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

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The mission of GlobalHAB is to improve understanding, prediction, management and mitigation of HABs in aquatic ecosystems.

GlobalHAB is developing partnerships and synergies with a variety of global, regional and national organizations and projects, to help promote GlobalHAB objectives worldwide and involve scientists in GlobalHAB.

GlobalHAB enlarges the scope of GEOHAB by including research on HABs in marine, brackish and freshwater areas, and incorporating new topics where HABs affect human society (health, economy, marine aquaculture) at present and in a rapidly changing world.

GlobalHAB aims to foster international planning and coordination among individual scientists and groups of scientists working on HABs and on other science fields to jointly advance HAB research and mitigation of HAB impacts.

Abstract

From 1998 to 2013, the international community of scientists dealing with 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 of these natural events that cause harm to humans and ecosystems. During this period, IOC and SCOR co-sponsored the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) program to facilitate progress in HAB research, observations, and modeling. In 2016, IOC and SCOR launched a new project on HABs, which is building on the foundation provided by GEOHAB, but also extending into freshwater systems and addressing several topics related to the effects of HABs on human society at present and in a rapidly changing world.
Genesis of GlobalHAB

As described in the paper in this issue by Kudela et al. (2017), GlobalHAB was developed as an output of the final Open Science Meeting (OSM) of the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) program in Paris, in April 2013 (GEOHAB, 2014). The main purpose of the OSM was to evaluate and synthesize the outcomes of GEOHAB. Participants at the meeting agreed that international coordination of HAB science was still needed, in order to advance understanding of factors controlling HABs and resulting in effects of HABs on humans and aquatic ecosystems. While GEOHAB focused on marine HABs and narrowly on the ecological and oceanographic aspects of HABs, meeting participants agreed that broadening the 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. IOC and SCOR appointed a Scientific Steering Committee (SSC) for the new GlobalHAB program in 2015, which met for the first time in March 2016.

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. There are many potential benefits of the GlobalHAB program:

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 scientists and social scientists).

2. GlobalHAB will provide a mechanism to bring together a critical mass of resources (expertise, equipment, finances) over an extended period to make progress on 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 to provide critical infrastructural support for 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 provide the international framework structure and endorsement to 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 HABs scientists together to work on issues of common interest. Therefore, the general mission of GlobalHAB is to foster international cooperative research on HABs, following the steps of GEOHAB. Furthermore, the overall goal of GlobalHAB is to improve understanding and prediction of HABs in aquatic ecosystems, and management and mitigation of their impacts. To achieve this goal, GlobalHAB will

- Address the scientific and societal challenges of HABs, including the environmental, human health, and economic impacts, in a rapidly changing world.
- Consolidate linkages with broader scientific fields, and other 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, informing science-based decision-making.

These approaches will be used to determine which activities to implement. A brief description of the topics included in GlobalHAB is given in the next sections. More details about GlobalHAB will be provided 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 adopted new topics suggested by the international community at the OSM in Paris (GEOHAB, 2014), where the important foundation set by GEOHAB through its five Program Elements (Figure 1) was also acknowledged. Although significant progress was made on these Program Elements (see Kudela et al., 2017), they still provide a sound and useful scientific framework to be incorporated and continued under GlobalHAB. The objectives addressed by these five Program Elements are:

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, some of the main challenges are establishing reference sequences to interpret molecular data and achieve 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 (morphology and molecular characterization, toxin composition, physiology, life history, etc.), and defining standardized protocols for physiological investigations. An understanding of the biodiversity and biogeography of harmful organisms and their toxins is fundamental to identify trends in HAB occurrence, enable prediction of HABs, and design of management and, when possible, mitigation plans of their impacts.

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 were achieved by GEOHAB on this research topic (see Glibert and Burford, 2017, this issue), which contributed, for instance, to the implementation of policies limiting nutrient input...
and proved useful to prevent 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. Furthermore, changes in nutrients may accompany climate change and other anthropogenic forcing factors. These questions are fundamental for both 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 of aquaculture-related nutrients and HAB occurrence and toxicity, and deoxygenation and anoxia processes resulting 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 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) clarified the important role of particular life history strategies (e.g., encystment and excystment processes, sexual reproduction), production of allelopathic substances (biologically active compounds that elicit specific responses in competitors or predators), and intrinsic defence against parasites (virus, protists) in the capacity to proliferate exhibited by harmful organisms. However, 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 the substrates and the development of the blooms. There is also a need to investigate the life history, floating, and dispersion strategies of macrophytes (e.g., *Sargassum*, *Enteromorpha*) and cyanobacterial HABs (cHABs) to understand their bloom dynamics. The new studies should
include assessment of adaptive biological traits and intra-specific interactions (e.g., physiology, toxin production, allelochemical properties, life history) of HAB species and populations in different environments. The new cutting-edge methodologies (metabolomics, proteomics, etc.) offer new possibilities for progress. Still, a main challenge is to estimate biological rates and other parameters at 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 community interactions respond similarly within comparable ecosystem types. The GEOHAB program adopted the comparative approach, from the cellular to the ecosystem (namely, upwelling and stratified systems, embayments and fjords) level (Berdalet et al., 2017a; Kudela et al., 2017; Pitcher et al., 2017). This approach is based on the view that the ecology and oceanography of HABs can best be understood through the 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 useful in modeling HABs, and management and mitigation of their effects.

The comparative approach is useful to continue in GlobalHAB, and extended 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 potential use of the comparative approach in GlobalHAB include comparisons of Gambierdiscus dynamics in the main affected areas (the Pacific Ocean and Caribbean Sea), dynamics of the main benthic HAB taxa (Ostreopsis and Gambierdiscus), and blooms of Pseudoachattonella species that have caused fish mortalities in northern Europe, as well as in Japan and South America.

Program Element 5: Observation, Modelling, 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 enable early warnings and predictions, and to support decision-making for the protection and management of coastal resources. During the lifetime of GEOHAB, technical advances improved our ability to observe HABs (see e.g., HABWATCH, 2004; GEOHAB, 2013; Berdalet et al., 2014). Observations can feed into models, which are essential tools for HAB prediction and management. A major activity of GEOHAB was the modeling workshop held in Galway, Ireland in 2009 (GEOHAB, 2011).

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 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 (e.g., 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**

This section describes the new topics included in GlobalHAB. These topics were raised by the international HAB science community during the final GEOHAB Open Science Meeting. When added to the GEOHAB Program Elements, this is admittedly a large number of topics that would require significant funding to address. The GlobalHAB SSC will seek such funding and will determine its priorities for implementation 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 was the last CRP launched by GEOHAB, in 2010 (GEOHAB, 2012). This CRP 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 illnesses in the world, often with significant long-term health effects. CFP globally affects up to 50-280 cases per 10,000 people per year in the affected areas, although the true incidence is difficult to ascertain due to under-reporting and other challenges (Friedman et al., 2017). The global importance and impact of CFP is reflected by the adoption by IOC, WHO, and FAO, of a "Global Ciguatera Strategy" (http://hab.ioc-unesco.org/) in 2015 and by the initiatives launched by international and 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 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 (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 be addressed to improve knowledge of the ecology, physiology, and toxin-transfer mechanisms through marine food webs, and to determine fundamental parameters for modeling BHAB dynamics. Direct collaboration with public health experts and people affected by BHAB impacts will be fundamental for progress. Attention on other BHAB species should also be addressed within GlobalHAB. Finally, the role of BHABs in marine ecosystems, such as effects on marine organisms, and the impacts of climate change on BHAB dynamics should be investigated as well.

Cyanobacterial HABs (cHABs) and HABs in freshwater (FHABs): 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, and cyanobacterial HABs in marine, brackish (Figure 4), and freshwater habitats (Figure 5). Freshwater HABs (FHABs) include a range of cyanobacterial
species (cHABs) 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 recently have been described in benthic habitats (e.g., Phormidium, Didymosphenia). cHABs can be a problem in freshwaters and brackish areas (e.g., Nodularia in the Baltic Sea), and marine ecosystems (especially associated with the proliferation of toxic filamentous cyanobacteria such as Lyngbya and Moorea in tropical regions). These species produce a wide range of toxins, including microcystins, cylindrospermopsins, anatoxins, nodularins, saxitoxins, aplysiaatoxins 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 on this topic 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 in freshwater, brackish, and marine habitats. 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 to protect farmed seafood products from HAB impacts. The aquaculture of shellfish and finfish has many benefits, including the creation of nutritious high-protein food, reducing the pressure on natural resources and supporting sustainable economic development and employment. Nevertheless, 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 from aquaculture in the promotion 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 micro-algae (raphidophytes, dictyophytes, haptophytes, dinophytes) continue to cause substantial losses to sea-cage fish-culture operations.

Progress in modelling (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 shellfish are becoming increasingly available, although further method developments, a wider range of targets, and validation studies are needed. These are important fields of applied research that 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 cross-cutting 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 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 better understanding of environmental controls of toxin production and to better predict the probable impact of the changes in the marine habitats on the toxicity of HAB species. Significant progress has been made in this regard for the 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, okadaic acid and 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 australae* (e.g. Wagoner et al., 2008; Lim et al., 2014) and of cytotoxic species affecting other marine cultured organisms (e.g., 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) and the protection of public health and food security. Progress has been made in the detection and characterization of several microalgal toxins due to the advances in analytical techniques, and cell-based and functional assays. However, official and reliable methods that are recognized in health regulations are still 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 collaborations 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 an integrated understanding of the health and environmental characteristics of the ocean, including HABs. In June 2016, the U.S. 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 (www.cdc.gov/). Other recent examples in Europe include position papers (Moore et al., 2013), the 2014 Oceans and Human Health Workshop in Cornwall, UK (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 and close communication and collaboration regarding it 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 diarrheic 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 (at both regional and national levels) the economic costs of HABs, as well as the costs of...
methods to predict and mitigate HABs. The main contribution of GlobalHAB will be to bring
together natural scientists with economists. Many of the economic studies in the past have been
led by or had significant contributions from natural scientists who study HABs. Many of the
studies on the negative economic impacts of HABs have employed relatively crude measures and
methodologies, the results of which often 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 (at the 2012 value of the dollar): 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 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 to be taken by the aquaculture
industry, their insurers, and coastal zone managers, and will facilitate better decision making on
scientific priorities.

Climate Change and HABs—This theme was started 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 CO2). There is increasing concern that global change may
stimulate geographic expansion and increases in severe impacts of HABs (e.g., Hallegraeff,
2010; Wells et al., 2015). There is ample evidence that the main control factors of 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 physico-chemical parameters and HAB occurrence, as a base for predictions of climate effects on HABs. Experimental work on climate effects on HABs should also be carried out, for example, laboratory and mesocosms experiments, as a base for predictions of climate change effects on HABs. GlobalHAB will encourage the development of comprehensive, region-specific studies integrating biological process data with downscaled climate projections. GlobalHAB will also develop activities that will promote the adoption of good practices in lab 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, GO2NE) to investigate 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 (EOVs, essential ocean variables) 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 and 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, this issue). The representatives of some partner organizations are contributing to the development of the GlobalHAB Science and Implementation Plan. Some of the organizations that 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 International Atomic Energy Agency (IAEA), the World Health Organization (WHO), the Food and Agriculture Organization (FAO), and 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, which 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 IOC (e.g., IOC/WESTPAC).

**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 central themes of the GlobalHAB project and give visibility to national projects.

More details about GlobalHAB can be obtained in the *GlobalHAB Science and Implementation Plan*, which will be available in mid-2017 through IOC and SCOR.

**Implementation of GlobalHAB**

The *GlobalHAB Science and Implementation Plan* will describe detailed implementation activities for the near term (1-3) and the more distant future of the project (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; the outcome of the workshops 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. β-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, and
- 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 cross-cutting 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 influence on 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 (ASLO), phycological meetings, ocean optics meetings, and the Trait-based Approaches to Ocean Life workshop series;
- A session on ciguatoxins and palytoxins (and analogues) detection could be included within a general toxicology congress; and
- FHAB and cHAB sessions at meetings of the Global Lake Ecological Observatory Network (GLEON).
Inter-calibration Activities—Some measurement methods and equipment are used by more than one laboratory, but there are no standard reference materials available (in particular for most phycotoxins) for laboratories to analyze and to make their results comparable. In chemical oceanography, it has been 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. Sometimes, suitable manuals already exist, but in other cases manuals will need to be developed for use in the training (see below). GlobalHAB will provide mechanisms to organize training materials and activities. 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, etc.);
• A workshop to address toxins 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; and
• A training workshop or summer school on the theme of improving communication among biologists, biological modelers, and ocean/climate modelers.

GlobalHAB will especially target training and capacity-building initiatives in these areas facing basic problems to attend HABs and their effects.

Manuals—GlobalHAB will develop “good practice” manuals to help standardize common methods and compare field data and experimental results, and provide instructions for people who want to use the methods. 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, and

• 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 an understandable and attractive format. GEOHAB produced a Summary for Policymakers (see Kudela et al., 2015) and GlobalHAB will do the same for topics for which there are no sources of objective and authoritative information. For example, policymakers could be helped by the following:

• Receiving credible and understandable information related to the "Global Ciguatera Strategy" of IPHAB,

• A manual for mitigation strategies and a list of priorities for understanding and managing cHABs,

• Evidence-based perspectives and resources for authorities responsible for granting access to the utilization of coastal water space for marine aquaculture,

• Advice to the aquaculture industry on the impacts of HABs on cultured fishes and seafood,

• An evidence-based perspective of the economic impact of HABs and methods to predict and mitigate their occurrence, and

• A credible, high-level outlook on HABs included in the reports of the Intergovernmental Panel on Climate Change and in the UN World Ocean Assessments.

Conclusion

GlobalHAB has been established to advance research, observations, and modeling related to harmful algal blooms. More detail about GlobalHAB plans will be available in the GlobalHAB Science and Implementation Plan. 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 HAB. The ultimate goal is to protect marine ecosystems and human health.

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Figure legends

Figure 1. Topics integrated in GlobalHAB, including the five Programme Elements of GEOHAB.

Figure 2. Images of plankton (left image) obtained with the Imaging Flow Cytobot (right image; the white instrument is a CTD), acquired at Tångesund, Swedish Skagerrak coast. Top row left to right: *Dictyocha fibula*, *Tripos lineatus* (syn. *Ceratium lineatum*), second row left to right: *Akashiwo sanguinea*, *Dinophysis norvegica* and *Alexandrium pseudogonyaulax*, third row: *Thalassiosira* sp., fourth row: *Pseudo-nitzschia* sp. and bottom row: *Chaetoceros* sp.

Photo: Michael Brosnahan and Bengt Karlson.

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

Figure 4. Surface accumulations of cyanobacteria in the Southern Baltic Sea in 2013.

Photo: Bengt Karlson.

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

Figure 6. Massive fish mortalities in Jakarta, Indonesia. Credits: Tumpak Sidabutar (HAN53).
Scientific basis for HAB Management and Mitigation of Impacts on Ocean and Human Health

Figure 1
Figure 2
Figure 3
Figure 4
Possible Cover photo #3. sampling for benthic HABs