Ecosystems Panel, the Group on Earth Observation's Blue Planet initiative, the International Society for the Study of Harmful Algae (ISSHA), IOCCG, the Partnership for Observation of the Global Oceans (POGO), the IAEA, the WHO, the FAO, the Integrated Marine Biosphere Research (IMBeR) project, and the Intergovernmental Panel on Climate Change (IPCC).

Regional Organizations and Projects

GlobalHAB is developing partnerships with a variety of regional organizations and projects that can help promote GlobalHAB objectives in their regions and involve regional scientists in GlobalHAB. These partners include PICES, ICES, the Mediterranean Science Commission (CIESM), and regional bodies that are part of the IOC (e.g., IOC/Sub-Commission for the Western Pacific).

Endorsed National Projects

GEOHAB endorsed numerous national projects over its lifetime. Endorsed national projects can provide valuable contributions to GlobalHAB, and GlobalHAB can help national projects work together around its central themes and give visibility to national projects.

IMPLEMENTATION OF GlobalHAB

The *GlobalHAB Science and Implementation Plan* will describe detailed implementation activities both for the near term (one to three years) and for the project's more distant future (10 years). GlobalHAB will help coordinate research internationally when this is possible, but will focus its efforts on activities to synthesize and communicate existing knowledge and to address specific knowledge and methodological gaps. Implementation activities arise from recognizing the need for interactions among some of the GlobalHAB topics and the benefits of working with other organizations with interests in these topics. As mentioned earlier, funding for implementation and prioritization of implementation activities will be evaluated annually at GlobalHAB SSC meetings. Some of the tasks to be undertaken are listed below.

Review Papers

Much can be accomplished in the early years of the program through scientific syntheses related to the topics that will be the focus of GlobalHAB. These syntheses will contribute important information to advance international HAB research and will provide a foundation for future GlobalHAB activities. Potential topics include the following:

- HAB species biodiversity
- Advances in new technologies for research and monitoring applications
- Relationships of HABs and aquaculture in specific regions
- Current knowledge and priority research on the mode of action of different toxins
- Validation studies of toxin kits or other analytical approaches
- A comprehensive review of publications and data relating to the economic impacts of HABs

Science Workshops

The workshop approach will be used by GlobalHAB to bring together small groups of invitees to address specific topics necessary to overcome barriers to HAB research; workshop outcomes will usually result in peer-reviewed journal articles, manuals, summaries for policymakers, and other publications. GlobalHAB has identified the need for workshops on the following topics:

- BHAB modeling, using PCR/qPCR for identification of *Gambierdiscus* (and possibly *Ostreopsis*) species
- Emerging species and toxins, and methodological challenges for benthic freshwater and marine HABs
- Novel cHAB and FHAB toxins (e.g., ß-methylamino-L-alanine [BMAA])
- The role (if any) of marine aquaculture in the promotion of HABs
- In situ monitoring technologies for the detection and monitoring of HABs in aquaculture systems
- Experiences with research on the different HAB-related diseases
- The economic impact of HABs

Open Science Meetings

OSMs provide opportunities for the international HAB community to gather for discussion of topics relevant to a variety of GlobalHAB themes. OSMs will be convened to provide opportunities for HAB scientists to present current research on specific GlobalHAB themes and to identify and prioritize research topics, debate controversial issues in HAB science, and establish new international research partnerships across disciplines. Potential OSMs that GlobalHAB could convene include the following:

- The 2nd Open Science Meeting on BHABs
- The 2nd International Conference on *Ostreopsis* Development (ICOD-2)
- An OSM on crosscutting issues and challenges for cHABs in marine, freshwater, and brackish systems
- An OSM to review the current state of knowledge and knowledge gaps related to the genetic basis of toxin production and the environmental factors that influence toxin production
- An OSM focused on aligning existing time-series observations with existing climate model hindcasts and projections

Special Sessions

For cases in which the number of scientists working on a specific topic is not large enough to merit an OSM, GlobalHAB will propose special sessions at international science meetings. Special sessions can be efficient at providing venues for scientists to present their results, not just to other scientists working on the same specific topic but also to the broader HAB community. Potential special sessions could include the following:

- Special sessions on HAB species biogeography, BHABs, and cHABs at the International Conference on Harmful Algae (ICHA)
- Special sessions on observation tools, not only at the ICHA meetings but also at other relevant scientific conferences not specifically focused on HABs, such as the meetings of the Association

for the Sciences of Limnology and Oceanography, phycological meetings, ocean optics meetings, and the Trait-based Approaches to Ocean Life workshop series
- A session on detection of ciguatoxins and palytoxins (and analogues) could be included within a general toxicology congress
- FHAB and cHAB sessions at meetings of the Global Lake Ecological Observatory Network (GLEON)

Intercalibration Activities

Some measurement methods and equipment are used by more than one laboratory, but no standard reference materials are available (in particular for most phycotoxins) that would allow laboratories to conduct their research on comparable bases. The chemical oceanography community has found that results from analyses using the same methods may vary widely due to subtle differences in techniques. GlobalHAB will facilitate intercalibration activities when it is suspected that differences among laboratories, methods, and/or equipment may be hindering progress in the field.

Training

Standard methods of research and observations are available for some areas of HAB science, but these methods need to be taught to a greater number of scientists and technicians. In some cases, suitable manuals already exist, but in other cases training manuals need to be developed (see below). GlobalHAB will provide mechanisms for organizing training materials and activities, especially targeting countries that have difficulty implementing basic strategies to address HABs and their effects. Important initiatives include the following:

- Taxonomic training initiatives for the identification of microalgae
- Training on methods to detect CTX activity (e.g., fluorescent RBA, radioactive methods)
- A workshop to address toxin biosynthesis and mechanisms of action
- A training workshop on methods for sampling BHAB organisms
- Training on taxonomy and toxin analysis, monitoring, and mitigation procedures
- Training and education activities and a summer school on analysis and interpretation of genetic data relevant to HAB toxicity
- A training workshop or summer school on the theme of improving communication between biologists, biological modelers, and ocean/climate modelers

Manuals

GlobalHAB will develop "good practice" manuals to help standardize common methods and compare field data and experimental results. Manuals that would be beneficial include the following:

- A user-friendly electronic manual on mitigation strategies for freshwater cHABs across the world
- A good-practice manual for the environmental evaluation of HABs that outlines the potential costs of HABs and methodologies to evaluate the cost/benefit of different response strategies
- Good-practices manuals for HAB and climate change research

Databases

GlobalHAB will promote the development of lists and databases that could be helpful for HAB sciences, for example, updating a list of fish-killing harmful algae in the IOC Reference List that feeds into the World Register of Marine Species.

Outreach to Policymakers

Scientific results from HAB studies are often not accessible to policymakers in understandable and attractive formats. GEOHAB produced a Summary for Policymakers (see Kudela et al., 2015), and GlobalHAB will provide information on topics for which there are no existing sources of objective and authoritative information. For example, policymakers could benefit from:

- Receiving credible and understandable information related to the "Global Ciguatera Strategy" of IPHAB
- Having a manual available describing mitigation strategies and that has a list of priorities for understanding and managing cHABs
- Having evidence-based perspectives and resources for authorities responsible for granting access to the utilization of coastal water space for marine aquaculture
- Knowing about the advice given to the aquaculture industry on the impacts of HABs on cultured fishes and seafood
- Having an evidence-based perspective of the economic impact of HABs and methods to predict and mitigate their occurrence
- Having a credible, high-level outlook on HABs included in the reports of the IPCC and in the UN World Ocean Assessments

CONCLUSION

GlobalHAB has been established to advance research, observations, and modeling related to harmful algal blooms. More information about GlobalHAB plans will be available in the *GlobalHAB Science and Implementation Plan,* expected to be available in mid-2017 through IOC and SCOR. Built upon the legacy of GEOHAB, GlobalHAB aims to serve the international community working on HABs by providing a scientific framework for the integration and coordination of research and expertise of many individual scientists in the study of HABs. The ultimate goal is to protect marine ecosystems and human health.

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