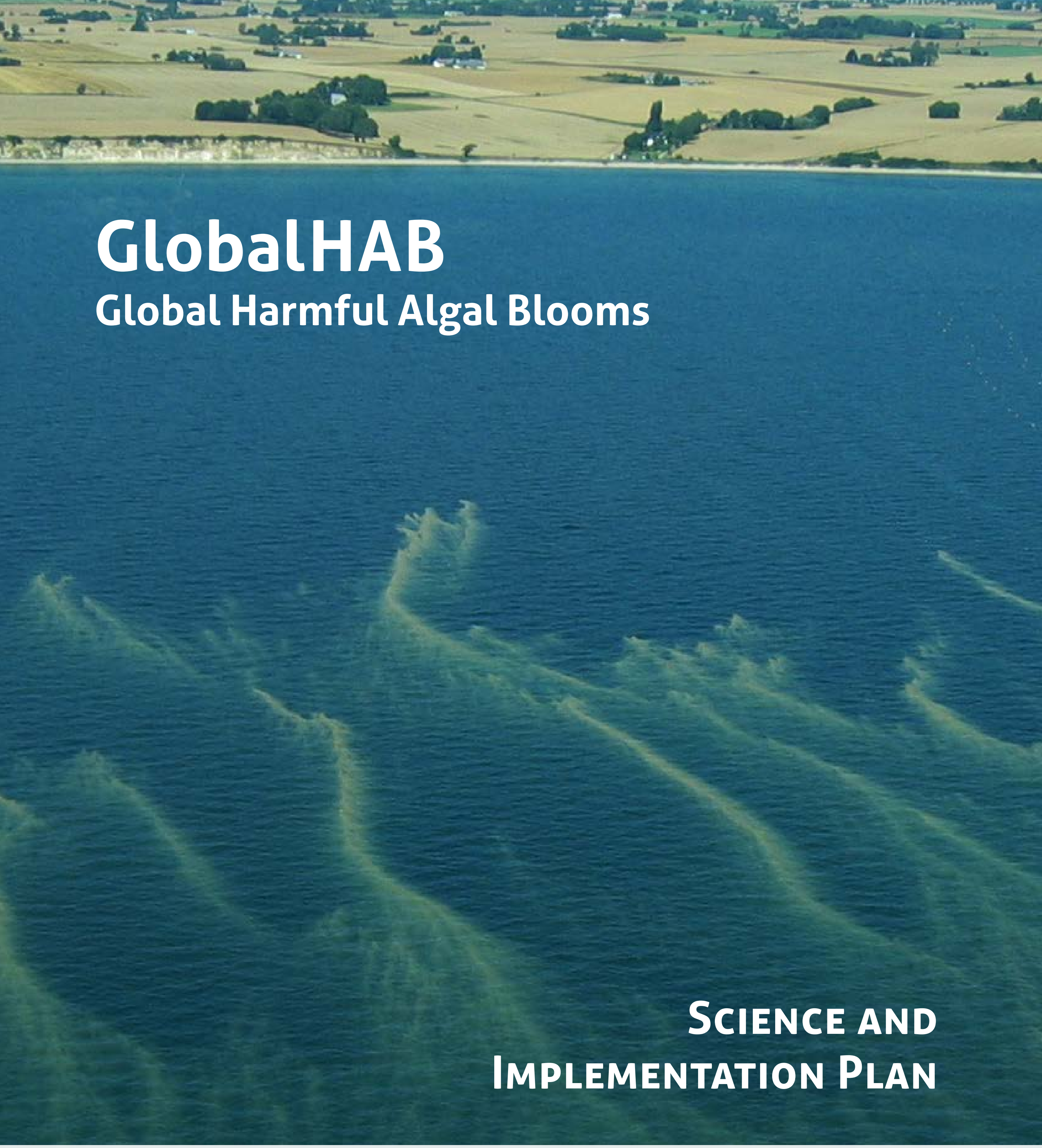
GlobalHAB
Global Harmful Algal Blooms



Science and Implementation Plan

International Council for Science
SCOR
Scientific Committee on Oceanic Research

GlobalHAB
IOC-SCOR

UNESCO
United Nations
Educational, Scientific and
Cultural Organization

Intergovernmental
Oceanographic
Commission

GlobalHAB
Global Harmful Algal Blooms

Science and Implementation Plan

An International Programme
Sponsored by the Scientific Committee on Oceanic Research (SCOR)
and the Intergovernmental Oceanographic Commission (IOC) of UNESCO

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Akashiwo sanguinea bloom, East coast of New Zealand.
Photo: Oliver Wade, Hawkes Bay Regional Council.

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www.globalhab.info, *www.jhu.edu/scor* and *ioc.unesco.org/hab*

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Index of Contents

List of Acronyms

ANCA	Algas Nocivas en el Caribe y Regiones Adyacentes (of IOC)
AOAC	Association of Analytical Communities
ASLO	Association for the Sciences of Limnology and Oceanography
ASP	Amnesic Shellfish Poisoning
BHAB	Benthic Harmful Algal Bloom
BMAA	β-Methylamino-L-alanine
BOOS	Baltic Operational Observing System
CDC	Centers for Disease Control (U.S.)
CFP	Ciguatera Fish Poisoning
cyanoHAB	Cyanobacterial Harmful Algal Bloom
CIESM	The Mediterranean Science Commission
CRP	Core Research Project
CTX	Ciguatoxin
DSP	Diarrheic Shellfish Poisoning
EOV	Essential Ocean Variable
EuroGOOS	European Global Ocean Observing System
FANSA	Floraciones Algales Nocivas en Sudamérica (of IOC)
FAO	Food and Agriculture Organization (UN)
FHAB	Freshwater Harmful Algal Bloom
GEO-BluePlanet	Group on Earth Observations Blue Planet project
GEOHAB	Global Ecology and Oceanography of Harmful Algal Blooms programme (IOC and SCOR)
GHSR	Global HAB Status Report
GLEON	Global Lake Environmental Observation Network
GODAE	Global Ocean Data Assimilation Experiment
MEAP-TT	Marine Ecosystem Analysis and Prediction Task Team
GOOS	Global Ocean Observing System
HAB	Harmful Algal Bloom
HAEDAT-	Harmful Algae Event Database
HABMAP	HAB Map
HTS	High Throughput Sequencing
IAEA	International Atomic Energy Agency
IBI-ROOS	Ireland, Biscay and Iberian Regional Operational Observing System
ICES	International Council for the Exploration of the Sea
ICHA	International Conference on Harmful Algae
ICSU	International Council for Science
ICTC	International Committee on Toxic Cyanobacteria
IMBeR	Integrated Marine Biosphere Research project (SCOR and Future Earth)
IOC	Intergovernmental Oceanographic Commission of UNESCO
IOCCG	International Ocean Colour Coordinating Group
WESTPAC	IOC Sub-commission for the Western Pacific
IPCC	Intergovernmental Panel on Climate Change
IPHAB	Intergovernmental Panel on Harmful Algal Blooms
ISSHA	International Society for the Study of Harmful Algae
ITS	Internal Transcribed Spacer
IWC	International Whaling Commission
LCMS	Liquid chromatography–mass spectrometry
MSFD	Marine Strategy Framework Directive

MON-GOOS	Mediterranean Oceanography Network for the Global Ocean Observing System
NIEHS	National Institute of Environmental Health Sciences (U.S.)
N2A	Neuroblastoma Assay
NOAA	National Oceanic and Atmospheric Administration (U.S.)
NOOS	North West European Self Operational Observing System
NORS	National Outbreak Reporting System (U.S.)
NSF	National Science Foundation (U.S.)
NSP	Neurotoxin Shellfish Poisoning
OBIS	Ocean Biogeographic Information System
OHHABS	One Health Harmful Algal Bloom System (CDC)
OSM	Open Science Meeting
OSPAR	Oslo-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic, coast of Europe
PE	Programme Element (of the GEOHAB Science Plan)
PICES	North Pacific Marine Science Organization
PICTs	Pacific Island Countries and Territories
PLTX	Palytoxin
PSP	Paralytic Shellfish Poisoning
PST	Paralytic Shellfish Toxin
qPCR	Quantitative (real-time) Polymerase Chain Reaction
RBA	Receptor-Binding Assay
rbcL	Large subunit Ribulose Bisphosphate Carboxylase/Oxygenase
SSU and -LSU	Ribosomal DNA, small and large subunits
ROOS	Regional Ocean Observing System
SCOR	Scientific Committee on Oceanic Research
SEM	Scanning Electron Microscope
SSC	Scientific Steering Committee
ToR	Term of Reference
UNESCO	United Nations Educational, Scientific, and Cultural Organization
WG	Working Group
WGHABD	Working Group on Harmful Algal Bloom Dynamics (of ICES and IOC)
WHO	World Health Organization

Preface

Harmful algal blooms (HABs) are proliferations of certain noxious and/or toxic micro- and macroalgae and cyanobacteria, regardless of their concentration, with negative impacts on aquatic ecosystems, and human health and wellbeing.

HABs are naturally occurring phenomena that are also facilitated by anthropogenic pressures (including eutrophication, habitat modification and introduction of exogenous HAB organisms). HABs constitute a complex global problem that might increase in severity and frequency, and be expanded in biogeographic range, in our changing planet. Decades of coordinated international research and monitoring have proven to be a powerful tool to advance scientific knowledge of HAB dynamics, necessary to predict them and to design efficient tools for the management and mitigation of their impacts. Indeed, relevant accomplishments have been achieved through GEOHAB (Global Ecology and Oceanography of Harmful Algal Blooms), the first international research programme that focused exclusively on harmful marine microalgae. From 1998 to 2013, GEOHAB was implemented by the HAB research community under the sponsorship of the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the Scientific Committee on Oceanic Research (SCOR).

The main scientific efforts of GEOHAB were focused on comprehension of physiological, behavioral, and genetic characteristics of harmful microalgal species, and the interactions between physical and other environmental conditions that promote the success of one group of species over another. With an international, multidisciplinary and comparative approach, GEOHAB advanced our understanding of the mechanisms underlying population dynamics of HABs within an ecological and oceanographic context, and also from the ecosystem perspective at the regional scale.

In 2016, following the recommendations of the international community studying HABs, "GlobalHAB: Global Harmful Algal Blooms", a new project building on the foundation provided by GEOHAB, was launched with the support of IOC and SCOR.

GlobalHAB adopts the partially accomplished GEOHAB objectives, extending them into brackish and freshwater systems and to a variety of harmful groups (including benthic microalgae, cyanobacteria and macroalgae) and will address several issues related to the effects of HABs on human societies (health, socio-cultural aspects, economic impacts). With new challenges, new tools and a wider multidisciplinary perspective, GlobalHAB will also address the potential trends of HABs and their impacts under climate change scenarios. The ultimate goal is to translate the improved knowledge on HABs into sound policy- and decision-making to efficiently protect marine ecosystems and human health.

This document constitutes the *GlobalHAB Science and Implementation Plan*, which represents an addendum to the *GEOHAB Science Plan*. It will be used as the basis for carrying out the proposed science over the next decade in coordination with other local, national, and international efforts focused on food and water security, human and ecosystem health, ocean observing systems, and climate change. The complete document is available at www.globalhab.info.

The GlobalHAB Scientific Steering Committee (SSC), on behalf of the entire international HAB community, thanks the sponsors of GlobalHAB, including the IOC of UNESCO and the U.S. National Science Foundation through SCOR, for their financial support of GlobalHAB. The SSC also thanks the valuable comments provided by the attendees of the Town Hall at the 17th International Conference on Harmful Algae (ICHA, Florianopolis, Brazil, October 2016), where GlobalHAB was presented for the first time. The suggestions to the draft version provided by different scientists outside the SSC contacted during the development of the Plan, as well as by the external panel of eleven reviewers, markedly contributed to the final version of the *GlobalHAB Science and Implementation Plan* presented here.

Executive Summary

The Global Harmful Algal Blooms (GlobalHAB) Programme is an international scientific programme on harmful algal blooms (HABs) aimed at fostering and promoting cooperative research directed toward improving the prediction of HAB events, and providing sound knowledge for policy- and decision-making to manage and mitigate HAB impacts in a changing planet.

HABs are proliferations of certain photosynthetic organisms (including unicellular phytoplankton and phytobenthos, macroalgae, cyanobacteria, and particular ciliates) that can cause massive fish kills, produce toxins that bioaccumulate in seafood, and/or cause ecological damage through the development of hypoxia/anoxia and other habitat alterations. HABs are natural processes that occur in all aquatic systems and cause worldwide problems with significant economic, socio-cultural, and human health consequences. There is considerable concern that some HABs and/or their associated impacts may be increasing and expanding globally due to a combination of natural and human-driven forcing, including climate change. In the past two decades, improvements in scientific understanding of the complex processes involved in HAB dynamics have contributed to better management of the risks associated with some harmful events. This progress has been possible with concurrent advances in technology, observation and modeling approaches, as well as the coordination of the international research fostered by the SCOR and IOC-UNESCO programme GEOHAB (Global Ecology and Oceanography of Harmful Algal Blooms).

Still, important gaps in knowledge and uncertainties about future trends of HABs require the continued coordination of international research on HABs in order to efficiently predict them and prevent and mitigate their impacts. For this reason, at the end of GEOHAB, the international HAB research community convened at the GEOHAB Synthesis Open Science Meeting (OSM) in Paris in April 2013, and recommended establishing a new programme built on the framework and legacy of GEOHAB. Accordingly, the “Global Harmful Algal Blooms”, GlobalHAB programme was launched in 2016, sponsored by SCOR and IOC-UNESCO, to operate for 10 years until 2025.

GlobalHAB will address the contemporary scientific and societal challenges of HABs through the application of new advanced technologies, training and capacity building, with a multidisciplinary approach. The programme will establish linkages with broader science domains, emphasize social science communications and address management priorities.

The overall **Goal of GlobalHAB** is to improve understanding and prediction of HABs in aquatic ecosystems, and management and mitigation of their impacts.

The Mission of GlobalHAB includes the following elements:

- Foster international coordination and cooperative research to 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 and cost-effective technologies.
- Promote training, capacity building and communication of HAB research to society.
- Serve as a liaison between the scientific community, stakeholders and policy makers, informing science-based decision-making.

This document, the ***GlobalHAB Science and Implementation Plan***, is an addendum to the *GEOHAB Science Plan* (GEOHAB 2001). The GlobalHAB Plan is structured with twelve themes identified at the initiation of GlobalHAB: *Biodiversity and Biogeography, Adaptive Strategies, Toxins, Nutrients and Eutrophication, Freshwater HABs and cyanobac-*

terial HABs, Benthic HABs, HABs and Aquaculture, Comparative Approach, Observation, Modeling and Prediction, HABs and Health, Economy, and *Climate Change and HABs.* New themes will be incorporated as a response to needs identified as the programme proceeds. These themes serve as a framework to guide priorities and research, and to define the scientific boundaries of the GlobalHAB programme, by covering processes from cell to ecosystem scales, concerning benthic and planktonic, unicellular and multicellular organisms. GlobalHAB also reinforces the multidisciplinary approach necessary to better understand HABs in all aquatic ecosystems, because HABs are natural phenomena resulting from the complex interplay of physical, chemical and biological processes. In addition, GlobalHAB will foster interaction between HAB and (traditionally) non-HAB disciplines such as health, economics and sociology. The objectives identified in GEOHAB for marine species and ecosystems also apply to freshwater and brackish waters. Furthermore, while GEOHAB studies were centered on unicellular planktonic microalgae and some marine cyanobacteria only, GlobalHAB will foster research on harmful marine phytobenthos, macroalgae and freshwater cyanobacteria as well.

The widest **international participation** of the research community and stakeholders will be essential to ensure the success of GlobalHAB. Scientists working in physics, chemistry and biology, as well as other disciplines related to harmful algal research – including toxicology, aquaculture, development of relevant instrumentation, modeling – are encouraged to contribute to this programme. Furthermore, special invitation is made to climate science, medical, economics and communication professionals and policy makers, whose expertise will be fundamental to find efficient strategies to reduce the impacts of HABs in the coming years.

This document provides a formal invitation to participate, accompanied by a description of the procedure for application, and associated responsibilities and benefits. Scientists are invited to participate in GlobalHAB by designing scientific activities in keeping with the goals and objectives of GlobalHAB, by applying for endorsement of such activities, and by participating in framework activities. The primary criterion for endorsement of activities or proposals is their applicability to any of the *GlobalHAB Science Plan* objectives.

In addition, despite GlobalHAB's unique role, GlobalHAB shares its scientific research interest on HABs with other international and regional entities and programmes. In consequence, GlobalHAB will find its niche within the international community and form strategic partnerships producing reciprocal benefits with other organizations and projects. At the initiation of GlobalHAB, some of these entities were already identified, due to past links with GEOHAB (e.g., GOOS, ICES, ISSHA, PICES) and their representatives contributed to the development of the *GlobalHAB Science and Implementation Plan*. New partnerships and synergies are intended to continue to be built or established in the future.

GlobalHAB will not establish CRPs as in GEOHAB. Instead, the GlobalHAB SSC will oversee the activities of each Theme, developing small teams of people to implement each specific activity. Expected outcomes from the GlobalHAB programme implementation activities include scientific papers and manuals, capacity-building activities, outreach and communication with the public and information for policy makers. In summary, GlobalHAB constitutes a platform to connect science-to-science and science-to-society to prevent and manage the impacts of HABs.

Introduction and Overview of the GlobalHAB Programme

Photosynthetic algae, a term that includes single-celled organisms (phytoplankton, phytobenthos and cyanobacteria) and macroalgae, constitute the base of the food webs in aquatic ecosystems. Under certain conditions, some species can form high-biomass and/or toxic proliferations of cells (or "blooms"), which can cause harm to aquatic ecosystems including plants and animals, and to humans. Ecosystem damage by high-biomass blooms may include, for instance, disruption of aquatic food webs, fish killing by gill damage, or the development of low oxygen "dead zones" after bloom degradation. Some species produce potent natural chemicals (toxins) that can persist in the water, causing harm via direct exposure to water-borne or aerosolized toxins, or enter the food web, leading (even at low to moderate densities, i.e. 10^2-10^4 cells L^{-1}) to illness or death of aquatic animals and/or human seafood consumers.

HABs are natural processes that occur in all aquatic systems and cause worldwide problems with significant economic, socio-cultural, and human health consequences. There is considerable concern that certain HABs, or at least their associated impacts, may be increasing globally. As with all algae dynamics, those of harmful species result from a combination of physical, chemical, and biological processes, only partially understood. Some HABs have been linked to human impacts, such as excessive coastal use, habitat modification, changes in nutrient inputs to aquatic ecosystems and human-mediated introduction of invasive species. In addition, other human-related and/or natural pressures may be involved in certain harmful events such as blooms of *Gambierdiscus* associated with ciguatera fish poisoning (CFP) in tropical areas, which is apparently expanding geographically. The effects of global or local climate change on HAB populations are poorly understood and require intensive, long-term and multidisciplinary observations and research.

In 2001, the first international programme, GEOHAB (Global Ecology and Oceanography of Harmful Algal Blooms) was created to foster international cooperation to advance understanding of HAB dynamics and to improve our ability to predict them (Kudela et al. 2017a). In GEOHAB, the main efforts were focused on the physiological, behavioral, and genetic characteristics of harmful marine microalgal species (mainly eukaryotes and a few cyanobacteria), and the interactions between physical and other environmental conditions that promote the success of one group of species over another. GEOHAB was designed to study HABs with a view to integrate global data from comparable ecosystems. With an international, multidisciplinary and comparative approach, GEOHAB advanced understanding of the mechanisms underlying population dynamics of HABs within an ecological and oceanographic context, and also from the ecosystem perspective at the regional scale. GEOHAB encouraged combined experimental, observational and modeling tools, using existing and innovative technologies in a multidisciplinary approach, consistent with the multiple scales and oceanographic complexity of HAB phenomena.

GEOHAB was supported by the Scientific Committee on Oceanic Research (SCOR) of the International Council for Science (ICSU) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO, and was also built on related national, regional and international efforts in HAB research. With strong administrative support from SCOR and IOC, and the active participation of the Scientific Steering Committee (SSC) and Core Research Project (CRP) working groups, GEOHAB accomplished many of its scientific goals, and left a strong legacy of international coordination and training for HAB research, a large number of endorsed projects, and a significant number of reports, special issues, and citations within the peer-reviewed literature (*www.geohab.info*). The achievements of the GEOHAB programme have been recently summarized in a special issue in *Oceanography* (Kudela et al. 2017b) and a book edited by Glibert et al. (in press). Briefly, GEOHAB produced and stimulated multiple special issues and it was directly acknowledged in or central to 330 publications in 75 journals, and cited in more than 1,000 publications as of 2016 (*Kudela et al. 2017a*). GEOHAB directly coordinated and/or co-sponsored research activities and provided endorsement for targeted, national, and regional programmes aligned with programme objectives. The programme provided increased visibility of HAB problems and integration and collaboration with other international programmes and organisations (e.g., LOICZ, GLOBEC, GOOS, PICES, ICES). It also raised awareness of the general scientific consensus that impacts from HABs on public health, recreation and tourism, fisheries, aquaculture, and ecosystems have increased over the past few decades and are continuing these trends (Kudela et al. 2015). The GEOHAB legacy continued beyond 2016 through ongoing research activities, training and capacity building, elaboration of reference materials, etc., initiated by the programme and now maintained by GEOHAB partners.

At the end of GEOHAB, the international HAB community at the Paris Open Science Meeting (OSM, April 2013) evaluated the outcomes of GEOHAB (GEOHAB 2014). Participants at the meeting encouraged a follow-on initiative, the new programme "GlobalHAB, Global Harmful Algal Blooms", to implement the most relevant and partially accomplished GEOHAB objectives on HAB research, to focus on the contemporary scientific challenges and management priorities, and to continue fostering the international coordination of HAB research.

Based on the Paris OSM (GEOHAB 2014) and subsequent discussions, and recommendations from the GEOHAB SSC, in consultation with SCOR and IOC representatives, the GlobalHAB programme was formally introduced in April 2015 to the IOC Intergovernmental Panel on Harmful Algal Blooms (IPHAB) and SCOR, and also received endorsements from the International Atomic Energy Agency (IAEA). IOC IPHAB and SCOR endorsed GlobalHAB as a new programme. As also decided at the Paris OSM, the *GlobalHAB Science and Implementation Plan* builds on the *GEOHAB Science Plan* (GEOHAB 2001). In consequence, it constitutes an addendum to that document and it includes a specific implementation strategy.

The GlobalHAB programme was launched in January 2016 to operate for 10 years. A Scientific Steering Committee (SSC) for GlobalHAB was formed with specific tasks of determining the scope of the research, developing the *GlobalHAB Science and Implementation Plan*, and assisting with the coordination and realization of the programme. The GlobalHAB SSC held its first meeting at the Scottish Association for Marine Science in Oban (Scotland, U.K.) on March 8-10, 2016. During the meeting, GlobalHAB SSC members analyzed the *Programme Elements* that structured GEOHAB (GEOHAB 2001, 2003; and see below) to identify the relevant aspects still valid for GlobalHAB and decided to carry them forward. In addition, the rationale and objectives of the new topics identified at the Paris OSM were established. A series of implementation activities at short or medium term were also listed. During the development of the *GEOHAB Science and Implementation Plan*, scientists outside the GlobalHAB SSC were invited to contribute to the document. The first draft was presented at the International Conference on Harmful Algae (ICHA) in Florianópolis, Brazil, in October 2016, where new inputs were received and the document was subsequently reviewed by eleven external reviewers. Here, the final version of the *GlobalHAB Science and Implementation Plan* is presented.

As stated above, the *GlobalHAB Science and Implementation Plan* constitutes an addendum to the *GEOHAB Science Plan* (GEOHAB 2001). The objectives identified in GEOHAB for marine species and ecosystems also apply to fresh and brackish waters. Furthermore, while GEOHAB studies were centered on unicellular planktonic microalgae and some marine cyanobacteria only, GlobalHAB will foster research on harmful marine benthic taxa, macroalgae and freshwater cyanobacteria as well. The integration of the former *GEOHAB Programme Elements* and the new topics, here after referred to as "*Themes*" (Figure 1), serve as a framework to guide priorities and research, and to define the scientific boundaries of the GlobalHAB programme. The *Themes* cover processes from cellular to ecosystem scales concerning benthic and planktonic, unicellular and multicellular organisms. GlobalHAB also reinforces the multidisciplinary approach necessary to better understand HABs in all aquatic ecosystems. Indeed, GlobalHAB integrates physical, chemical and biological processes (represented by the term "*Ecology*" in Figure 1), and allows interaction between HAB and (traditionally) non-HAB disciplines such as health, economics and sociology.

GlobalHAB Themes include the Programme Elements that formerly structured GEOHAB (GEOHAB 2001), namely *Biodiversity and Biogeography, Nutrients and Eutrophication, Adaptive Strategies, Comparative Approach, Observations, Models and Predictions.* As these elements remain valid and given the scientific and technology advances in recent years (see Kudela et al. 2017a, c), continued study in these areas will contribute to the progress of research on HABs. GlobalHAB also incorporates several new, timely topics not specifically addressed in GEOHAB: *Freshwater HABs and cyanobacteria HABs, Aquaculture and HABs, Toxins, Health, Economy* and *Climate Change*. Some of these new topics directly relate to the effects of HABs on human societies at present and in a rapidly changing world. Although these terms were mentioned in the *GEOHAB Science Plan*, the topics were either deliberately omitted in order to focus on oceanography and ecology of marine microalgae, or could not be examined fully during GEOHAB because they were not yet mature. Exceptionally, research on Benthic HABs was fostered through the creation of a new CRP towards the end of GEOHAB (GEOHAB 2012) given the increasing demand for research on CFP. The relevance of the problem and the rapid progress achieved in this research area (Berdalet et al. 2017a; Berdalet and Tester 2017) justifies the inclusion of the *Benthic HABs* theme in GlobalHAB with objectives that reach beyond the GEOHAB CRP to encompass other benthic HAB issues.

The different GlobalHAB themes are conceptually interlinked as shown in Figure 1 (see also section LINKAGES AMONG PROGRAMME THEMES). The "Comparative Approach" continues to be a keystone to address research at all levels as in GEOHAB (Kudela et al. 2017a, c). Multidisciplinary and integrated research should provide advice to manage the impacts of HABs on humans and the environment. While retaining a strong research-based focus, GlobalHAB will concurrently contribute to the application of new knowledge to management strategies and practices in order to broaden international support.

Figure 1. The Themes integrated in GlobalHAB range from small-scale (e.g., cellular) subjects (e.g., biodiversity, adaptive strategies) to studies at ecosystem scale and climate change-related processes. GlobalHAB's perspective is multidisciplinary, integrating physics, chemistry and biology, and addressing the impacts of HABs on the environment and human societies (including Health, Economy and Socio-cultural aspects). Improved observation within and across the different themes should result in better predictions of HAB events and contribute to the management of their impacts. Terms shown in italics (i.e., Planktonic, Ecology, Socio-culture) are not established as individual GlobalHAB themes, but are intrinsically integrated in HAB research.

This document presents the rationale and the general and specific objectives of the twelve themes identified at the inception of GlobalHAB. However, the programme is open to include new themes in response to the emerging challenges continuously posed by HABs. The themes are presented following a sequence determined by the scale of the processes they mainly concern, that is, from small to large scale. Some short- and medium-term activities to implement the GlobalHAB programme within the next 10 years are also indicated. GlobalHAB is not a funding programme, but – as was GEOHAB – is a mechanism to facilitate actions that require cooperation among nations, such as the comparison and standardization of methodologies, and the co-sponsorship of workshops, meetings and research activities. National, regional and/or international funding agencies (especially those focused on food and water security, human and ecosystem health, ocean observing systems, and climate change) will sponsor activities that respond to diverse HAB-oriented scientific priorities. GlobalHAB will provide a framework for the integration of research and expertise of many individual scientists in the study of HABs. The active participation and engagement of this international community is fundamental to achieve the overall goal of GlobalHAB: *Improve the understanding and prediction of HABs in aquatic ecosystems, and management and mitigation of their impacts*.

The GlobalHAB Goal and Mission

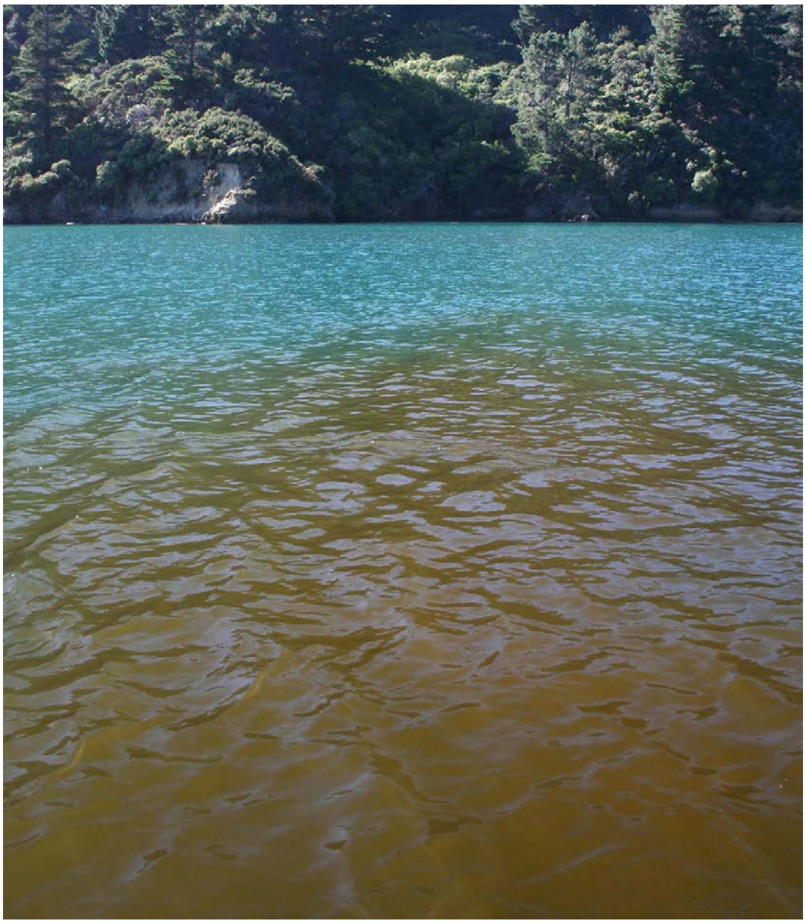
GOAL

To improve understanding and prediction of HABs in aquatic ecosystems, and management and mitigation of their impacts.

MISSION

GlobalHAB will

- Foster international coordination and cooperative research to 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 and cost effective technologies.
- Promote training, capacity building and communication of HAB research to society.
- Serve as a liaison between the scientific community, stakeholders and policy makers, informing science-based decision-making.



Alexandrium pacificum bloom, Marlborough Sounds, New Zealand. Photo: Lincoln Mackenzie.

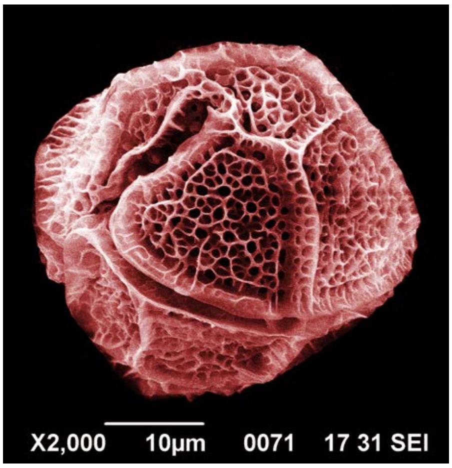
This section presents a brief rationale and the general and specific objectives of the twelve themes identified at the start of GlobalHAB. In the case of the GEOHAB Programme Elements (namely, "Biodiversity and Biogeography", "Nutrients and Eutrophication", "Adaptive Strategies", "Comparative Approach", "Observations, Models and Predictions"), more information on the accomplishments achieved along the GEOHAB time life can be found in Kudela et al. 2017b and Glibert et al. (in press).

THEME 1. Biodiversity and Biogeography

Overall objective: To identify the factors that determine the changing distribution of HAB species, their genetic variability, and the biodiversity of associated communities.

Rationale. Correct taxonomic identification of harmful species is crucial to determine the biogeographic distribution, range of expansion, population dynamics, ecology and links with toxin production. Thus, the specific objectives of this theme, identified in GEOHAB (2001) as Programme Element 1, are still endorsed, although the recent advances in technology offer new perspectives. In the case of microalgae, the list of harmful species that have been the focus of research until now includes 122 eukaryote and 20 cyanobacteria taxa (*www.marinespecies.org/hab/index.php*). However, the number of HAB species keeps changing due to new entries and to new studies that help to refine species descriptions. Genetic characterization using molecular markers (e.g., rDNA -SSU and LSU-, ITS, *cox1* and *cob* mitochondrial markers, rbcL gene) is revealing the existence of cryptic or pseudo-cryptic diversity among HAB species formerly defined based on morphological characters. This is the case for many "morpho-species" in the genera *Alexandrium* (e.g., Kremp et al. 2014), *Pseudo-nitzschia* (Lelong et al. 2012) and *Dinophysis* (Raho et al. 2008, Zhang et al. 2008). Furthermore, functional genes (e.g., sxtA4 coding for saxitoxin production, John et al. 2014) and sensitive markers like microsatellites (e.g., Casteleyn et al. 2010, Genovesi et al. 2015) have revealed intra-specific and strain diversity in toxin composition (e.g., *Karlodinium veneficum*, Bachvaroff et al. 2009) and can also allow us to distinguish between toxic and non-toxic species and populations (e.g., Van de Waal et al. 2014 and references therein). These tools, combined with increasing and improved sampling, have identified novel species and genotypes within a genus (e.g., *Gambierdiscus*, Litaker et al. 2010, Pawlowiez et al. 2014) which, in turn, helps ascertain the true distributions of the toxic taxa. The ongoing changes in our environment, with potential modifications of HAB distributions (see *Theme 12. Climate Change and HABs*), make it urgent to establish solid baseline information on biodiversity and biogeography of harmful taxa to be able to assess future changes (Boyd et al. 2013).

For monitoring purposes, different molecular approaches (e.g., qPCR, fluorescent *in situ* hybrid-



Lingulodinium polyedrum (antapical view, SEM coloured). Photo: Callum Whyte (SAMS).

ization, microarrays) implemented over recent decades offer new possibilities, facilitating faster identifications at the species level (reviewed by Kudela et al. 2010). Also High Throughput Sequencing (HTS) approaches are increasingly used to assess plankton diversity. These analytical methods have been improved and costs are decreasing, but there is an urgent need for reference sequences to interpret the data and achieve identifications at the species level. However, it is also important that comparisons between molecular methods and traditional morphologically based identification and quantification are carried out to standardize the methods. A new generation of taxonomists is required, who bridge the morphological know-how with modern techniques.

Specific objectives

- Assess the genetic variability of HAB species in relation to their toxicity, population dynamics, and biogeography.
- Determine changes in microalgal species composition and diversity in response to environmental and climate changes (see *Theme 12. Climate Change and HABs*).
- Determine the changes in the biogeographical range of HAB species caused by natural mechanisms or human activities.
- Support research and training to improve species delimitation using an integrated approach (e.g., morphology, molecular, toxin composition, physiology, life cycle).
- Define standardized protocols for physiological investigations, for example, genotype-environment interactions (gene expression).
- Investigate intra-specific diversity to determine population genetic structure related to physiological traits (especially toxin composition) at different spatial and temporal scales.
- Contribute to the collection of curated reference sequences to interpret HTS data.
- Investigate the functional differences amongst species/populations using omic-based approaches.

Example tasks

- Align with and contribute to the Global HAB Status Report (GHSR) and associated HAEDAT-HAB-MAP initiatives, to establish a baseline of the biogeographic species distribution
- Support long time series, such as the ones considered within the recently finished SCOR Working Group 137 “Global Patterns of Phytoplankton Dynamics in Coastal Ecosystems: Comparative Analysis of Time Series Observations” (*wg137.net/time-series/time-series-map*) or the new IOC Working Group to Investigate Change and Global Trends of Phytoplankton in the Oceans (TrendsPO), where biological data are collected, and encourage data analysis focused on different HAB species within an ecological context
- Support initiatives to identify and populate a database for reference sequences of HAB species; co-sponsor specific workshops focused on harmful species within the wide framework of eukaryote and protist database initiatives.

Outcomes

- A baseline of HAB species distribution based on morphological and genomic information available at the inception of GlobalHAB at local, regional, and global scales.
- Coordinated long time series on HAB events and species distribution (GHSR) to ascertain potential future trends related to climate changes and other anthropogenic forcing factors.
- Coordinated Establishment of the basis for genetic information on HAB species.

THEME 2. Adaptive Strategies

Overall objective: To determine the adaptations of HAB species and how they help to explain their proliferation or harmful effects.

Rationale. Each species has adaptive characteristics that define its niche, that is, the suite of physiological, morphological and life cycle features that determine its distribution in space and time. Within GEOHAB, specific characteristics and adaptations of HAB species were investigated in different marine ecosystem types, including upwelling systems (Pitcher et al. 2017), fjords and coastal embayments (Roy et al. 2017), stratified systems (Berdalet et al. 2017b) and eutrophic systems (Glibert and Burford 2017). Important contributions were provided for our understanding of i) the diversity of life histories of various HAB species – such as production and germination of resting stages, sexual reproduction – and their role in population dynamics (reviewed in Bravo and Figueroa 2014, Azanza et al. 2017); ii) the potential positive and negative interactions amongst species mediated by various allelochemical compounds (Ianora et al. 2011); iii) physiological adaptations of, for example, species producing long-lasting brown tides (Gobler and Sunda 2012); iv) complex interactions between HABs and their grazers, parasites and viruses (e.g., Chambouvet et al. 2008, Lu et al. 2016); v) in the case of non-swimming organisms (diatoms and cyanobacteria), ability to regulate buoyancy to access light and nutrients; and vi) genetic variability among cyanobacteria strains within populations and over time of a wide range of physiological adaptation strategies including akinete (=cyst) formation under adverse conditions, superior nutrient scavenging capacity, fixing atmospheric nitrogen, and synthesis of secondary metabolites (O'Neil et al. 2012). Finally, there is increasing evidence of the mixotrophic (combination of phototrophic with phagotrophic and/or osmotrophic nutritional modes) capacity of many HAB species, but their physiology is not known yet (Mitra and Flynn 2010).

Improvements in the characterization, both at theoretical and observational levels, of physical dynamics at the small scales of biological relevance have facilitated a better understanding of the physical-biological interactions that modulate HAB dynamics, for instance, in thin layers in stratified systems (e.g., GEOHAB 2008, GEOHAB 2013, Berdalet et al. 2014, Raine et al. in press). Stratification is a key factor modulating phytoplankton bloom dynamics and likely, there are also common strategies involved in the proliferation of cells in thin layers. However, the particular mechanisms leading to the selection of different noxious taxa such as *Karenia, Dinophysis* or *Pseudo-nitzschia,* are not known.

Detecting unique characteristics and adaptations of HAB species in particular environments could help in the development of predictive models. However, cosmopolitan rather than unique species thrive in upwelling systems (Smayda 2010) and no specific flora have been identified in fjords or coastal embayments (Roy et al. 2017). Even though some species may be specially favored by eutrophic conditions, the general view is that there is a wide range of combined nutrient availability and physical dynamics that define variable sub-habitats within the major ecosystem types mentioned above. Within them, particular life history strategies will allow individual species to proliferate. In upwelling, open water systems, identifying resting forms is still a challenge. Bottom-dwelling resting stages seem to play an important role in semi-confined systems, and may also be important in benthic systems. Advances in the characterization of the life histories and life strategies of benthic HAB species and macrophytes (e.g., *Sargassum*, *Ulva*) are also required. Research on the life history of the benthic dinoflagellates genera *Gambierdiscus* and *Ostreopsis* is still developing and particular adaptations include flattened shapes and production of mucus to attach to surfaces, which may play a key role in the colonization of surfaces and the development of the blooms. Finally, investigation on the role of toxins as traits that have evolved as a defence mechanism is relatively new (Selander et al. 2015).

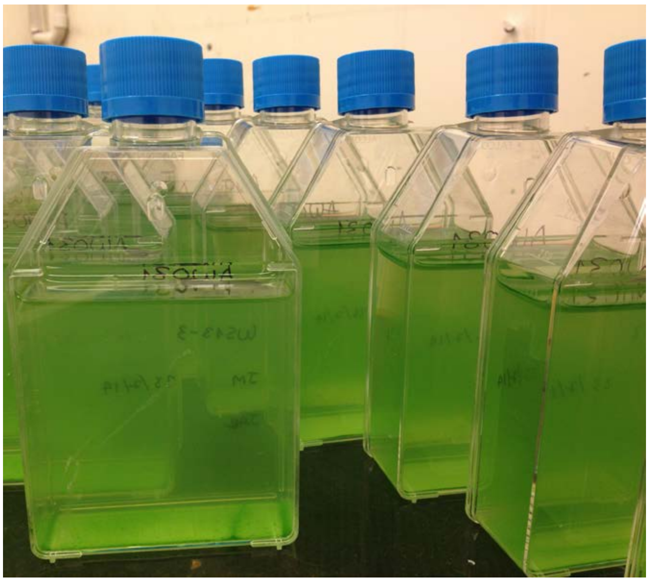
Our planet is facing climatic changes at an unprecedented rate and there is an urgent need to assess the potential evolutionary response of HAB species to selective pressures driven by a changing environment. As an example, it has been shown that high CO_2 concentration can induce rapid adaptive changes in the genotype composition of toxic cyanobacteria (Sandrini et al., 2016). However, it is important to assess both phenotypic plasticity and genetic adaptation to climate change with appropriate approaches to gain a clear picture (Merilä and Hendry 2014). Cutting-edge -omics technologies will be relevant for advances in these directions. In addition to strain- and species-specific adaptations, advances can be made through generalization of adaptive strategies based on trait-based approaches (i.e., exploring the potential common traits across HAB species) and would facilitate integration of the outcomes from this theme on Adaptive Strategies into new modeling approaches (see *Theme 9. Observation, Modeling, Prediction*). Furthermore, mixotrophy can constitute a relevant strategy in nutrient acquisition, growth, and production of HAB species, with consequences on the food webs (Mitra et al. 2016).

Specific objectives

- Define the characteristics of HAB species that determine their intrinsic potential for growth and persistence.
- Describe and quantify chemical and biological processes affecting species interactions.
- Identify the functional role of cell properties.
- Assess biological traits and intra-specific interactions (e.g., physiology, toxin production, allelochemical properties, life histories, mixotrophy) of HAB species and/or populations in different environments.
- Define and quantify physical-biological interactions at the scale of individual cells.
- Build on the existing knowledge of adaptive strategies of cyanoHABs and macrophyte blooms, including an improved understanding of strain variability and implications for responses to environmental conditions.
- Investigate physical and biological interactions at the scale of individual cells including, for example, grazing selection or avoidance, role of mucus in structuring the benthic environment, active migration and aggregation dynamics, and interactions with bacteria.
- Improve and/or develop observation and analysis systems at the microscale (e.g., micro-cinematography, rheology approaches, imaging-flow cytometry; see also *Theme 9. Observation, Modelling and Prediction*).
- Determine resting stage formation, deposition and emergence fluxes in the field, with proven methods, and identify the factors affecting the viability and abundance of these life history stages.
- Develop new tools to identify and quantify the various life stages (gametes, zygotes, etc.) and cell growth and mortality rates of HAB taxa in the field.
- Assess the adaptive response of HAB species to environmental change.

Example tasks

- Determine tolerance ranges and optima for growth and toxin production in response to a suite of environmental variables.
- Define the effect of fluctuating environmental regimes on growth processes (reproduction), life history events (excystment and encystment), vertical migration behaviour, nutritional modes (mixotrophy), etc.



Cultures of cyanobacteria testing the effect of environmental conditions on growth. Photo: Michele Burford, Griffith University, Australia.

- Assess the importance of toxin production (particulate and dissolved fractions, including toxic mucilage) and other cellular properties (cell surface lectin, etc.) in selective grazing.

Outcomes

- Establishment of HAB strains and species within an international network of reference culture collections.
- Identification of key adaptive strategies of particular HAB species.
- Ecologically based classification of different species according to their adaptations and characteristics.
- Quantification, parameterization, and prioritization of ecophysiological processes at the cellular level for incorporation into models.

THEME 3. Toxins

Overall objective: To characterize the genetic and environmental aspects of toxin production, to determine the mode of action of selected toxins, and to address several limitations in toxin analysis and field detection.

Rationale. Toxins are a cross-cutting subject and a common concern through all the GlobalHAB themes. In consideration of their importance, GlobalHAB includes a specific topic on toxins to facilitate addressing fundamental and applied objectives that would be beneficial to the scientific community, and to management and regulatory authorities. Research should concern some of the aspects already indicated in the *Biogeography and Biodiversity, Adaptive Strategies, Nutrients and Eutrophication* themes and the ones specified here. The research objectives are focused on known phycotoxins as well as "rare" or "emerging" toxins such as gonyodomines and gymnodomines since the causative organisms may be expanding (see related references in Berdalet et al. 2016).

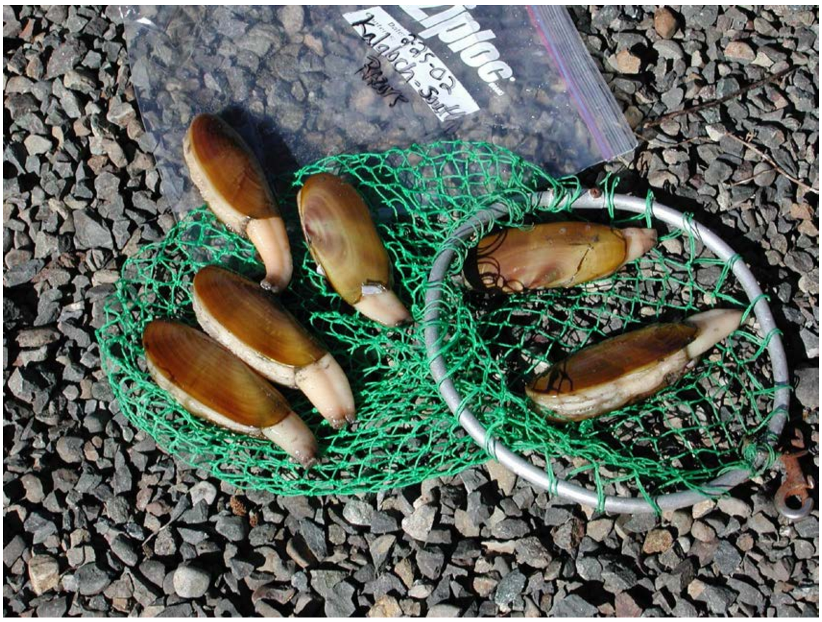
A first challenge is to obtain comprehensive understanding of toxin biosynthesis pathways and the genes involved. This knowledge is necessary to better predict the probable impact of changes in the global marine environment on the toxicity of HAB species. Knowledge of the genetic basis of toxin production could be revealed if there are suitable target genes for the discrimination of toxic species and their detection *in situ* (e.g., Murray et al. 2011; Farrell et al. 2016). Additionally, such knowledge will lead to better understanding of environmental controls of toxin production. Significant progress has been made in this regard for certain known and emerging phycotoxins, although knowledge gaps still exist (see e.g., Kellmann et al. 2008 for saxitoxin; Krüger et al. 2010 for ß-methylamino-L-alanine [BMAA]; Savela et al. 2014 for microcystin; Jeffery et al. 2004 for domoic acid; Kohli et al 2015 for polyketides), while no studies have addressed okadaic acid so far. The development of metabolomics from both intra- and extracellular compounds produced by HABs would bring great advances in that field (Pisapia et al. 2017). The role of different toxin analogues in species that produce multiple toxin families, and their biostability for overall toxicity, are also aspects that require further attention (e.g., cyanobacteria that produce combinations of paralytic shellfish toxins (PST) and hepatotoxins; Pearson et al. 2016).

A second challenge is identification of the mode of action of microalgae-produced toxins. After decades of research, it is now fairly well understood that many of these toxins are neurotoxic to mammals, operating through the blockage or activation of sodium or calcium channels (e.g., Durán-Riveroll et al. 2016). Many algal species are known to be cytotoxic, allelopathic (Legrand et al. 2003) or hemolytic; however, the nature and mode of actions in other organisms remain unclear. Along with identification of unknown emerging toxins, toxicity tests should be performed on different target cells, as some toxins may have different targets in nature.

In the case of fish-killing species, such as *Margalefidinium (=Cochlodinium) polykrikoides, Chattonella* spp., *Pseudochattonella* spp., *Heterosigma akashiwo,* and *Karlodinium australe* (e.g., Lim et al. 2014, Wagoner et al. 2014) the toxins produced could act through physical damage, hypoxia or anoxia, ichtyotoxicity, or synergistic effects through known or unknown direct biological effects (Black et al. 1991). The mechanism of fish-kill events associated with the colonial diatom species, *Leptocylindrus minimus* (Clément and Lembeye 1993), *Skeletonema costatum, and Thalassiosira spp.* (Kent et al. 1995) required further clarification. This information is crucial in the development of countermeasures by the aquaculture industry in dealing with massive fish-kill events due to different microalgal blooms. However, establishing general mitigation strategies is difficult because the impacts can vary among regions. For example, in 2002, *Prorocentrum minimum* blooms in the Philippines caused massive fish kills (Azanza et al. 2005), but similar blooms in Johor Strait, Malaysia did not cause any losses to local aquaculture (Usup et al. 2003).

A third need is the availability of sensitive, accurate, and cost-effective means of microalgal toxin analysis for the protection of public health and food security, and sustainability of aquaculture. Progress has been made in the detection and characterization of several microalgal toxins due to the advancement in analytical techniques, cell-based and functional assays. However, official methods are not yet available for some toxins, with ciguatoxin being the most notable.

Over the past two decades, live animal bioassays for microalgal toxins have gradually been replaced by analytical methods and *in vitro* assays, such as the neuroblastoma (N2A) assay, and sodium and calcium channel receptor-binding assay-RBA (e.g., PSTs, Oshima 1995, Turner et al. 2015; ciguatoxins, Yogi et al. 2011; karlotoxin, Wagoner et al. 2008). While several of these analytical and *in vitro* methods still require further development and validation in order to be accepted as official methods, they do offer the sensitivity, accuracy and high throughput needed for regulatory purposes. More studies are needed to get these methods accepted as official methods, and improve their robustness and user-friendliness. Similar efforts are required for the extraction of problematic toxins, such as CTX. A very important aspect of detecting and quantifying toxins is the availability of pure toxins, certified reference materials and secondary stan-



Razor clams harvested from the Washington State, U.S., Pacific coast beaches. These clams can retain the toxin, domoic acid, for many months. Photo credit: Vera Trainer, NOAA.

dards in the case of RBA. The need is most urgent for the two arguably most important toxin groups, namely PSP and CFP toxins.

A major problem faced by many toxin-testing laboratories, particularly in developing countries, is the inability to cope with the financial and staffing demands of testing large numbers of fish and shellfish samples in order to produce results in a timely manner. Under normal conditions most of those samples could be negative to toxin presence in seafood and do not require detailed testing. Thus, it would be highly desirable to make available reliable and affordable toxin screening kits that could be used on site or in laboratories with minimal facilities.

Specific objectives

- Determine the genetic basis of, and environmental influence on, toxin production and gene expression of toxin-producing algae.
- Establish the modes of action of the known and unknown emerging toxins and their activities (cytotoxic, allelopathic or hemolytic) on different aquatic organisms (fish, shellfish).
- Encourage production of certified standards and reference material for all major microalgal toxins.
- Promote and facilitate inter-laboratory validation studies that lead to acceptance of toxin analysis methods as official methods.
- Establish working linkages with different agencies in the development of CFP toxin detection and monitoring methods, including production of toxin reference material.

Fish kills caused by *Karlodinium australe* bloom. Photo: Po Teen Lim, University of Malaya, Malaysia.

Example tasks

- Revision of the current state of knowledge and gaps on the genetic basis of selected microalgae toxicity, and its modulation by environmental factors; identification of the technology and methods availability and needs for progress in this area including toxin gene detection in the field.
- Revision of the current knowledge and priority research areas on the mode of action of toxins of fish-killing HABs and genetic data relevant to HAB toxicity.
- Endorsement of research on new instrumental methods of toxin analysis and support of inter-laboratory trials and validation studies to prove their efficacy and enable their acceptance as accredited methods by international food safety authorities.
- GlobalHAB will encourage the organization of training and inter-laboratory validation of rapid methods of analysis using toxin test kits.

Outcomes

- An updated list with inclusion of toxin-producing and ichthyotoxic harmful algal species in Algae Base and IOC Taxonomic Reference list of Harmful Algae.
- A document on the genetic basis of and environmental influence on selected microalgae toxicity, summarizing priority research areas, best practice guidelines for research, and including a list of Task Team experts.
- Publication of the results of the validation studies on toxin kits or other analytical approaches in appropriate journals (e.g., *Journal of the Association of Official Analytical Chemists*).
- Information for policy makers and aquatic products industry on the impacts of HABs in marine fish and shellfish aquaculture and fisheries activities.

THEME 4. Nutrients and Eutrophication

Overall objective: To determine how the availability and utilisation of multiple forms of nutrients influence the occurrence of different types of HABs and their harmful effects.

Rationale. This Theme constituted Programme Element 4 in GEOHAB (GEOHAB 2001), which was implemented by the CRP on Eutrophic Systems (GEOHAB 2006). Important progress in research and management was achieved through the implementation of GEOHAB (e.g., see recent review by Glibert and Burford 2017), but the specific objectives identified at the beginning of that programme are still relevant and applicable in GlobalHAB. Coastal nutrient eutrophication is often considered to be primarily responsible for the increased number of high-biomass HAB occurrences in marine, brackish and freshwater habitats (Heisler et al. 2008, Glibert and Burford 2017 and references therein). Increases in HABs associated with eutrophication or nutrient loading have been widely reported (e.g., Anderson et al. 2002, Heisler et al. 2008). Although a simple link can be established because nutrient inputs yield changes in algal biomass (Ryther and Dunstan 1971), the effect of nutrients on specific harmful species is still poorly understood. Variations in nutrient supply can impact biodiversity and the success of HAB species depends on the intersection of the physiological adaptations of the harmful algal population, environmental conditions, and interactions with co-occurring organisms, as summarized by Glibert and Burford (2017) (and references therein). However, in some cases, HABs are not directly driven by anthropogenic nutrients (Gowen et al. 2012). Nutrient loading is most frequently associated with high-biomass blooms, rather than to low-biomass biotoxin-producing blooms. However, even high-biomass HABs can occur in areas with low anthropogenic nutrient additions (Davidson et al. 2014). For example, toxic HABs of genera such as *Alexandrium* can occur in regions that do not experience significant anthropogenic nutrient additions, and the most toxic HABs occur in the most pristine areas in the world, such as Patagonia and Alaska.

Fundamental questions remain unresolved in relation to understanding how the fluxes of both inorganic and organic nutrients from anthropogenic and natural sources promote high- and low-biomass HABs, and how nutrient fluxes are connected to the drivers of climate change and other environmental stressors. Specific studies are required to understand the role of nutrients in the promotion of particular species, and how changes in nutrient dynamics are linked to the onset, maintenance and decay (potentially leading to hypoxia and/anoxia, Anderson et al. 2002) of HABs, and the modulation of toxin production. These questions are fundamental for better understanding of the response of planktonic (e.g., *Pseudo-nitzschia, Alexandrium*) and benthic (e.g. *Gambierdiscus, Ostreopsis*) HAB taxa to nutrient availability. In the case of BHABs, the limited available data do not allow drawing a clear causal relationship between inorganic nutrient supply and benthic blooms (GEOHAB 2012). The nutrients required to reach bloom concentrations are likely acquired directly from nutrient-rich sediments, or directly from the macroalgal surfaces (Litaker et al. 2010 and references therein). Furthermore, it is hypothesized (but not tested) that nutrient inputs, which favor the growth of macroalgae (Lapointe et al. 2010), could also promote blooms. Finally, the role of nutrient availability on toxicity requires detailed studies (Chinain et al. 1999; Vanucci et al. 2012). Understanding the link between the supply and availability of different forms of nutrients with the occurrence of HABs and their harmful effects, is fundamental to design management strategies.

Specific objectives

- Determine the physiological responses of HAB and non-HAB species to specific nutrient inputs.
- Determine the effects of varying nutrient inputs on the harmful properties of HABs.
- Determine the role of nutrient cycling processes in HAB development.
- Determine the composition and relative importance of different nutrient inputs associated with human activities and natural processes on the occurrences of BHAB events.
- Clarify the role of nutrient availability on out-

breaks of harmful benthic organisms and macroalgal (e.g., *Sargassum, Ulva*) blooms.
- Investigate the links of nutrients (in combination with other environmental drivers) to freshwater HABs and cyanobacterial HABs.
- Investigate the links of aquaculture-related nutrients and HABs.
- Investigate the variability of different toxins as a function of nutrient availability.
- Investigate the links between nutrients, climate change and HABs.
- Investigate the link of eutrophication-induced HABs and deoxygenation processes in marine coastal and oceanic ecosystems, and the potential future trends related to the climate change as well.

Example tasks

Many activities under this theme will be integrated with those under other themes, in particular, *Benthic HABs, Aquaculture and HABs, Freshwater HABs and CyanoHABs, Toxins, Climate Change and HABs*. Other actions specific to this theme include the following:

- Development of a coordinated database on the temporal and spatial extent of HAB occurrences associated with nutrient loading in different coastal and continental areas.
- Experiments on the nutrient uptake and growth kinetics and toxin production of selected harmful species.
- GlobalHAB will collaborate with the recently established Global Ocean Oxygen Network (GO2NE) working group of IOC-UNESCO (*www.unesco.org/new/en/natural-sciences/ioc-oceans/sections-and-programmes/ocean-sciences/global-ocean-oxygen-network/*). The working group was formed to address concerns relating to declining oxygen concentrations in the ocean. The collaboration between GlobalHAB and GO2NE will be focused on investigation of the likely global increase in episodic oxygen depletion associated with increasing high-biomass HABs in the coastal environment.

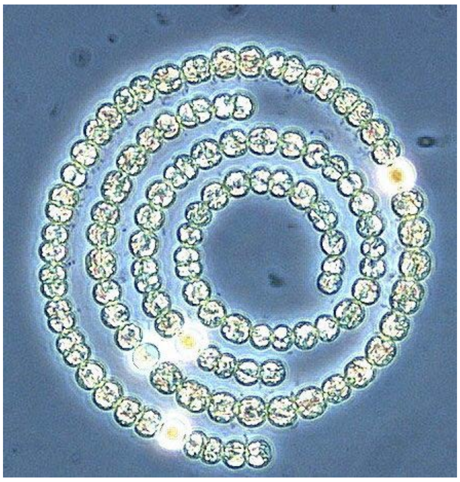
Outcomes

- Improved scientific understanding of the modulation of HAB events and toxin production by inorganic and organic nutrients and their ratios.
- Scientific advances on the understanding of the role of HABs on episodic oxygen depletion in coastal zones.
- Information for policy makers:
  - Guidance for development of policies related to eutrophication in coastal and inland areas, and HABs.
  - Improved basis for establishing site selection criteria for aquaculture operations.
  - Quantitative baseline information for integrated coastal management.

Alexandrium minutum bloom in a tropical coastal zone. Photo: Po Teen Lim, University of Malaya, Malaysia.

THEME 5. Freshwater HABs and Cyanobacterial HABs (CyanoHABs) from Marine to Freshwater Systems

Overall objective: To develop a global perspective in advancing the science and management of freshwater HABs, and cyanobacterial HABs in marine, brackish and freshwater habitats.



Trichome of the freshwater cyanobacterium *Dolicospermum*. Photo: Michele Burford, Griffith University, Australia.

Rationale. Freshwater HABs include a range of cyanobacterial species (cyanoHABs) and some eukaryote groups. Historically, much of the research has focussed 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*). In brackish waters, cyanobacterial HABs are also a major problem in some areas of the world, for example, *Nodularia* in the Baltic Sea (Kahru and Elmgren 2014). Other toxic filamentous cyanobacteria, such as *Lyngbya* and *Moorea,* also bloom in certain marine (especially tropical) areas. These species produce a wide range of toxins, including microcystins, cylindrospermopsins, anatoxins, nodularins, saxitoxins, aplysiatoxins and lyngbyatoxins. Information on harmful events caused by these species and their ecophysiology can be found in the revision by O'Neil et al. (2012). This study also analyzes the potential effect of eutrophication and climate change on the increased magnitude and frequency of cyanoHAB events.

Freshwater and cyanoHABs have major economic, social and environmental impacts. The cost of eutrophication, including cyanobacteria blooms, on water quality, recreation use, fishing, and property values in U.S. freshwaters is estimated at approximately US$2.2 billion annually (Dodds et al. 2008). Bloom events in 2011 and 2014 in Lake Erie, USA, had an estimated average economic loss (measured as property values, tourism, and recreation) of US$70 million (Hamilton et al. 2014). Worldwide, water authorities also spend millions of dollars annually testing water supplies and mitigating the effects of cyanoHABs. There are already several international groups focused on cyanobacterial and freshwater algal research. GlobalHAB aims to play a role by bridging the gaps between freshwater and marine HAB researchers to share knowledge, techniques and approaches. Additionally, there is the need to communicate more effectively with policy makers internationally about the current state of knowledge and potential approaches to managing, mitigating and predicting harmful cyanobacterial outbreaks in freshwater, brackish and marine habitats.

Specific objectives

- Promote the comparative approach for studying cyanoHABs in contrasting environments.
- Improve communication between scientists and managers working on freshwater HABs in general and cyanoHABs in all relevant habitats via cross-fertilization of ideas and technologies.
- Identify emerging issues for cyanoHABs across freshwater, brackish and marine habitats, both benthic and pelagic.
- Promote the development of faster, cheaper kits for measuring toxins.
- Synthesize and share existing information on mitigation strategies on freshwater HABs and cyanoHABs with environmental and resource managers, especially in areas where human populations may be most dramatically affected by contaminated drinking water.

Example tasks

- Convene an open science meeting on cross-cutting issues and challenges for cyanoHABs in marine, freshwater and brackish systems. This would have a focus on emerging species/species changes and toxins/secondary metabolites, mitigation, management and modeling strategies, technologies and approaches from the research community studying non-harmful cyanobacteria. This meeting could be undertaken in collaboration with the International Committee on Toxic Cyanobacteria (ICTC) or the International Society for the Study of Harmful Algae (ISSHA), or alternatively could be a stand-alone meeting. The outcomes from this activity would be identification of pressing issues in each field with a view to future workshops, and novel insights that advance fields, which might lead to papers or a special issue of a journal.
- Share technologies and information with other relevant groups. For example, exploring mechanisms to link freshwater HAB questions with groups such as the Global Lake Environmental Observation Network (GLEON). Explore the potential for cyanoHAB sessions at GLEON meetings. Examine the potential use of technologies developed for marine systems in lakes and reservoirs and vice versa.
- Further targeted workshops or sessions at conferences as identified in the OSM on cyanoHABs. This may include a workshop on benthic freshwater and marine HABs, for example, on emerging species and toxins and methodological challenges, and a workshop on emerging toxins (e.g., BMAA) and cyanobacteria.
- Undertake training workshops on taxonomy and toxin analysis, monitoring and mitigation procedures in developing countries. This requires liaison with relevant agencies such as WHO and other relevant foreign aid organisations.
- Develop global interactive map of occurrence of key cyanoHAB species.
- Develop a user-friendly electronic manual on mitigation strategies for freshwater cyanoHABs across the world.

Outcomes

- Information on the trends of freshwater HABs and cyanoHABS driven by eutrophication and climate change.
- Information for policy makers:
  - List of priorities for understanding and managing cyanoHABs.
  - A manual for freshwater HABs and cyanoHAB mitigation strategies.

Bloom of the toxic cyanobacterium *Microcystis* in a drinking water reservoir in southeast Queensland. Photo: Michele Burford, Griffith University, Australia.

THEME 6. Benthic HABs (BHABs)

Overall objective: 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.

Rationale. The CRP on "HABs in Benthic Systems" was the last CRP launched by GEOHAB, in 2010 (GEOHAB 2012), created because of more frequent events and geographic expansion of benthic microalgae (BHABs). Tropical regions have been traditionally threatened by CFP associated with blooms of the toxic benthic dinoflagellate *Gambierdiscus*. It is assumed that ciguatoxins (CTX) produced by *Gambierdiscus* are bioaccumulated in reef fishes. CTXs are responsible for the most common algal toxin-related illnesses, globally affecting the greatest number of victims and often with significant long-term health effects (see for instance the recent review by Friedman et al. 2017). Recently, *Gambierdiscus* has also been documented in new areas, in subtropical and temperate latitudes (e.g., Fraga et al. 2011; Nishimura et al. 2014). Blooms of another benthic and toxic dinoflagellate, *Ostreopsis*, have become more frequent and intense, especially in temperate waters (e.g., Rhodes 2011; Selina et al. 2014). *Ostreopsis* produces palytoxins (PLTX) and analogues (ostreocins and ovatoxins) that have been related to fatal seafood intoxications in the tropics (Randall 2005). In temperate areas, while such impacts have not been reported yet, some outbreaks have been associated with massive benthic faunal damage and respiratory irritation in humans exposed to aerosols in the area affected by *Ostreopsis* proliferation (Vila et al. 2016 and references therein). Global warming can be a main factor of the biogeographic extension of benthic HAB species (e.g., Tester et al. 2010), but other anthropogenic disturbances may also be involved. Examples include coral reef destruction (Lehane and Lewis 2000) and increasing plastic pollution, which may constitute an efficient dispersal mechanism for benthic species (e.g., Masó et al. 2003, Zettler et al. 2013).

The objectives identified in the BHAB CRP (GEOHAB 2012) were intensively addressed by the international community and significant progress was achieved in a relatively short time, as reviewed in Berdalet et al. (2017a) and Berdalet and Tester (in press). Still, the objectives and questions formulated in GEOHAB (2012) are valid, constitute a main research focus in the affected areas and will benefit from international cooperation and coordination. For these reasons, the BHAB CRP will be continued in GlobalHAB, as a GlobalHAB theme.

Furthermore, recognition of the global importance and impact of CFP is reflected by the adoption by the IOC, in coordination with the World Health Organization (WHO), the Food and Agriculture Organization (FAO) and the International Atomic Energy Agency (IAEA) of a "Global Ciguatera Strategy" in 2015 and by the initiatives launched by other agencies, including the U.S. NOAA and specific laboratories. These initiatives are aimed at capacity building (such as the training events held in Tahiti, Dominican Republic and Nantes in 2015 and 2016), development of official toxin detection and quantitation methods (e.g., development of the fluorescent RBA method for CTX detection, Hardison et al. 2016), and documenting the actual human and economic impacts of CFP. GlobalHAB will work in coordination with the mentioned agencies to implement the "Global Ciguatera Strategy".

The benthic harmful dinoflagellate, *Ostreopsis* cf. *ovata*. Left: Light micrograph of a natural sample from the Gulf of Naples (Mediterranean Sea). Right: Scanning Electron Micrograph of a culture isolated from that area. Photo: Laura Escalera, Stazione Zoologica Anton Dohrn, Naples (Italy).

Although *Gambierdiscus* and *Ostreopsis* are the most important BHAB genera and most research has been focused on these taxa, GEOHAB (2012) also noted the need to clarify the toxic potential of other organisms, including certain dinoflagellates (*Coolia* spp., *Prorocentrum lima*), diatoms (*Nitzschia navis-varingica*, *Amphora coffeaformis*) and cyanobacteria (*Hydrocoleum glutinosum*, *Phormidium laysanense*, *Spirulina weissi*, *Oscillatoria* cf. *bonnemaisonii*, *Anabaena* sp., and *Trichodesmium erythraeum*). Recent observations from French Polynesia have also highlighted similar potential health risks linked to consumption of the gastropod *Tectus niloticus* (Gatti et al., 2015). A new ecotoxicological phenomenon, ciguatera shellfish poisoning (CSP) to describe CTXs in shellfish has been proposed, and it is recommended that cyanobacteria should be monitored concurrently with other toxic microalgae in order to manage tropical seafood poisonings effectively.

Specific objectives

- Improve knowledge of the ecology, physiology, toxicity and toxin transfer mechanisms through marine food webs, to determine fundamental parameters for modeling BHAB dynamics.
- Standardize sampling methods for organisms and toxins.
- Develop official methods for toxin detection and quantification, and fast screening in fish and other seafood.
- Determine the impacts of BHABs on marine organisms and ecosystems.
- Investigate the impacts of climate change and anthropogenically driven changes on BHAB dynamics.
- Determine the epidemiology of CFP in cooperation with health agencies and monitoring agencies (see also *Theme 10. Health*).
- Estimate the global and local socio-economic costs of CFP (see also *Theme 11. Economy*).
- Facilitate data sharing among research groups for modeling studies, to ascertain the trends on BHAB events, to design management and prevention strategies, etc.
- Clarify the uncertainties regarding the toxicity of other benthic genera, especially cyanobacteria.
- Coordinate with the IPHAB Task Team to implement the multi-agency IOC-IAEA-FAO- WHO "Global Ciguatera Strategy" (*hab.ioc-unesco.org/*).

In Tuamotu atolls (French Polynesia), coral extraction represents one of the major human disturbances responsible for coral reef destruction, thus leading to enhanced ciguatera risk. © Institut Louis Malardé (Tahiti, French Polynesia).

Example tasks

- Inter-comparison and teaching workshop on the methods to detect CTX activity (e.g., fluorescent RBA, radioactive methods, etc.).
- A modeling workshop centered on BHAB dynamics.
- An Open Science Meeting on BHABs, as a continuation of the 1st OSM on BHABs, organized by GEOHAB in June 2010, in Honolulu.
- A 2nd International Conference on *Ostreopsis* Development (ICOD-2), as a follow-on to the 1st conference, held in Villefranche in 2011, with a special issue of a journal as a deliverable.
- Specific sessions at ICHA meetings, for example, in Nantes (France), 2018, and in Los Cabos (Mexico), 2020.
- Coordination of GlobalHAB with IOC regional groups (FANSA, WESTPAC) in areas affected or potentially affected by CFP.
- Engage appropriate health and fishery professionals through existing channels and regional meetings of FAO and WHO to better understand needs and abilities to implement tools related to management of CFP, as identified also in *Theme 10. Health*.

Outcomes

- Develop cost-effective methods to detect CTX and toxic *Gambierdiscus* species.
- Determine the potential risk of PLTX-like toxins in seafood-borne poisoning in the Mediterranean Sea.
- Clarify the natural and anthropogenic factors favoring BHABs.
- Information for policy makers:
  - Define alert conditions for BHAB events to prevent exposure to CTX (*Gambierdiscus*) or irritative compounds-containing aerosols (*Ostreopsis*)
  - Guidelines for habitat preservation in order to prevent BHAB outbreaks.
  - Coordination to implement the multiagency IOC-IAEA-FAO-WHO "Global Ciguatera Strategy".

THEME 7. HABs and Aquaculture

Overall objective: To determine the link between marine aquaculture and HAB occurrence in different regions and to find efficient methods to protect farmed seafood products from HAB impacts.

Rationale. Fin-fish, shellfish, crustaceans and macroalgae aquaculture has many benefits, including the production of nutritious high-protein food, reducing the pressure on natural resources and supporting sustainable economic development and employment. In some countries, marine aquaculture is an important contributor to the national economy and future projections suggest there will be large increases in global production in coming decades.

Nevertheless, for a variety of reasons, aquaculture operations (particularly sea-cage fin-fish rearing) in coastal waters are frequently controversial. Because the improved awareness and identification of HAB events has occurred alongside growth in aquaculture, a plausible hypothesis is that these developments have increased the frequency and intensity of HABs. In some situations the transfer of aquaculture equipment and cultured organisms may facilitate HAB species dissemination (Hegaret et al. 2008). However, with respect to fin-fish farming, a more common concern is that the additive effect of numerous closely sited farms discharging large nutrient loads into coastal waters may cause eutrophication, or shifts in macro-nutrient ratios, that enhance the potential for the generation of high-biomass or toxic species-dominated HABs (e.g., Buschmann et al. 2009). Although links between HABs and coastal eutrophication (Heisler et al. 2008) exist in some situations, the scientific literature on the impact of fish farming provides a much more equivocal point of view. For example most empirical evidence (e.g., Gowen et al. 2012; Price et al. 2015) suggests that in many situations it is difficult to directly attribute a significant response by phytoplankton in general, let alone harmful species, to water nutrient enrichment due to discharges from sea cage operations.

The perception that fin-fish aquaculture (and perhaps shellfish and macro-algae aquaculture) leads to increased problems with HABs is an important planning question, on which it is difficult to confidently provide an expert opinion in the absence of long-term time-series data on biological and physical parameters and appropriate modelling expertise to simulate potential impacts. This uncertainty may permit unsustainable developments or constrain otherwise environmentally acceptable enterprises. An increased scientific focus on this topic is needed to inform industry, ensure that coastal resource managers have the best available information, and to provide new protocols and technologies for better evaluating the impact of aquaculture on the water column.

Biophysical modelling is useful to simulate the spatial and temporal response of harmful phytoplankton (Anderson et al. 2005) to environmental forcing factors, especially when combined with satellite remote sensing data (Anderson et al. 2016; Davidson et al. 2016; Ruiz-Villarreal et al. 2016). These approaches have been successful in providing real-time predictions that have been incorporated into national forecasting systems for public health and aquaculture protection. They have been most effective when focused on large-scale events in extensive offshore-coastal ecosystems (e.g., Gulf of Maine, Coastal California, the Western European seaboard), but in many aquaculture contexts HABs are most problematic in nearshore semi-enclosed waters caused by resident toxic algae populations. Improved bloom simulation models that incorporate complex growth and life cycle behaviours and bloom termination factors (e.g., nutrient limitation, zooplankton grazing and disease) in these situations are needed.

Phycotoxin contamination and mass mortalities of cultured animals caused by HABs can have devastating impacts on aquaculture operations. Although conventional monitoring methods successfully protect bivalve aquaculture from harvesting toxic shellfish, the costs of routine sample collection and analysis are high and improved surveillance and prediction methods are required. Blooms of a variety of micro-algae (raphidophytes, dictyophytes, haptophytes, dinophytes) continue to cause substantial losses to sea-cage fish-rearing operations (Clément et al. 2016) and early warning methods have yet to be perfected. Importantly, considerable uncertainty remains about the mechanisms of action of most fish-killing algae, which is a major impediment to the development of antidotes and mitigation measures. Also within this context, new toxic compounds produced by micro-algae are being discovered that may have hitherto unrecognised effects on cultured marine species (e.g., Borcier et al. 2017).

Autonomous *in situ* molecular and imaging flow

Oyster racks, New Zealand. Photo: Cawthron Institute.

Mussel harvester, Marlborough Sounds, New Zealand. Photo: Cawthron Institute.

cytometry methods have proved capable of real-time sensing of impending blooms (e.g., Campbell et al. 2010), but 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 development, 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 in real-world aquaculture situations.

Specific objectives

- Encourage research on the potential effects of nutrients, shifting nutrient ratios, and dissolved and particulate organic matter from aquaculture in promoting HABs.
- Comprehensively review evidence for link(s) between aquaculture and the promotion of HABs in different regions.
- Foster international collaboration on the development and field trial of new technologies for aquaculture, for the monitoring, forecasting and mitigation of HABs.

Example tasks

- Facilitate collaboration between local, regional and international organizations (e.g., PICES, ICES) and relevant end users (local environmental regulators and the aquaculture industry) to jointly investigate the links between HABs and aquaculture.
- An international workshop on the mechanism of toxicity of fish-killing HABs and methods for mitigating their effects in coordination with the ICES Working Group on fish-killing algae in the North Atlantic and the IOC Task Team on fish-killing algae.
- Through project endorsement assist researchers with international technology transfer, validation and field trials of innovative monitoring methods (e.g., autonomous *in situ* technologies and new mass spectrometry analytical methods).

Outcomes

- A special journal issue (or a stand-alone volume) including a series of scientific papers examining the evidence for links between aquaculture and HABs in regions (e.g., Chile, Norway, Scotland, Ireland, U.S./Canada, Japan, Korea, China, Vietnam, Thailand, Australia, New Zealand, etc.) with significant coastal caged-fish farming industries.
- A better understanding of the potential and real impacts of HABs will provide tools for improved management of aquaculture resources and practices to prevent negative effects.
- Information for policy makers:
  - Guidelines for the optimum location and nutrient loading rates for aquaculture to minimize the risk of HABs.
  - An evidence-based perspective and resource for authorities responsible for granting access to the utilization of coastal water space.
  - Independent scientific advice to seafood regulators and industry on the efficacy of alternative monitoring and mitigation methods for the maintenance of food security and international market access for aquaculture products.

THEME 8. Comparative Approach

Overall objective: Determine the extent to which HAB species, their population dynamics, and community interactions respond similarly within comparable ecosystem types.

Rationale. The GEOHAB programme adopted the comparative approach (Anderson et al. 2005) from the cellular to the ecosystem level. 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. Important physical processes occur over a wide range of scales. Similarly, relevant biological processes occur at subcellular and cellular levels, as well as at the population, community, and ecosystem levels including, for example, symbiosis, parasitism, allelopathy, and viral infections (e.g., Chambouvet et al. 2008; Ianora et al. 2011). Because HABs are natural phenomena, application of the comparative approach can also provide further insights in the understanding of plankton ecosystem dynamics. Improved generalizations about the causes and consequences of HABs would be particularly useful in management and mitigation of their effects. GlobalHAB will continue to use the comparative approach for studies within and between different aquatic systems (coastal, brackish, open oceanic and freshwater environments).

Case studies reported by GEOHAB (e.g., GEOHAB 2005, GEOHAB 2010) and elsewhere (e.g., Pitcher et al. 2017) illustrate some of the advances achieved by the application of the comparative approach. Ongoing and future research on HABs can progress by applying this method with the suitable experimental design to carry out comparisons in a scientific way (Underwood 1992). Some examples are briefly presented here, but not described in detail. The comparative approach can contribute to understand similarities and differences concerning CFP incidence and *Gambierdiscus* dynamics in the main affected areas, the Pacific Ocean and the Caribbean Sea. Comparing the dynamics of the main benthic HAB taxa, *Ostreopsis* and *Gambierdiscus*, can also shed light on poorly known ecological aspects related to the benthic life strategies and facilitate the design of effective management tools in each case. This information would also support the development of trait-based approaches for both comparative systems and modeling by identifying commonalities across the two genera. An interesting comparison could also be addressed on the mechanisms of human intoxication via sea spray associated with the benthic *Ostreopsis* (Vila et al. 2016) versus the planktonic *Karenia* blooms (Pierce et al. 2005).

Another example of blooms suitable for the comparative approach are the blooms of *Pseudochattonella* spp. (Dictyochophyceae) that have caused fish mortalities in northern Europe, as well as in Japan (e.g., Okaichi 1997) and in South America. In Scandinavia, blooms started in 1998 (Granéli et al. 1993; Dahl et al. 2005) and the organisms are likely to have been introduced to the area. Initially, blooms occurred in early summer, but since 2001 blooms have happened immediately after or together with the spring diatom bloom, usually in March. In 2016, blooms of *Pseudochattonella* caused mortalities of 20% of the total Chilean salmon production in a few days (Clément et al. 2016) and subsequent exceptional blooms of *Alexandrium catenella* devastated shellfish production (Hernández et al. 2016). By comparing the blooms in different geographic areas, an increased understanding of why blooms occur and their effects will be achieved.

Tools for managing blooms of biotoxin-producing dinoflagellates in shellfish production areas can also be obtained by application of the comparative approach. For instance, *Dinophysis* spp. that produces okadaic acid and other diarrhetic toxins are found in areas with contrasting environmental conditions such as the west coast of the Iberian Peninsula, Scandinavia and the east coast of North America. During the past decade, understanding of *Dinophysis* ecology has increased significantly through laboratory work (e.g., Reguera et al. 2012). Applying this new knowledge in field studies in different environments is likely to result in a better understanding of bloom development and how toxin content per cell varies. Similarly, *Alexandrium*, producer of paralytic toxins, is another key genus suitable for the comparative approach. It has a worldwide distribution and is found in very different environments and climates, including the Mediterranean Sea region, and Chilean and Scandinavian fjords (Anderson et al. 2012). Furthermore, in the case of *Alexandrium* and *Dinophysis*, comparisons at the level of single species could clarify taxonomy and physiology questions such as the ones indicated in the *Biogeography and Biodiversity* and *Adaptive Strategies* themes, respectively.

Finally, toxin-producing filamentous cyanobacteria such as *Nodularia* occur in contrasting areas such as the Baltic Sea (Kahru and Elmgren 2014), river mouths in Australia (Huber 1984) and in lakes in Brazil (Karlson et al. 2012), where nutrient conditions and the capability of nitrogen fixation are key forcing factors. By studying conditions leading to blooms at different latitude, salinities, etc., an increased understanding of bloom formation and effects of climate change on cyanobacteria blooms may be achieved.

Specific objectives

- Quantify the response of HAB species to environmental factors in natural ecosystems.
- Identify and quantify the effects of physical processes on accumulation and transport of harmful algae.
- Identify and quantify the community interactions influencing HAB dynamics.
- Define functional groups in communities containing HAB species.

Example tasks

- Continue the work of GEOHAB towards more detailed, global comparison of phytoplankton time series.
- Extend the work of the SCOR WG 137 (*wg137.net/time-series/time-series-map*) that, over the past 5 years, has compiled long-term (decadal) time-series datasets obtained from geographically and climatically diverse regions around the globe and analysed these data sets. Following WG 137, the recently formed IOC TrendsPO Working Group aims to more fully recognize and understand commonalities and contrasts with regard to ecological responses to natural, man-made changes and climate change captured by our global network of coastal phytoplankton time series. A meta-analysis of the various separate data sets is suitable. See also *Theme 1. Biodiversity and Biogeography.*

Outcomes

- Identification of common physiological and behavioural characteristics of HAB species in given ecosystem types.
- Quantitative descriptions of the effects of physical forcing on bloom dynamics in different ecosystems.
- Information for policy makers:
  - Bases for developing management and mitigation strategies tailored to the characteristics of particular organisms in different areas.

Surface accumulations of cyanobacteria in the Southern Baltic Sea in 2013.
Photo: Bengt Karlson, Swedish Meteorological and Hydrological Institute, Sweden.

THEME 9. Observation, Modeling, and Prediction

Overall objective: To improve the detection and prediction of HABs by developing capabilities in observation and modeling.

Rationale. GEOHAB highlighted the need for specialized and highly resolved measurements to observe and describe the biological, chemical, and physical interactions that determine the population dynamics of individual species in natural communities. Furthermore, it emphasized the central role of long-term coordinated observation and effective monitoring systems to develop and evaluate early warning and prediction systems, 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).

Closely related to observation is modelling, also identified as an essential tool for HAB prediction and management. Specific tasks were conducted under GEOHAB, a major one being the Modelling Workshop held in Galway, Ireland (GEOHAB 2011). Improvements needed in modelling HABs include better parameterization of the biological, physical and chemical processes of interest, 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), and sustaining long time series of observing systems that measure environmental forcing in relation to HAB and plankton community response.

There are several different types of HAB models. The ones that have the most predictive power for short-term HAB forecasts are often site- and organism-specific. These models do not always give general biological insight and are the hardest to scale up to be used for producing scenarios for novel combinations of environmental conditions (e.g., under future climate or other anthropogenic change). However, modeling efforts focused on short-term predictive power can be complemented with analysis of positive ecological feedbacks (e.g., Sunda and Shertzer 2014) or trait-based approaches that model phytoplankton community strategies instead of species. These approaches have the potential to generalize across many HAB species or populations. In any effort at generalization and upscaling, international coordination is fundamental for advancement.

Specific objectives

- Develop capabilities to observe HAB organisms in situ, their properties (e.g., life stages, nutritional condition), and the processes that influence them.
- Develop capabilities in real-time observation (with capacity to resolve fine-scale processes, such as thin layers) and prediction of HABs.
- Develop and evaluate systems for long-term monitoring of HAB species.
- Establish and endorse the continuation of long-term HAB sentinel sites and encourage their inclusion in climate change observing systems where the data are made freely available in international databases. This objective is especially linked to the GlobalHAB *Theme 12. Climate Change* and aligns with international programmes and initiatives such as GOOS (Global Ocean Observing System) and the ICES Working Group on Harmful Algal Bloom Dynamics (WGHABD).
- Promote the use of new technologies (e.g., *in situ* imaging flow cytometry, molecular methods, mooring and profiling instruments and automated underwater vehicles, AUVs) with established methodologies in monitoring programmes. This objective reinforces the themes on "*Aquaculture*" and "*Climate Change*" (Themes 7 and 12 respectively).
- Encourage multi-method approaches to study HAB dynamics where in situ observations are combined with remote sensing and modeling. To accomplish this, it is important to foster multi- and cross-disciplinary collaborations centered on specific HAB prediction problems.
- Develop models to describe and quantify the biological, chemical, and physical processes related to HABs.

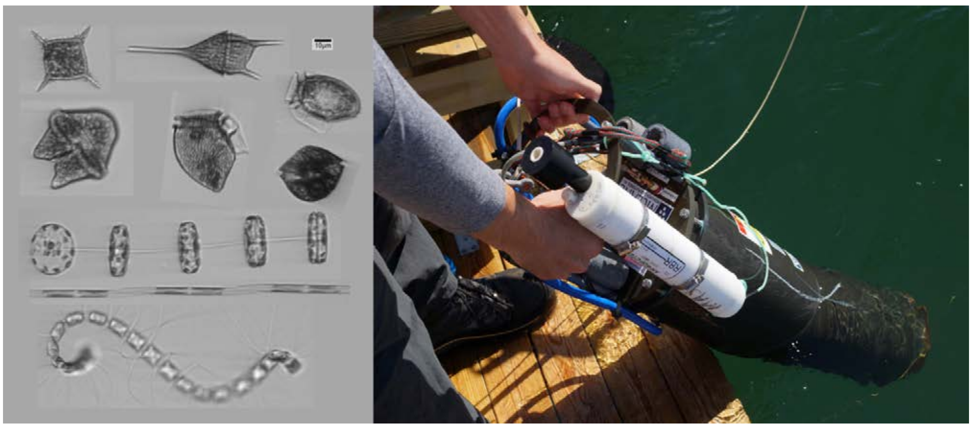
- Develop capabilities for describing and predicting HABs with empirical models.
- Encourage long-term investment in biological modeling approaches with the potential to generalize across many HAB species or populations (e.g., trait-based approaches), as a complement to modeling efforts focused on short-term predictive power.
- Improve model formulations linking land-use models with regional ocean models, and that incorporate dynamic physiological behavior.
- Develop modelling capabilities for projecting the response of HAB species to climate change (see *Theme 12. Climate Change*).

Example tasks

- Organize special sessions on observation tools at relevant scientific conferences, such as ICHA, ASLO, phycological meetings, Ocean Optics, Trait-based Approaches to Ocean Life workshop series, etc.
- Contribute towards activities planned by ICES-IOC WGHABD in the 2018-2020 period, such as reviewing progress in development and routine application of molecular genetic technologies for taxonomic identification, phylogenetic reconstruction, biodiversity, toxin detection and population dynamic studies of HABs.
- Organize a workshop on imaging methods (imaging flow cytometry, in situ video, etc.), bio-optical methods and remote sensing, including satellites and airborne (aircraft and drones) to detect HABs.
- Encourage and facilitate international collaboration to compile and share data on HAB species and events in OBIS (*www.iobis.org*) and its Harmful Algae Event Database component HAEDAT (*haedat.iode.org*).
- Cooperate and interact with GOOS sections including the "Biology and Ecosystem Panel", and regional level regional ocean observing systems (ROOSes), such as EuroGOOS (*www.eurogoos.org*) in Europe that includes BOOS (Baltic Operational Oceanographic System, *www.boos.org)*, NOOS (North West European Shelf Operational Oceanographic System, *noos.eurogoos.eu*), IBI-ROOS (Ireland-Biscay-Iberia Regional Operational Oceanographic System, *www.ibi-roos.eu*), MONGOOS (Mediterranean Operational Network for the Global Ocean Observing System, *www.mongoos.eu*), Black Sea GOOS, and Arctic ROOS.
- Interact with the EU Marine Strategy Framework Directive (MSFD), where HABs are included in the Eutrophication section.

Outcomes

- Improved capabilities in early warning and real-time observation and prediction of HABs.
- Complete long time series on HABs and related environmental parameters that will allow determining trends on HAB species and events (HAEDAT, GHSR) in different regions.
- Review advances in novel technologies for HAB research and monitoring applications including, for example, toxic gene detection in the field.
- Information for policy makers: scientifically sound information on HAB trends, especially in the context of climate change, to develop policies aimed at the protection and management of coastal resources and human health.



Left: Images of phytoplankton from an imaging flow cytometer (Imaging FlowCytobot) deployed in situ near a mussel farm on the Swedish west coast in 2016. Right: The Imaging Flow Cytobot. The white instrument is a CTD. Photos: Michael Brosnahan (WHOI, US) and Bengt Karlson (Swedish Meteorological and Hydrological Institute, Sweden).

THEME 10. HABs and Human and Animal Health

OVERALL OBJECTIVE: To increase collaborations among HAB scientists with medical, veterinary, public health, and social science expertise to help understand and minimize the risk of HAB impacts to human and animal health.

Rationale. The main reason to investigate HAB dynamics, which led to the establishment of the international GEOHAB programme, was to help understand and mitigate the effects on human and animal health and wellbeing. The specific link between phycotoxins and human and animal health aspects has also been included in several ICHA meetings, such as in the 2016 conference in Brazil (*www.icha2016.com/program/*). In recent decades, however, progress has been made towards the confluence of HAB and ocean research within the medical/public health and social sciences.

This *Health* theme in GlobalHAB is particularly timely, as it 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. As an example, activities in Oceans and Human Health were launched in the United States in early 2000s, sponsored by NSF, NIEHS, and NOAA, addressing the known and potential links between human health and HABs (as well as microbial and chemical pollution, and natural products from the ocean). In June 2016, the U.S. Centers for Disease Control and Prevention 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 (*www.cdc.gov/habs/ohhabs.html*). OHHABS is a module within the National Outbreak Reporting System (NORS) specifically designed to collect information on cases of human and animal 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/*; Fleming et al. 2014), 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 and close communication and collaboration on efficient illness prevention among HAB scientists, public health researchers, and local, state and tribal health departments at academic, community outreach, and policy levels. Finally, the potential links of HABs with marine mammal mortalities was the focus of a workshop of the International Whaling Commission in Slovenia (May 2017).

GlobalHAB aims to increase interdisciplinary and inter-institutional collaborations among HAB scientists with medical, veterinary, public health, and social science expertise to help understand, assess and minimize the risks of the different human and animal diseases caused by phycotoxins in marine and freshwater habitats. This general objective will be initiated by focusing on CFP, due to the high incidence worldwide of these human illnesses (e.g., Chateau-Degat et al. 2007, Skinner et al. 2011, Friedman et al. 2017) and because this problem has already resulted in innovative research and collaborations. The experience gained from CFP would then be used to stimulate analogous multidisciplinary research initiatives focused on DSP and PSP, cyanobacterial toxins in freshwater (drinking and recreational water), potential contamination in desalination plants, and other emerging phycotoxin-related health issues (see e.g., Table 1 in Berdalet et al. 2016).

CFP is the most frequently reported non-bacterial illness associated with fish consumption globally and an apparent increase associated with climate change in the biogeographic distribution of the causal organisms (*Gambierdiscus* spp.) may exacerbate its impacts on human health and wellbeing in the future (as reviewed recently by Friedman et al. 2017). At present, in some of the most affected areas, there is a solid background of medical and public health information, including material comprising methods of risk communication. Also, public health and HAB specialists have begun to establish systems for compiling inter/transdisciplinary environmental and human health data. This is the case both for OHHABS in the United States, and for the Ciguatera Platform at the Institute Louis Malardé (*www.ciguatera-online.com/index.php/en/*) in French Polynesia. The simultaneous collection of environmental and human health data over time will help public health practitioners identify long-term trends in HAB-related diseases in humans and animals. However, such background of medical and public health information is lacking for most Caribbean Islands, highly impacted by CFP. Importantly, at the international level, a coordinated multiagency IOC-IAEA-FAO-WHO "Global Ciguatera Strategy" was adopted in 2015 (*hab.ioc-unesco.org*) for improved research (including ecology, toxicology, medicine and epidemiology) and management and a task team has been established to implement the strategy.

This theme's objectives are shared by at least three other GlobalHAB themes, including *BHABs, Economy,* and *Climate Change* (see Themes 7, 11 and 12, respectively). For this reason, some implementation activities will be designed to coordinate with those indicated in the corresponding sections. The activities fostered by the Health theme will have a marked inter/transdisciplinary character designed to foster interactions between HAB scientists, Health and Public Health departments, medical professionals at national, regional and international levels, Poison Information Centers, and veterinary scientists. The outcomes of these activities will be of interest from local to international levels (including the IPCC). These activities include both citizen science and outreach.

Specific objectives

- Improve coordination between algal ecology and biotoxin monitoring and public health surveillance activities in the affected areas, including freshwater, brackish water, and marine systems.
- Foster the establishment of a centralized reporting system to collect data on HAB-related disease surveillance and epidemiology (starting from local and regional levels).
- Facilitate the collaborations of HAB researchers with public health experts and decision-makers to conduct long-term surveillance, risk assessments and response plans for the different phycological toxin-induced human diseases.

Razor clams harvesting in Washington State, U.S., Pacific coast beaches. These clams can retain the toxin, domoic acid, for many months. Photo credit: Washington State Department of Health.

Example tasks

- Endorse and participate in the implementation of the multiagency coordinated IOC-IAEA-FAO-WHO "Global Ciguatera Strategy".
- Engage appropriate health and fishery professionals through existing channels and regional meetings of FAO and WHO to better understand needs and abilities to implement tools related to management of CFP, as identified also in *Theme 7. Benthic HABs*.
- Convene an interdisciplinary workshop for HAB and other possibly interested scientists to share experiences with research on the different HAB-related diseases. The workshop would include aquatic biologists and ecologists, toxicologists, veterinary professionals, epidemiologists, public health and health care professionals, social scientists, and economists.
- Foster interactions between HAB scientists and non-HAB professionals concerning the freshwater HABs and cyanoHABs theme (Theme 5), especially those occurring as a consequence of the drinking and recreational use of freshwater.
- Collaborate to assess whether CDC's OHHABS for surveillance of HAB-related diseases in animals and people could be adopted for use in other countries; especially in areas where CFP, PSP, or DSP are endemic. See the OHHABS website at *www.cdc.gov/habs/ohhabs.html.*
- Establish communication and active collaboration with cetacean biologists and specific working groups such as the ICES Marine Mammal Ecology Working Group to facilitate tissue testing for HAB toxins and to understand the contribution of HAB toxins to marine mammal mortality and morbidity.

Outcomes

- More informed public outreach based on inter/transdisciplinary initiatives.
- Contribution to the implementation of the IOC-IAEA-FAO-WHO "Global Ciguatera Strategy".
- Development of joint health and environment data series to be incorporated into analyses for future IPCC reports.
- Information for policy makers and health providers: Guidance for improved mitigation of HAB health effects through greater collaboration between HAB and public health experts, and through advances in HAB-related disease surveillance.

Island communities which rely primarely on subsistence fishing are particularly vulnerable to ciguatera risk.
© Institut Louis Malardé (Tahiti, French Polynesia)

THEME 11. Economy

Overall objective: To develop cross-community understanding of the economic impacts of HABs and hence to define methodologies and criteria capable of robustly assessing (at both regional and local levels) the economic costs of HABs, as well as the costs of methods to predict and mitigate HABs.

Rationale. HABs have the potential to negatively affect the economies of the regions in which they occur. Much of the scientific literature on the economic impacts of HABs has 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 closures and fish kills, insurance costs, possible medium and long-term declines in coastal and marine recreation and tourism, and the costs of monitoring, management and mitigation. Estimates of the economic impacts of HABs should (but often do not) account for all of the mentioned aspects (Morgan et al. 2010). Quantification of the so-called "halo effect" offers a means to evaluate the indirect impact of HABs, but a consistent and accepted methodology to achieve this is lacking. Aggregating economic effects – both within and across these categories – can also be problematic with current data and currently used methodologies (Hoagland et al. 2002).

The economic cost of freshwater HABs in drinking water reservoirs has been indicated in *Theme 5. Freshwater HABs*. In marine systems, an example of an economic evaluation of HABs at a regional level was given by Anderson et al. (2000), who estimated the economic effects of HABs in the United States to be US$49 million per year (at the 2000 value of the dollar), which amounts to US$100 million per year in 2012 dollars (Davidson et al. 2012). The proportional breakdown of these costs were as follows: 45% for public health costs, 37% in terms of the costs of closures and losses experienced by commercial fisheries, 13% for the impact on lost recreation and tourism opportunities, and 4% for monitoring and management costs. Multi-year losses from several countries bordering the North Pacific Ocean were analyzed and reported at the PICES "Workshop on Economic Impacts of Harmful Algal Blooms and Aquaculture" (Trainer and Yoshida 2014). Among the presented data, the total economic losses in farmed fish and shellfish production was estimated as US$94.0 million for Korea, Japan and China from 2006 to 2012. Furthermore, the increasing magnitude of macroalgal (*Ulva*, *Sargassum*) HABs is dramatically impacting the economy of countries highly dependent 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 HAB events and hence lack even basic data on HAB costs. Environmental evaluation of HABs also needs to be extended to ensure that the less tangible benefits of HAB mitigation are included, for

Fish products are a source of both basic nutrition and significant income for many communities in the Pacific region. © Institut Louis Malardé (Tahiti, French Polynesia) example, the value in terms of health and well-being of eating seafood and of maintaining sustainable employment in remote regions to foster their sustainable development. More robust 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 allow better decision making on scientific priorities.

Specific objectives

- Undertake capacity-building activities to foster links and common understanding of HAB problems, associated financial risks and economic methodologies between the HAB research community, the environmental economic research community, the aquaculture industry, the insurance industry, seafood and coastal zone regulators and other stakeholders.
- Identify regional differences in economic priorities and responses related to HAB events and their impact on economic assessment (e.g., explore the advantages and problems associated with the use of clay to mitigate some HAB events).
- Evaluate the economic cost/benefit of early warning and mitigation methodologies, taking into account regional differences in priorities and sharing best practice.
- Develop guidelines for the application of economic assessment of HABs at both regional and local levels.

Example tasks

- A comprehensive review of publications and data relating to the economic impacts of HABs identifying methodologies used, estimated costs, regional differences, data gaps, and methodological deficiencies.
- A joint science and stakeholder forum consisting of representatives of the HAB research community, environmental human health economists, the aquaculture industry, the insurance industry and coastal zone managers, to identify strategies to assess the economic impacts of HABs.
- A working group containing representatives of the HAB research community, environmental human health economists, the aquaculture industry, the insurance industry and coastal zone managers, to address the study of the impacts of particular HABs in specific areas.
- Dissemination and outreach activities on the economic impacts of HABs, including the available knowledge, research priorities and policy needs.

Outcomes

- A position paper on the economic impact of HABs: knowns and unknowns.
- A best 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.
- Information for policy makers: An evidence-based perspective of the economic impact of HABs and methods to predict and mitigate their occurrence, including regulatory and industry-based monitoring.

Mussel aquaculture lines in the Marlborough Sounds, New Zealand. Photo credit Cawthron Institute.

THEME 12. Climate Change and HABs

Overall objective: To understand global patterns in HAB responses to common drivers (thermal windows, stratification, changing levels of CO_2).

Rationale. Although not explicitly discussed in the *GEOHAB Science Plan* (GEOHAB 2001) when the programme was launched, the potential impacts of climate change on HAB dynamics was noted. Indeed, "*long-term climatic changes*" was already mentioned as a driver of increased HABs. Furthermore, the effects of climate change were highlighted in some specific areas of GEOHAB concerning the Programme Elements "Biogeography and Biodiversity" and "Observation, Modeling and Prediction".

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 drivers of the general dynamics of microalgae (surface water temperature, ocean stratification, wind and water circulation patterns, precipitation-linked nutrient inputs, but also changes such as salinization of estuaries which may lead to expansion of marine HABs) are changing in ways that could stimulate more HABs. Further anthropogenic pressures on aquatic ecosystems include surface water acidification derived from increasing CO_2 emissions and alteration of natural habitats, especially in the coastal zones.

Forecasting the future occurrence of HABs requires continuing our efforts to improve the fundamental knowledge of the mechanisms driving these events, as identified in GEOHAB. A fundamental question is whether the environmental windows of opportunity for HAB species are expanding, or simply shifting geographically and/or seasonally. It is necessary to investigate the responses of the harmful microalgae (including toxin production) not only in relation to individual natural drivers (i.e., temperature, salinity, nutrients, CO_2) but also to changes in the interactions among them. For instance, in cold fjords regions (Chile, Norway) high runoff due to increased snow melting may modify water stratification and mixing dynamics. The indirect effect of temperature on salinity may have consequences on the occurrence of certain HAB events in these and other areas. Shellfish exposed to new HAB species to which they were not adapted, will be very vulnerable. This situation was already hypothesized by Bricelj et al. (2005), later validated during the *Alexandrium catenella* bloom in 2016 described in Hernández et al. (2016) and its effect in mass mortality of clams (Álvarez et al. 2017).

The particular impact of ocean acidification on HABs requires special attention, because the knowledge is just developing and the experimental approaches are not clearly established yet. Indeed, although CO_2 levels are rising, they also fluctuate diurnally and undergo a large seasonal cycle. In coastal systems, the daily (24 hours) change in CO_2 can be larger than the projected change in the coming century. Further, highly eutrophic systems (which are prone to HABs) can experience CO_2 levels exceeding levels projected for open oceans for 300 years from now. The key fact is that CO_2, an important driver for coastal microalgal communities, is rising and it is dynamic in coastal systems. Long-term studies are needed, including effects of CO_2 on algal population dynamics in general, but also related to CO_2 effects on different harmful species.

Finally, forecasting requires consistent and long-term data series.

Specific Objectives

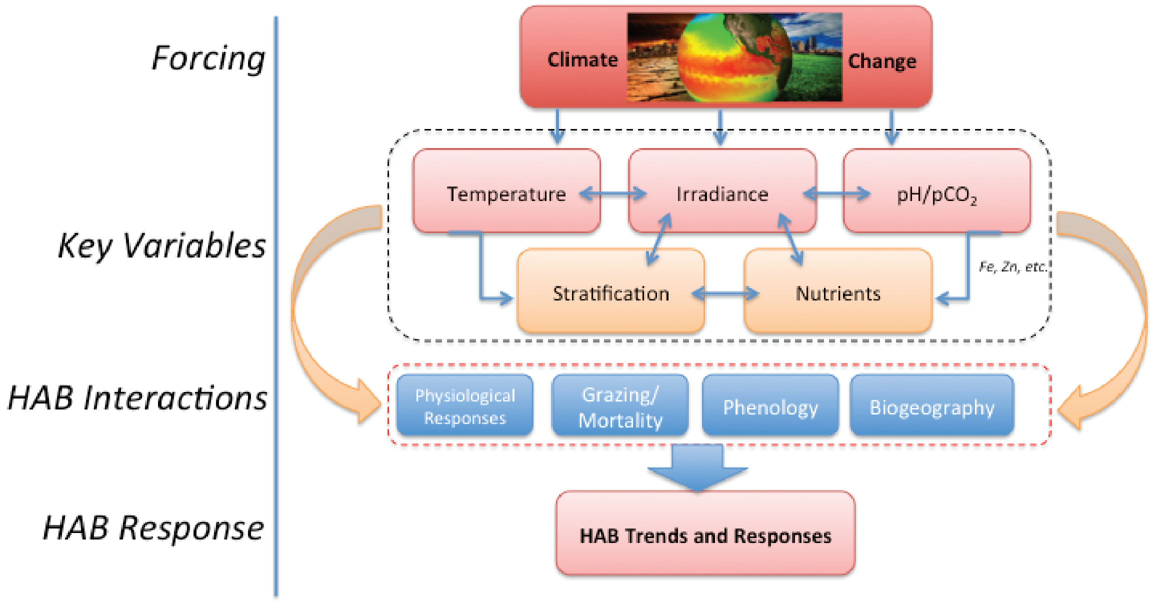
- Understand global and regional patterns in HAB responses to the most common identified drivers (thermal windows, stratification, changing levels of CO_2).
- Encourage and facilitate the use of data from the "natural laboratory", that is, long time series on weather, physical and chemical parameters and HAB occurrence, as a base for predictions of climate effects on HABs.
- Encourage experimental work on climate effects on HABs, for example, laboratory and mesocosm

experiments, as a base for predictions of climate effects on HABs.

- Support an expansion of the number of comprehensive, region-specific studies integrating biological process data with downscaled climate projections.
- Encourage the adoption of best practices in lab and field approaches to investigate HAB responses to climate-linked drivers (see Wells et al. 2015).
- Create synergies with other international groups to investigate ocean deoxygenation in response to climate change and eutrophication, with a specific focus on HABs.
- Explore the use of paleoceanographic records to understand HAB variability in response to past climate events.

Example tasks

- Coordination with other international bodies that share interest in the modulation of HABs by climate change, including GOOS, GODAE MEAP-TT, GO_2NE, GEO/BluePlanet, IPCC.
- In coordination with GOOS, contribute to the development of HABs as part of the "Phytoplankton EOV" (Essential Ocean Variable) by completing a list of existing time-series locations, and identifying super-sites for time-series observations of HABs and related oceanographic parameters to track the potential impact of climate change on HABs.
- Convene an open modeling workshop focused on aligning existing time-series observations with existing climate hindcasts and projections (e.g., GODAE MEAP-TT).
- Produce a best-practices manual for HAB and climate change research, coordinated with IOC updates, including definition of procedures to collect and store data concerning species distribution and what reference information is needed in order to provide standardized information (genetic characterization, etc.).
- Coordinate a global-scale analysis of responses to common drivers in an ensemble of existing projections, with the lists of HAB case studies, models, and participants growing out of modeling workshop above.
- Hold training workshop or summer school for junior scientists, on the theme of improving communication among biologists, biological modelers, and ocean/climate modelers, in pursuit of a mechanistic understanding of diverse responses to climate-driven variables in key taxa.
- Support new culturing experiments to fill physiological information gaps (as noticed in the *Theme 2. Adaptive strategies*).
- Support the development of new model ap-



The progression of climate change pressure on key variables and related HAB interactions that will drive HAB responses in the future ocean. From Wells et al. (2015), with permission from the journal.

proaches, and the application of existing trait-based phytoplankton models to HABs (as noted in the *Theme 8. Observation, Modelling and Prediction*).

- Encourage the incorporation of genomic information on trait regulation and the molecular basis of observed population-level changes into monitoring and modeling (as noted in *Theme 1. Biodiversity and Biogeography*).

Outcomes

- Comprehensive understanding of the global and regional patterns in HABs under different climate change scenarios.
- Best practices manual to investigate the responses of HAB species and future trends in HABs under different climate change scenarios
- Information for policy makers: Credible, high-level outlook on HABs included in IPCC reports

Linkages among Programme Themes

The scientific goal of GlobalHAB is to improve understanding and prediction of HABs in aquatic ecosystems, and management and mitigation of their impacts.

Understanding, and ultimately predicting, HABs will require a broad range of laboratory and field studies, observations, multidisciplinary approaches, development in technologies, etc. described in the individual themes, as well as coordination among those themes. Although many activities and objectives have been presented independently for each element, these must ultimately be linked and integrated to achieve the understanding required. Examples of such coordination among themes and activities have been indicated throughout the document. Figure 1 represents this integrated and coordinated perspective of the GlobalHAB themes.

For instance, the theme *Observation, Modeling, and Prediction*, establishes the framework for prediction based on observation and modeling. As indicated in that section, modeling will be based on classical HAB biomass estimation, but also species-specific or trait-based information as described in the *Adaptive Strategies* and the *Benthic HAB* themes. Accurate taxonomic identification using novel genetic tools as emphasized in the *Biodiversity and Biogeography* theme will contribute to prediction by documenting the present and historical distribution of key HAB species. Studies under the scope of *Nutrients and Eutrophication* intrinsically link to the *HABs and Aquaculture* and the *Toxins* themes, for instance. In turn, the objectives under the *Toxins* theme intersect with *HABs and Aquaculture*, *Benthic HABs* and *Adaptive Strategies*. *BHABs* and *Health* themes share a common interest in the prevention of human and ecosystem health impacts related to CFP. Joint meetings and collaborative activities involving HAB scientists, other disciplines, stakeholders and policy makers are needed to address the objectives of the *Economy* and *Health* themes. The *Comparative Approach* theme integrates the findings of biodiversity, nutritional, and eutrophication effects, and adaptive strategies by examining – through field studies in different hydrographic and ecological systems – the physical, chemical, and biological characteristics of the environment. Finally, understanding trends of HABs under climate change scenarios requires new data and information provided by most of the themes. Overall, improved understanding of HAB population dynamics, and ultimately, improved predictions of HAB events within particular ecosystem types, and prevention and mitigation of their impacts, clearly requires the integration of knowledge derived from the different themes.

In summary, GlobalHAB is a combined experimental, observational, and modeling programme, using existing and innovative technologies in a multidisciplinary approach consistent with the multiple scales and aquatic ecology complexity of HAB phenomena, in their interaction with humans and other organisms.

Implementation Activities

GlobalHAB will help coordinate research internationally when this is possible, focusing its efforts on activities to synthesize and communicate existing information and to address specific knowledge and methodological gaps. Implementation activities arise from recognizing the need for interactions among some of the GlobalHAB themes and the benefits of working with other organizations with interests in these themes. GlobalHAB will not establish CRPs as in GEOHAB. Instead, the GlobalHAB SSC will oversee the activities of each Theme, developing small teams of people to implement each specific activity. Funding for implementation and prioritization of implementation activities will be evaluated annually, at GlobalHAB SSC meetings. The tasks identified within each theme in the former sections are listed below.

Review Papers

Much can be accomplished in the early years of the programme through scientific syntheses related to the themes 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 and other analytical approaches, and
- 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:

- Modeling BHAB dynamics;
- Using PCR/qPCR for identification of *Gambierdiscus* (and possibly *Ostreopsis*) species;
- Methodological challenges to detect known and emerging HAB toxins in benthic, freshwater and marine habitats;
- The role of marine aquaculture in the promotion of HABs;
- In situ cost-effective monitoring technologies for the detection and monitoring of HABs species and toxins in aquaculture systems;
- Experiences with research on the different human and animal 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, and non-HAB experts when appropriate, 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 cyanoHABs 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 affecting 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 cyanoHABs at the ICHA meetings in Nantes, France, 2018 and Los Cabos, Mexico, 2020;
- Special sessions on observation tools, at the ICHA meetings and 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 CTX and PLTX (and analogues) detection could be included within the "International Symposium on Marine and Freshwater Toxins Analysis" organized by the AOAC (Association of Analytical Communities) International; and
- Freshwater HABs and cyanoHABs sessions at the GLEON meetings.

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 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; and
- A training workshop or summer school on the theme of improving communication among biologists, biological modelers, and ocean and climate modelers.

GlobalHAB will especially target training and capacity-building initiatives in those areas facing basic problems in studying 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 cyanoHABs 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 align with the Global HAB Status Report (GHSR) and HAEDAT-HABMAP initiatives, to establish a baseline of the biogeographic species distribution. It will also 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 cyanoHABs,
- 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.

The different activities listed here can be conducted within a near term (1-3 years) and the more distant future of the programme (10 years).

Collaboration with other International Bodies

GlobalHAB shares its scientific research interest on HABs with other international entities (Figure 2). In consequence, collaborations between GlobalHAB and these bodies are fundamental for success and reciprocal benefit. At the inception of GlobalHAB, some collaborations have already started (listed below in alphabetic order), and new links are expected and envisioned in the future. For instance, other regional programmes (e.g., IOCARIBE/ANCA, IOC/WESTPAC, UN Environment Regional Seas) and international organizations and programmes (e.g., IPCC, PICES, UN Environment) are or will also be contacted to establish synergies with GlobalHAB.

EuroGOOS – Traditionally focused on physical oceanography processes, the incorporation of FerryBox systems and instrumented oceanographic buoys may facilitate research on HABs.

GEO/Blue Planet – The relationship with GEO/Blue Planet and GlobalHAB will be fostered through collaboration by arranging joint activities such as workshops or symposia and by inviting members of the respective steering committees to the other programmes' meetings for planning future work.

GOOS Biology and Ecosystems Panel has identified phytoplankton, including HABs, as an Essential Ocean Variable (EOV). GlobalHAB will help develop and oversee this EOV and the GOOS webpages can raise the visibility of GlobalHAB.

IAEA– IAEA developed a receptor-binding assay method for PSP and is now focusing on ciguatera (CTX detection method). IAEA participates in monitoring (sampling devices), provides support for lab equipment, is producing reference materials, and is incorporating epidemiology on the Pacific Island Countries and Territories (PICTs). All these aspects are relevant for the implementation of GlobalHAB objectives.

ICES - The ICES/IOC WG on Harmful Algal Bloom Dynamics (WGHABD), which concerns the ecology of HAB species within the ICES area, was pivotal in the development of GEOHAB. The new ToRs of the WGHABD in 2017 will incorporate "GlobalHAB" as a new descriptor. Furthermore, GlobalHAB could

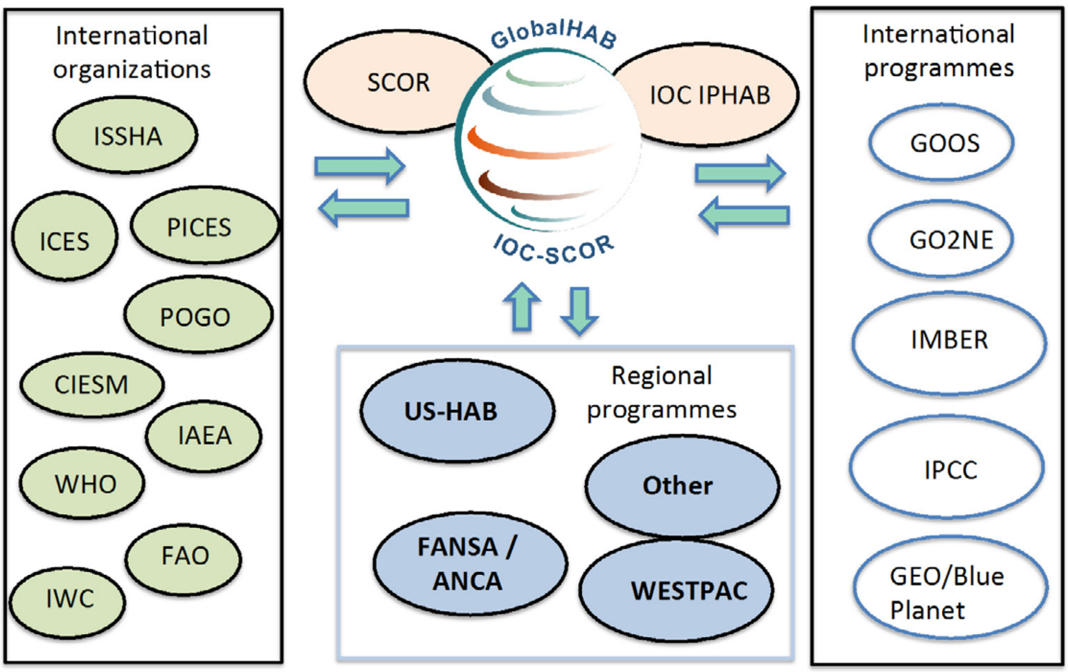


Figure 2. Links of GlobalHAB with other international entities that include HABs in their terms of reference or objectives.

co-sponsor a 2017 workshop on novel methods for HAB species detection.

IOCCG– The joint working group between GEOHAB and IOCCG can continue with GlobalHAB, and contribute to improve the use of satellite tools for HAB detection and modelling.

IPHAB – IPHAB identifies priority needs related to HABs and addresses IOC high-level objectives (e.g., the development of a Global HAB Status Report, a UN interagency strategy on ciguatera for improved research and management). Support to GlobalHAB from IPHAB could include training workshops (e.g., on taxonomy), interaction with member states and regional grouping on HAB issues, technical support through IPHAB Task Teams on Toxins and economic costs of HABs, and encouragement of countries to support their scientists to engage in GlobalHAB activities. The IOC liaison also includes links to IOC regional programmes such as IOC/WESTPAC/HAB, which could contribute to GlobalHAB, for instance, by creating outreach materials and sending regional experts to GlobalHAB-related meetings.

ISSHA – ISSHA is the sponsor of the International Conferences on Harmful Algae (ICHA) convened every two years. GlobalHAB will collaborate with ISSHA to identify specific sessions to advance in the progress of GlobalHAB objectives and to facilitate the engagement of the international community on the implementation of the programme.

PICES has a Section on Ecology of Harmful Algal Blooms in the North Pacific. PICES could collaborate with GlobalHAB in future studies, through the alignment of PICES work with specific GlobalHAB objectives, providing ex officio status for GlobalHAB representatives on PICES Expert Groups that organize special meetings, workshops, and symposia, etc.

References

Álvarez, G., M. Godoy, M. Araya, I. Ganuza, R. Pino, J. Rengel, E. Uribe, J. Blanco. 2017. Effects of Harmful Algal Bloom of *Alexandrium catenella* in the mass mortality of the surf clam *Mesodesma donacium* in Chiloé Island, Chile. *In* Abstracts of the 11th International Conference on Molluscan Shellfish Safety, Galway, May 2017 *http://www.conference.ie/Conferences/menu.asp?menu=2262&Conference=451*

Anderson, C.R., R.M. Kudela, M. Kahru, Y. Chao, L.K. Rosenfeld, F.L. Bahr, D.M. Anderson, and T.A. Norris. 2016. et al. 2016. Initial skill assessment of the California Harmful Algae Risk Mapping (C-HARM) system. *Harmful Algae* 59:1-18.

Anderson, D.M., Y. Kaoru, and A.W. White. 2000. Economic Impacts from Harmful Algal Blooms (HABs) in the United States. *Technical report WHOI-2000-11.* Woods Hole Oceanographic Institute, Massachusetts.

Anderson, D.M., P.M. Glibert, and J.M. Burkholder. 2002. Nutrient Sources, Composition, and Consequences. *Estuaries* 25:704-726.

Anderson, D.M, G.C. Pitcher, and M. Estrada. 2005. The comparative "systems" approach to HABs research. *Oceanography* 18:148-157.

Anderson, D.M., T.J. Alpermann, A.D. Cembella, Y. Collos, E. Masseret, and M. Montresor. 2012. The globally distributed genus *Alexandrium*: Multifaceted roles in marine ecosystems and impacts on human health. *Harmful Algae* 14:10-35.

Azanza, R.V., Y. Fukuyo, L.G. Yap, and, H. Takayama. 2005*. Prorocentrum minimum* bloom and it possible link to massive fish kill in Bolinao, Pangasinan, Northern Philippines*. Harmful Algae* 4:519-524.

Azanza, R.V., M.L. Brosnahan, D.M. Anderson, I. Hense, and M. Montresor. 2017. *In press*. The role of life cycle characteristics on harmful algal bloom dynamics. *In* P.M. Glibert, E. Berdalet, M. Burford, G. Pitcher, and M. Zhou (eds.), *Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB)*. Ecological Studies Series, Springer International Publishing AG, Switzerland, Ecological Studies - Analysis and Synthesis Series.

Bachvaroff, T. R., J.E. Adolf, and A.R. Place. 2009. Strain variation in *Karlodinium veneficum* (Dinophyceae): toxin profiles, pigments, and growth characteristics. *Journal of Phycology* 45:137-53.

Berdalet, E., M.A. McManus, O.N. Ross, H. Burchard, F.P. Chavez, J.S. Jaffe, I.R. Jenkinson, R. Kudela, I. Lips, U. Lips, A. Lucas, D. Rivas, M.C. Ruiz-de la Torre, J. Ryan, J.M. Sullivan, and H. Yamazaki. 2014. Understanding Harmful Algae in Stratified Systems: Review of Progress and Future Directions. *Deep-Sea Research, Part II: Topical Studies in Oceanography* 101:4-20.

Berdalet, E., L.E. Fleming, R. Gowen, K. Davidson, P. Hess, L.C. Backer, S.K. Moore, P. Hoagland, H. Enevoldsen. 2016. Marine harmful algal blooms, human health and wellbeing: challenges and opportunities in the 21st century. *Journal of the Marine Biological Association of the United Kingdom* 96: 61–91.

Berdalet, E., and P. Tester. 2017. *In press.* Recent Research Advances on Harmful Algal Blooms in Benthic Systems. *In* P.M. Glibert, E. Berdalet, M. Burford, G. Pitcher, and M. Zhou (eds.), *Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB)*. Ecological Studies Series, Springer International Publishing AG, Switzerland, Ecological Studies - Analysis and Synthesis Series.

Berdalet, E., P.A. Tester, M. Chinain, S. Fraga, R. Lemée, W. Litaker, A. Penna, G. Usup, M. Vila, and A. Zingone. 2017a. Harmful Algal Blooms in Benthic Systems: recent progresses and future research. *Oceanography* 30:36–45.

Berdalet, E., M. Montresor, B. Reguera, S. Roy, H. Yamazaki, A. Cembella, and R. Raine. 2017b. Harmful algal blooms in fjords, coastal embayments, and stratified systems: Recent progress and future research. *Oceanography* 30:46–57.

Black, E.A., J.N.C. Whyth, J.W. Bagshaw, and N.G. Ginther. 1991. The effects of *Heterosigma akashiwo* on juvenile *Oncorhynchus tshawytscha* and its implications for fish culture. *Journal of Applied Ichthyology* 7:168–175.

Borcier, A. E., R. Morvezen, P. Boudry, P. Miner, and J. Laroche. 2017. Effects of bioactive extra-cellular compounds and paralytic shellfish toxins produced by *Alexandrium minutum* on growth and behaviour of juvenile great scallops *Pecten maximus*. *Aquatic Toxicology* DOI: 10.1016/j.aquatox.2017.01.009

Boyd, P.W., T.A. Rynearson, E.A. Armstrong, F. Fu, K. Hayashi, Z. Hu, D.A. Hutchins, R.M. Kudela, E. Litchman, M.R. Mulholland, U. Passow, R.F. Strzepek, K.A. Whittaker, E. Yu, and M.K. Thomas. 2013. Marine Phytoplankton Temperature *versus* Growth Responses from Polar to Tropical Waters – Outcome of a Scientific Community-Wide Study. *PLoS ONE* 8:e63091.

Bravo, I. and R. Figueroa. 2014. Towards an ecological understanding of dinoflagellate cyst functions. *Microorganisms* 2:11-32.

Bricelj, V.M., L. Connell, K. Konoki, S. P. MacQuarrie, T. Scheuer, W. A. Catterall, and V. L. Trainer. 2005. Sodium channel mutation responsible for saxitoxin resistance in clams increases risk of PSP. *Nature* 434:763-767.

Casteleyn, G., F. Leliaert, T. Backeljau, A.-E. Debeer, Y. Kotaki, L. Rhodes, N. Lundholm, K. Sabbe, and W. Vyverman. 2010. Limits to gene flow in a cosmopolitan marine planktonic diatom. *Proceedings of the National Academy of Sciences* 107:12952-57.

Chambouvet, A., P. Morin, D. Marie, L. Guillou. 2008. Control of toxic marine dinoflagellate blooms by serial parasitic killers. *Science* 322 (5905):1254–1257.

Chateau-Degat, M.-L., E. Dewailly, N. Cerf, N.L. Nguyen, M.-O. Huin-Blondey, B. Hubert, F. Laudon, and R. Chansin. 2007. Temporal trends and epidemiological aspects of ciguatera in French Polynesia: A 10- year analysis. *Tropical Medicine and International Health* 12:485–492.

Chinain, M., M. Germain, X. Deparis, S. Pauillac, and A.M. Legrand. 1999. Seasonal abundance and toxicity of the dinoflagellate *Gambierdiscus* spp (Dinophyceae), the causative agent of ciguatera in Tahiti, French Polynesia. *Marine Biology* 135:259–267.

Clément, A., and G. Lembeye. 1993. Phytoplankton monitoring program in the fish farming region of south Chile. *In* T. Smayda, and Y. Shimizu (eds), *Toxic Phytoplankton Blooms in the Sea*, pp. 223-228. Elsevier Science Publishers, New York.

Clément, A., L. Lincoqueo, M. Saldivia, C.G. Brito, F. Muñoz, C. Fernández, F. Pérez, C.P. Maluje, N. Correa, V. Moncada, and G. Contreras. 2016. Exceptional summer conditions and HABs of *Pseudochattonella* in Southern Chile create record impacts on salmon farms. *Harmful Algae News* 53:1-3.

Dahl, E., E. Bagøien, B. Edvardsen, and N.C. Stenseth. 2005. The dynamics of *Chrysochromulina* species in the Skagerrak in relation to environmental conditions. *Journal of Sea Research* 54:15–24.

Davidson, K., R.J. Gowen, P.J. Harrison, L.E. Fleming, P. Hoagland, G. Moschonas. 2014. Anthropogenic nutrients and harmful algae in coastal waters. *Journal of Environmental Management* 146:206-216.

Dodds, W.K., W.W. Bouska, J.I. Eitzmann, T.J. Pilger, K.L. Pitts, A.J. Riley, and D.J. Thornbrugh. 2008. Eutrophication of U.S. freshwaters: analysis of potential economic damages. *Environmental Science and Technology* 43:12-19.

Durán-Riveroll L.M., A.D. Cembella, C.J. Band-Schmidt, J.J. Bustillos-Guzmán, and J. Correa-Basurto. 2016. Docking Simulation of the Binding Interactions of Saxitoxin Analogs Produced by the Marine Dinoflagellate *Gymnodinium catenatum* to the Voltage-Gated Sodium Channel Na_v1.4. *Toxins (Basel)* 8(5):129. doi: 10.3390/toxins8050129.

Farrell, H., W. O'Connor, F. Seebacher, D.T. Harwood, and S. Murray. 2016. Molecular detection of the sxtA genef rom saxitoxin-producing *Alexandrium minutum* in commercial oysters. *Jorunal of Shellfish. Research 35:*169–177.

Fleming, L.E., N. McDonough, M. Austen, L. Mee, M. Moore, M.H. Depledge, M. White, K. Philippart, P. Bradbrook, and A. Smalley. 2014. Oceans and Human Health: A Rising Tide of Challenges and Opportunities for Europe. *Marine Environment Research* 99:16-19.

Fraga S., F. Rodríguez, A. Caillaud, J. Diogène, N. Raho, and M. Zapata .2011. *Gambierdiscus excentricus* sp. nov. (Dinophyceae), a benthic toxic dinoflagellate from the Canary Islands (NE Atlantic Ocean). *Harmful Algae* 11:10–22.

Friedman, M.A., M. Fernandez, L.E. Fleming, L.B. Backer, J. Bernstein, K. Schrank, S. Kibler, W. Stephan, M.O. Gribble, P. Bienfang, R.W. Dickey, R. Bowen, H. Flores-Quintana, C. Loeffler, S. Degrasse, R. Weisman, D. Blythe, E. Berdalet, D. Ayyar, D. Clarkson-Townsend, R. Benner, and T. Brewer. 2017. An updated review of ciguatera fish poisoning: Clinical, Epidemiological, Environmental, and Public Health Management. *Marine Drugs* 15(72), *https://doi.org/10.3390/md15030072*.

Gatti, C.M., H.T. Darius, M. Chinain, and D. Lonati. 2015. First report of a mass-poisoning outbreak following the consumption of *Tectus niloticus* (Gastropod) in French Polynesia: a novel pathway of Ciguatera Shellfish Poisoning? *Harmful Algae News* 50: 19-20, *http://www.e-pages.dk/ku/1086*.

Genovesi, B., P. Berrebi, S. Nagai, N. Reynaud, J.H. Wang, and E. Masseret. 2015. Geographic structure evidenced in the toxic dinoflagellate *Alexandrium pacificum* Litaker (*A. catenella* - group IV (Whedon & Kofoid) Balech) along Japanese and Chinese coastal waters. *Marine Pollution Bulletin* 98:95-105.

GEOHAB. 2001. *Global Ecology and Oceanography of Harmful Algal Blooms, Science Plan.* P. Glibert and G. Pitcher (eds.), SCOR and IOC, Baltimore and Paris. 87 pp.

GEOHAB. 2003. *Global Ecology and Oceanography of Harmful Algal Blooms: Implementation Plan.* P. Gentien, G. Pitcher, A. Cembella, and P. Glibert (eds.), SCOR and IOC, Baltimore and Paris. 36 pp.

GEOHAB. 2005. *Global Ecology and Oceanography of Harmful Algal Blooms, GEOHAB Core Research Project: HABs in Upwelling Systems*. G. Pitcher, T. Moita, V. Trainer, R. Kudela, F. Figueiras, and T. Probyn (eds.), IOC and SCOR, Paris and Baltimore, 82 pp.

GEOHAB. 2006. *Global Ecology and Oceanography of Harmful Algal Blooms, Harmful Algal Blooms in Eutrophic Systems*. P. Glibert (ed.). IOC and SCOR, Paris and Baltimore, 74 pp.

GEOHAB. 2010. *Global Ecology and Oceanography of Harmful Algal Blooms, GEOHAB Core Research Project: HABs in Fjords and Coastal Embayments*. A. Cembella, L. Guzmán, S. Roy, and J. Diogène (eds), IOC and SCOR, Paris, France, and Newark, Delaware, 57 pp.

GEOHAB 2011. *GEOHAB Modelling: A Workshop Report.* D.J. McGillicuddy, Jr., P.M. Glibert, E. Berdalet, C. Edwards, P. Franks, and O. Ross (eds.). IOC and SCOR, Paris and Newark, Delaware. 85 pp.

GEOHAB 2012. *Global Ecology and Oceanography of Harmful Algal Blooms: Core Research Project – Harmful Algal Blooms in Benthic Systems*. E. Berdalet, P. Tester, and A. Zingone (eds.), IOC of UNESCO and SCOR, Paris and Newark, 64 pp.

GEOHAB. 2013. *Global Ecology and Oceanography of Harmful Algal Blooms, GEOHAB Core Research Project: HABs in Stratified Systems. Workshop on "Advances and Challenges for Understanding Physical-Biological Interactions in HABs in Stratified Environments"*. M.A. McManus, E. Berdalet, J. Ryan, H. Yamazaki, J.S. Jaffe, O.N. Ross, H. Burchard and F.P. Chavez (eds.), IOC and SCOR, Paris and Newark, Delaware, U.S., 62 pp.

GEOHAB. 2014. *Global Ecology and Oceanography of Harmful Algal Blooms, GEOHAB Synthesis Open Science Meeting.* E. Berdalet, S. Bernard, M.A. Burford, H. Enevoldsen, R.M. Kudela, R. Magnien, S. Roy, P.A. Tester, E. Urban, and G. Usup (eds.). IOC and SCOR, Paris and Newark, Delaware, U.S., 78 pp.

Glibert, P.M., and M.A. Burford. 2017. Globally changing nutrient loads and harmful algal blooms: Recent advances, new paradigms, and continuing challenges. *Oceanography* 30:58–69.

Glibert, P., E. Berdalet, M. Burford, and G. Pitcher (eds.) 2017. *In press.* GEOHAB: Global Ecology and Oceanograpy of Harmful Algal Blooms. Ecological Studies Series, Springer International Publishing AG, Switzerland, Ecological Studies - Analysis and Synthesis Series.

Gobler, C. J., and W. Sunda. 2012. Ecosystem disruptive algal blooms of the brown tide species, *Aureococcus anophagefferens* and *Aureoumbra lagunensis*. *Harmful Algae* 14:36-45.

Gowen, R.J., P. Tett P, E. Bresnan, K. Davidson, A. McKinney, S. Milligan, D.K. Mills, J. Silke, A. Gordon, A.M. Crooks. 2012. Anthropogenic Nutrient Enrichment and Blooms of Harmful Micro-algae. *Oceanography and Marine Biology: An annual review.* 50:65-126.

Granéli, E., E. Paasche, and S. Maestrini. 1993. Three years after the *Chrysochromulina polylepis* bloom in Scandinavian waters in 1988: some conclusions of recent research and monitoring. *In* T.J. Smayda, and Y. Shimizu (eds), *Toxic Phytoplankton Blooms in the Sea. Developments in Marine Biology 3. Proceedings of the Fifth International Conference on Toxic Marine Phytoplankton, October 28–November 1 1991, Newport USA*, Amsterdam: Elsevier Science, 23–32.

Grattan L.M., S. Holobaugh, and J.G. Morris Jr. 2016. Harmful algal blooms and public health. *Harmful Algae* 57: 2-8.

HABWATCH. 2004. *Real-time Coastal Observing Systems for Marine Ecosystem Dynamics and Harmful Algal Blooms: Theory, Instrumentation and Modelling*. M. Babin, C. Roesler, and J. Cullen (eds.), *Oceanographic Methodology series*, UNESCO Printers, 799 pp.

Hallegraeff, G.M. 2010. Ocean climate change, phytoplankton community responses, and harmful algal blooms: a formidable predictive challenge. *Journal of Phycology* 46:220-235.

Hamilton, D.P., S.A. Wood, D.R. Dietrich, and J. Puddick. 2014. Costs of harmful blooms of freshwater cyanobacteria. *In* N.K. Sharma, A.K. Rai, and L.J. Stal (eds.), *Cyanobacteria: An Economic Perspective*, 1st Edition. Wiley, New York, pp. 245–256.

Hardison, D.R., W.C. Holland, J.R. McCall, A.J. Bourdelais, D.G. Baden, H.T. Darius, M. Chinain, P.A. Tester, D. Shea, H.A. Flores Quintana, J.A. Morris Jr., and R.W. Litaker. 2016. Fluorescent receptor binding assay for detecting ciguatoxin in fish. *PLos ONE*, *http://dx.doi.org/10.1371/journal.pone.0153348*.

Heisler, J., P.M. Glibert, J.M. Burkholder, D.M. Anderson, W. Cochlan, W.C. Dennison, Q. Dortch, C.J. Gobler, C.A. Heil, E. Humphries, A. Lewitus, R. Magnien, H.G. Marshall, K. Sellner, D.A. Stockwell, D.K. Stoecker, and M. Suddleson. 2008. Eutrophication and harmful algal blooms: a scientific consensus. *Harmful Algae* 8, 3-13.

Hegaret, H., S.E. Shumway, G.H. Wikfors, S. Pate, and J.M. Burkholder. 2008. Potential transport of harmful algae via relocation of bivalve molluscs. *Marine Ecology Progress Series* 361:169-179.

Hernández C., P.A. Díaz, C. Molinet, and M. Seguel. 2016. Exceptional climate anomalies and northwards expansion of Paralytic Shellfish Poisoning outbreaks in Southern Chile. *Harmful Algae News* 54:1-2.

Hoagland, P., D.M. Anderson, Y. Kaoru, and A. White. 2002. The economic effects of harmful algal blooms in the United States: estimates, assessment issues, and information needs. *Estuaries* 25:677-695.

Huber, A.L. 1984. *Nodularia* (Cyanobacteriaceae) akinetes in the sediments of the Peel-Harvey Estuary, Western Australia: Potential inoculum source for *Nodularia* blooms. *Applied Environmental Microbiology* 47:234-238.

Ianora, A., M.G. Bentley, G.S. Caldwell, R. Casotti, A.D. Cembella, J. Engstrom-Ost, C. Halsband, E. Sonnenschein, C. Legrand, C.A. Llewellyn, A. Paldaviciene, R. Pilkaityte, G. Pohnert, A. Razinkovas, G. Romano, U. Tillmann, and D. Vaiciute. 2011. The relevance of marine chemical ecology to plankton and ecosystem function: An emerging field. *Marine Drugs* 9:1625-48.

Jeffery, B., T. Barlow, K. Moizer, S. Paul, and C. Boyle. 2004. Amnesic shellfish Poison. *Food and Chemical Toxicology* 42: 545-557.

John, U., W. Litaker, M. Montresor, S. Murray, M. Brosnahan, and D.M. Anderson. 2014. Formal revision of the *Alexandrium tamarense* species complex (Dinophyceae) taxonomy: the introduction of five species with emphasis on molecular-based (rDNA) classification. *Protist* 165:779–804.

Kahru, M., and R. Elmgren. 2014. Multidecadal time series of satellite-detected accumulations of cyanobacteria in the Baltic Sea. *Biogeosciences* 11:3619-3633.

Karlson B., F.J.A. Nascimento, S. Suikkanen and R. Elmgren. 2012. Benthic fauna affects recruitment from sediments of the harmful cyanobacterium *Nodularia spumigena*. *Harmful Algae* 20:126-131.

Kellmann, R., T.K. Mihali, B.A. and Neilan B.A. 2008. Identification of saxitoxin biosynthesis gene with a history of frequent horizontal gene transfers. *Journal of Molecular Evolulation* 67: 526-538.

Kent, M.L., J.N.C. Whytel, and C. LaTrace. 1995. Lesions and mortality in seawater pen-reared Atlantic salmon *Salmo salar* associated with a dense bloom of *Skeletonema costatum* and *Thalassiosira* species. *Diseases of aquatic organisms* 22:77-81.

Kohli, G.S., U. John, F.M. Van Dolah, and S.A. Murray. 2016. Evolutionary distinctiveness of fatty acid and polyketide synthesis in eukaryotes. *The ISME Journal* 10:1877-1890.

Kremp, A., P. Tahvanainen, W. Litaker, B. Krock, S. Suikkanen, C.P. Leaw, and C. Tomas. 2014. Phylogenetic relationships, morphological variation, and toxin patterns in the *Alexandrium ostenfeldii* (Dinophyceae) complex: implications for species boundaries and identities. *Journal of Phycology* 50:81-100.

Krüger T., B. Mönch, S. Oppenhäuser, and B. Luckas. 2010. LC-MS/MS determination of the isomeric neurotoxins BMAA (β-N-methylamino-L-alanine) and DAB (2,4-diaminobutyric acid) in cyanobacteria and seeds of *Cycas revoluta* and *Lathyrus latifolius*. *Toxicon* 55:547–557.

Kudela, R.M., M.D.A. Howard, B.D. Jenkins, P.E. Miller, and G.J. Smith. 2010. Using the molecular toolbox to compare harmful algal blooms in upwelling systems. *Progress in Oceanography* 85:108-121.

Kudela, R.M., E. Berdalet, S. Bernard, M. Burford, L. Fernand, S. Lu, S. Roy, P. Tester, G. Usup, R. Magnien, D.M. Anderson, A. Cembella, M. Chinain, G. Hallegraeff, B. Reguera, A. Zingone, H. Enevoldsen, and E. Urban. 2015. Harmful Algal Blooms. A Scientific Summary for Policy Makers. IOC-UNESCO, Paris (IOC/INF-1320.).

Kudela, R.M., E. Berdalet, H. Enevoldsen, G. Pitcher, R. Raine, and E. Urban. 2017a. GEOHAB–The Global Ecology and Oceanography of Harmful Algal Blooms Program: Motivation, Goals, and Legacy. *Oceanography* 30:12–21.

Kudela, R.M., H. Enevoldsen, and E. Urban (Eds.). 2017b. *International Cooperation in Harmful Algal Bloom Science. Oceanography* 30, special issue.

Kudela, R.M., E. Berdalet, E. Urban, and H. Enevoldsen. 2017c. The Global Ecology of Oceanography and Harmful Algal Blooms Programme (GEOHAB): History and Impacts. *In* P.M. Glibert, E. Berdalet, M. Burford, G. Pitcher, and M. Zhou (eds.), *Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB)*. Ecological Studies Series, *In press.* International Publishing AG, Switzerland, Ecological Studies - Analysis and Synthesis Series.

Lapointe, B.E., R. Langton, B.J. Bedford, A.C. Potts, O. Day, and C. Hu. 2010. Land-based nutrient enrichment of the Buccoo Reef Complex and fringing coral reefs of Tobago, West Indies. *Marine Pollution Bulletin* 60:334-343.

Legrand, C., K. Rengefors, G.O. Fistarol, and E. Granéli. 2003. Allelopathy in phytoplankton – biochemical, ecological and evolutionary aspects. *Phycologia* 42:406–419.

Lehane L., and R.J. Lewis. 2000. Ciguatera: recent advances but the risk remains. *International Journal of Food Microbiology* 61:91-125.

Lelong, A., H. Hégaret, P. Soudant, and S.S. Bates. 2012. *Pseudo-nitzschia* (Bacillariophyceae) species, domoic acid and amnesic shellfish poisoning: revisiting previous paradigms. *Phycologia* 51: 168-216.

Lim, H.C., C.P. Leaw, T.H. Tan, N.F. Kon, L.H. Yek, K.S. Hii, S.T. Teng, R. Mohd Razali, G. Usup, M. Iwataki, and P.T. Lim. 2014. A bloom of *Karlodinium australe* (Gymnodiniales, Dinophyceae) associated with mass mortality of cage cultured fishes in West Johor Strait, Malaysia. *Harmful Algae* 40: 51-62.

Litaker, R.W., M.W. Vandersea, M. Faust, S.R. Kibler, A.W. Nau, W.C. Holland, M. Chinain, M.J. Holmes, and P.A. Tester. 2010. Global distribution of ciguatera causing dinoflagellates in the genus *Gambierdiscus*. *Toxicon* 56: 711-730.

Lu, Y. M., S. Wohlrab, M. Groth, G. Glockner, L. Guillou, and U. John. 2016. Transcriptomic profiling of *Alexandrium fundyense* during physical interaction with or exposure to chemical signals from the parasite *Amoebophrya*. *Molecular Ecology* 25:1294-307.

Masó, M., E. Garcés, F. Pagès, and J. Camp. 2003. Drifting plastic debris as a potential vector for dispersing Harmful Algal Bloom (HAB) species. *Scientia Marina* 67:107–111.

Merilä, J. and A.P. Hendry. 2014. Climate change, adaptation, and phenotypic plasticity: the problem and the evidence. *Evolutionary Applications* 7:1-14.

Mitra, A., and K.J. Flynn. 2010. Modelling mixotrophy in harmful algal blooms: More or less the sum of the parts? *Journal of Marine Systems* 83: 158-169.

Mitra, A., K.J. Flynn, U. Tillmann, J. A. Raven, D. Caron, D.K. Stoecker, F. Not, P.J. Hansen, G. Hallegraeff, R. Snaders, S. Wilken, G. McManus, M. Johnson, P. Pitta, S. Våge, T. Berge, A. Calbet, F. Thingstad, H.J. Jeong, J. Burkholder, P.M. Glibert, E. Granéli, and V. Lundgren. 2016. Defining planktonic protist functional groups on mechanisms for energy and nutrient acquisition; incorporation of diverse mixotrophic strategies. *Protist* 167: 106-120.

Moore, M.N., M.H. Depledge, L.E. Fleming, P. Hess, D. Lees, P. Leonard, L. Madsen, R. Owen, H. Pirlet, J. Seys, V. Vasconcelos, A. Viarengo, and Marine Board, E.S.F.W.G.O. 2013. Oceans and Human Health (OHH): a European Perspective from the Marine Board of the European Science Foundation (Marine Board-ESF). *Microbial Ecology* 65: 889-900.

Moore, S.K., J.A. Johnstone, N.S. Banasand E.P. Salathé Jr. 2015. Present-day and future climate pathways affecting *Alexandrium* blooms in Puget Sound, WA, U.S.. *Harmful Algae* 48:1-15.

Morgan, K.L., S.L. Larkin, and C.M. Adams. 2010. Red tides and participation in marine based activities: estimating the response of Southwest Florida residents. *Harmful Algae* 9:333-341.

Murray, S.A., M. Wiese, A. Stuken, S. Brett, R. Kellmann, G. Hallegraeff, and B.A. Neilan. 2011. sxtA-Based quantitative molecular assay to identify saxitoxin-producing harmful algal blooms in marine waters. *Applied Environmental. Microbiology 77*:7050–7057.

Nishimura T., S. Sato S, W. Tawong H. Sakanari, H. Yamaguchi, and M. Adachi. 2014. Morphology of *Gambierdiscus scabrosus* sp. nov. (Gonyaulacales): A new epiphytic toxic dinoflagellate from coastal areas of Japan. *Journal of Phycology* 50:506-514.

O'Neil, J.M., T.W. Davis, M.A. Burford, and C.J. Gobler. 2012. The rise of harmful cyanobacteria blooms (CHABs): Role of eutrophication and climate change in freshwater, estuarine and marine ecosystems. *Harmful Algae* 14:313-334.

Okaichi, T. 1997. Red tides in the Seto Inland Sea. *In* T. Okaichi, and T. Yanagi (eds), *Sustainable Development in the Seto Inland Sea, Japan, from the Viewpoint of Fisheries*. Tokyo: Terra Scientific, 251–304.

Oshima, Y. 1995. Postcolumn derivatization liquid chromatographic method for paralytic shellfish toxins. *Journal of the Analytical and Official Association of Chemistry International* 78:528–532.

Pawlowiez, R., J.S. Morey, H.T. Darius, M. Chinain, and F.M. Van Dolah. 2014. Transcriptome sequencing reveals single domain Type I-like polyketide synthases in the toxic dinoflagellate *Gambierdiscus polynesiensis*. *Harmful Algae* 36:29-37.

Pearson, L.A., E. Dittmann, R. Mazmouz, S.E. Ongley, P.M. D'Agostino, and B.A. Neilan. 2016. The genetics, biosynthesis and regulation of toxic specialized metabolites of cyanobacteria. *Harmful Algae* 54:98-111.

Pierce, R.H., M.S. Henry, P.C. Blum, S.L. Hamel, B. Kirkpatrick, Y.S. Cheng, Y. Zhou, C.M. Irvin, J. Naar, A. Weidner, L.E. Fleming, L.C. Backer, and D.G. Baden. 2005. Brevetoxin composition in water and marine aerosol along a Florida beach: Assessing potential human exposure to marine biotoxins. *Harmful Algae* 4: 965–972.

Pisapia, F., M. Sibat, C. Herrenknecht, K. Lhaute, G. Gaiani, P.-J. Ferron, V. Fessard, S. Fraga, S.M. Nascimento, R.W. Litaker, W.C. Holland, C. Roullier, and P. Hess. 2017. Maitotoxin-4, a Novel MTX Analog Produced by *Gambierdiscus excentricus*. *Marine Drugs* 15:220; doi:10.3390/md15070220.

Pitcher, G.C., A.B. Jiménez, R.M. Kudela, and B. Reguera. 2017. Harmful algal blooms in eastern boundary upwelling systems: A GEOHAB Core Research Project. *Oceanography* 30:22–35.

Raho, N., G. Pizarro, L. Escalera, B. Reguera, and I. Marín. 2008. Morphology, toxin composition and molecular analysis of *Dinophysis ovum* Schütt, a dinoflagellate of the *Dinophysis acuminata* complex. *Harmful Algae* 7:839–848.

Raine, R., E. Berdalet, H. Yamazaki, I. Jenkinson, and B. Reguera. 2017. Key questions and recent advances in research on harmful algal blooms in stratified systems. *In* P.M. Glibert, E. Berdalet, M. Burford, G. Pitcher, and M. Zhou (eds.), *Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB)*. Ecological Studies Series, Springer International Publishing AG, Switzerland, Ecological Studies - Analysis and Synthesis Series.

Randall, J.E. 2005. Review of clupeotoxism, an often fatal illness from the consumption of clupeoid fishes. *Pacific Science* 59:73-77.

Reguera, B., L. Velo-Suárez, R. Raine, and M.G. Park. 2012. Harmful *Dinophysis* species: A review. *Harmful Algae* 14:87-106.

Rhodes, L. 2011. World-wide occurrence of the toxic dinoflagellate genus *Ostreopsis* Schmidt. *Toxicon* 57:400-407.

Roy S., M.M. Montresor, and A. Cembella. 2017. *In press*. Key questions and recent research advances on harmful algal blooms in fjords and coastal embayments. *In* P.M. Glibert, E. Berdalet, M. Burford, G. Pitcher, and M. Zhou (eds.), *Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB)*. Ecological Studies Series, Springer International Publishing AG, Switzerland, Ecological Studies - Analysis and Synthesis Series.

Ruiz-Villarreal, M., L.M. García-García, M. Cobas, P.A. Díaz, and B. Reguera. 2016. Modelling the hydrodynamic conditions associated with *Dinophysis* blooms in Galicia (NW Spain). *Harmful Algae* 53:40-62.

Ryther, J.H., and W.M. Dunstan. 1971. Nitrogen. Phosphorus, and Eutrophication in the Coastal Environment. *Science* 171(3975):1008-1013.

Sandrini, G., X. Ji, J.M.H. Verspagen, R.P. Tann, P.C. Slot, V.M. Luimstra, J.M. Schuurmans, H.C.P. Matthijs, and J. Huisman. 2016. Rapid adaptation of harmful cyanobacteria to rising CO_2. *Proceedings of the National Academy of Sciences* 113:9315-20.

Savela, H., M. Vehniäinen, L. Spoof, S. Nybom, J. Meriluoto, and U. Lamminmäki. 2014. Rapid quantification of mcyB copy numbers on dry chemistry PCR chips and predictability of microcystin concentrations in freshwater environments. *Harmful Algae* 39:280–286.

Selander, E., J. Kubanek, M. Hamberg, M.X. Andersson, G. Cervin, and H. Pavia. 2015. Predator lipids induce paralytic shellfish toxins in bloom-forming algae. *Proceedings of the National Academy of Sciences* 112:6395–400.

Selina, M.S., D.I. Morozova, D.I. Vyshkvartsev, and T.I. Orlova. 2014. Seasonal dynamics and spatial distribution of epiphytic dinoflagellates in Peter the Great Bay (Sea of Japan) with special emphasis on *Ostreopsis* species. *Harmful Algae* 32:1-10.

Skinner, M.P., T.D. Brewer, R. Johnstone, L.E. Fleming, and R.J. Lewis. 2011. Ciguatera fish poisoning in the Pacific Islands (1998 to 2008). *PLoS Neglected Tropical Diseases* 5(12): e1416, *https://doi.org/10.1371/journal.pntd.0001416*.

Smayda, T.J. 2010. Adaptations and selection of harmful and other dinoflagellate species in upwelling systems 1. Morphology and adaptive polymorphism. *Progress in Oceanography* 85:53-70.

Smetacek, V., and Zingone, A. 2013. Green and golden seaweed tides on the rise. *Nature* 504(5):84-88.

Sunda W.G., and K.W. Shertzer. 2014. Positive feedbacks between bottom-up and top-down controls promote the formation and toxicity of ecosystem disruptive algal blooms: A modeling study. *Harmful Algae* 39:342–356.

Tester, P.A., R.L. Feldman, A.W. Nau, S. R. Kibler, and R.W. Litaker. 2010. Ciguatera fish poisoning and sea surface temperatures in the Caribbean Sea and the West Indies. *Toxicon* 56:698-710.

Trainer, V. L., and Yoshida, T. (eds.) 2014. Proceedings of the Workshop on Economic Impacts of Harmful Algal Blooms on Fisheries and Aquaculture. *PICES Scientific Report* No 47, 85 pp.

Turner, A.D., P.S. McNabb, D.T. Harwood, A.I. Selwood, and M.J. Boundy. 2015. Single laboratory validation of a multi-toxin UPLC-HILIC-MS/MS method for quantitation of paralytic shellfish toxins in bivalve shellfish. *Journal of the Analytical and Oficial Association of Chemistry International* 98: 609-621.

Underwood, A.J.. 1992. Beyond BACI: experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Australian Journal of Marine and Freshwater Research* 42:569-587.

Usup, G., M.Y. Cheah, B.K. Rozirwan, C.P. Leaw, M. Othman, and A.L. Fayaz. 2003. Identification of species responsible for harmful algal blooms event in Selat Tebrau in 2002. *Malaysian Applied Biology* 32:59-62.

Van de Waal, D.B., U. Tillmann, H. Martens, B. Krock, Y. van Scheppingen, and U. John. 2014. Characterization of multiple isolates from an *Alexandrium ostenfledii* bloom in The Netherlands. *Harmful Algae* 49:94-104.

Vanucci, S., L. Pezzolesi, R. Pistocchi, P. Ciminiello, C. Dell'Aversano, E. Dello Iacovo, E. Fattorusso, L. Tartaglione, and F. Guerrini. 2012. Nitrogen and phosphorus limitation effects on cell growth, biovolume, and toxin production in *Ostreopsis* cf. *ovata*. *Harmful Algae* 15:78-90.

Vila, M., R. Abós-Herràndiz, J. Isern-Fontanet, J. Àlvarez, and E. Berdalet. 2016. Establishing the link between *Ostreopsis* cf. *ovata* blooms and human health impacts using ecology and epidemiology. *Scientia Marina* 80S1:107-115.

Wagoner, R.M.V., J.R. Deeds, M. Satake, A.A. Ribeiro, A.R. Place, J.L.C. Wright. 2008. Isolation and characterization of karlotoxin 1, a new amphipathic toxin from *Karlodinium veneficum. Tetrahedron Letters* 49:6457-6461.

Wells, M.L., V.L. Trainer, T.J. Smayda, B.S.O. Karlson, C.G. Trick, R.M. Kudela, A. Ishikawa, S. Bernard, A. Wulff, D.M. Anderson, and W.P. Cochlan. 2015. Harmful algal blooms and climate change: learning from the past and present to forecast the future. *Harmful Algae* 49:68-93.

Yogi, K., N. Oshiro, Y. Inafuku, M. Hirama, and T. Yasumoto. 2011. Detailed LC-MS/MS analysis of ciguatoxins revealing distinct regional and species characteristics in fish and causative algae from the Pacific. *Analytical Chemistry* 83:8886-8891.

Zhang, H., D. Bhattacharya, L. Maranda, and S. Lin. 2008. Mitochondrial cob and cox1 genes and editing of the corresponding mRNAs in *Dinophysis acuminata* from Narraganset Bay, with special reference to the phylogenetic position of the genus *Dinophysis*. Applied Environmental Microbiology 74:1546–1554.

Zettler, E.R., T.J. Mincer, and L.A. Amaral-Zettler. 2013. Life in the "Plastisphere": microbial communities on plastic marine debris. *Environmental Science and Technology* 47(13):7137.

Governance and Members of the GlobalHAB SSC (2016-2018)

The first GlobalHAB SSC is composed by:

Elisa Berdalet (Chair)	Spain
Neil Banas	UK
Michele Burford	Australia
Chris Gobler	USA
Bengt Karlson	Sweden
Raphael Kudela (Vice-chair)	USA
Po Teen Lim	Malaysia
Lincoln Mackenzie	New Zealand
Marina Montresor	Italy
Kedong Yin	China

Ex-officio

Keith Davidson	UK

Liaisons with international entities

Eileen Bresnan	ICES-WGHABD
Gires Usup	IPHAB
Vera Trainer	PICES and ISSHA
Raphael Kudela	GOOS Biology and Ecosystems Panel

Sponsors Representatives

Henrik Enevoldsen	IOC-UNESCO
Ed Urban	SCOR

At the inception of the programme the members of the GlobalHAB SSC covered the scientific expertise necessary to address the different topics identified at the OSM in Paris to be included in GlobalHAB, and allowed the links with other international entities.

Invitation to Participate. Endorsement Procedure

The international community is invited to participate in the GlobalHAB programme, through seeking endorsement of relevant research, monitoring, and modeling activities

Procedures and criterion for obtaining GlobalHAB endorsement of science activities

GlobalHAB will provide an international structure for planning and coordinating international scientific activities related to HABs in aquatic environments and their effects on the environment, and human health and well-being. In addition, GlobalHAB will help provide a framework for national and regional projects to (1) coordinate their activities and, (2) participate in coordinated initiatives of research, observations, and modeling on HABs.

Scientists are invited to participate in GlobalHAB by designing scientific activities in keeping with the goals and objectives of GlobalHAB, by applying for endorsement of such activities, and by participating in framework activities.

The GlobalHAB SSC may endorse already funded projects, project proposals before these are submitted for funding, or even letters of intent. The primary criterion for endorsement is applicability to any of the GlobalHAB Science Plan objectives. Requests for endorsement are initiated by submission of the accompanying application form, emailed to the Chair of the GlobalHAB SSC. GlobalHAB SSC members will comment on the application within ten working days. The GlobalHAB chair (or vice-chair, if the chair is unavailable) will then assess the comments and make a decision about endorsement. The applicant will be notified no later than three weeks after submission of the request. Notification will be in the form of an official letter on GlobalHAB letterhead, sent via email and followed up with original signed printed copy.

Benefits

Researchers that participate in international GlobalHAB will receive the following benefits from their association with the programme:

- GlobalHAB will provide the justification and resources for international standardization and intercalibrations of sampling methods, observations, modeling, and toxins quantification worldwide.
- GlobalHAB will assist the efforts of PIs and agencies to secure funding via letters of support and endorsement for research proposals and initiatives.
- GlobalHAB will support the communication and knowledge on HABs to the public, managers, and policymakers.
- GlobalHAB will facilitate establishment of links with other relevant international programmes and related projects also endorsed by GlobalHAB.
- GlobalHAB will facilitate dissemination of project information through newsletters, web site and other communication mechanisms.

Responsibilities

- Communication of project progress with the GlobalHAB SSC for inclusion in the newsletters, web sites and other communication mechanisms.
- Acknowledgement of endorsement by GlobalHAB in scientific publications, and provision of copies of scientific publications for listing as GlobalHAB Programme outputs.

GlobalHAB Application Form for Endorsement of Activities

To be completed in English and sent to the Chair of the GlobalHAB SSC.
For further guidance consult the Chair and/or Vice-chair of the GlobalHAB SSC.

Date:

1. PROJECT TITLE:

Planned duration of activity, from: to:

2. APPLICANT(S):
Name and title:
Address:
Tel/Fax: E-mail:
Home page URL (if applicable):
Other key persons (name, title and institution):

3. PROJECT DESCRIPTION:
Attach brief summary or abstract. One page is sufficient; no more than five pages please.

Project web site (if applicable):
Data management contact (web site and/or contact person, if applicable):

4. BENEFITS FROM GlobalHAB:
Please comment on a) how the activity could benefit from endorsement by GlobalHAB, and b) how the SSC might assist the activity:

5. CONTRIBUTION TO THE GlobalHAB SCIENTIFIC OBJECTIVES AND TOPICS
Indicate how the project contributes to the Implementation of the Objectives of GlobalHAB.

6. LINKAGES WITH OTHER PROGRAMMES:
Is the project part of a National Programme?
Yes: ____No: ____ If yes, give title:

Is the activity part of, coordinated with, or affiliated with, other international/regional programmes?
Yes: ___ No. ____ If yes, give programme title:

7. FUNDING
Has funding been obtained?
Yes: No: (Prospective) source(s):

8. APPENDICES
Feel free to attach any relevant additional materials, such as an illustration (graphic/map) to accompany the description of the project on the GlobalHAB web site.

A cyanobacteria bloom in the Baltic Sea 27 July, 2008. Photo by the Swedish coast guard.