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(of UNESCO)

Thirteenth Session of the IOC Intergovernmental Panel on Harmful Algal Blooms

SCOR-IOC GlobalHAB program Progress Report 2015-2017

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Progress Report 2015-2017

I. *In response to Decision IPHAB-XII.1. HABs in a Changing World: A Global Approach to HAB Research to Meet Societal Needs, GlobalHAB*

The Mission and Terms of Reference of the new programme GlobalHAB, developed by the GEOHAB SSC, were already presented at the IPXAB-XII. Raphe Kudela and Elisa Berdalet served as executives of the new GlobalHAB SSC, and in coordination with Henrik Enevoldsen and Ed Urban (representing IOC and SCOR, respectively) worked on the list of potential members of the new SSC covering the different areas of expertise required for implementation of the programme, taking into account gender and geographic representation. The list was proposed at the SCOR Annual General Meeting in Goa, December 2015 and approved. The GlobalHAB programme was launched in January 2016. The activities conducted by the GlobalHAB SSC during 2015 to 2017 are briefly presented next.

I.1. March 8-10, 2016. First meeting of the GlobalHAB Scientific Steering Committee.

The GlobalHAB Scientific Steering Committee (SSC) held its first meeting at the Scottish Association for Ocean Sciences (SAMS) in Oban (Scotland, UK) on March 8-10, 2016. The SSC is constituted by Elisa Berdalet (Chair, Spain), Raphael Kudela (Vice-chair, USA), Neil Banas (UK), Michele Burford (Australia), Chris Gobler (USA), Bengt Karlson (Sweden), Po Teen Lim (Malaysia), Lincoln Mackenzie (New Zealand), Marina Montresor (Italy), and Kedong Yin (China). The SSC includes liaisons from the International Council for the Exploration of the Sea (ICES) Working Group on Harmful Algal Bloom Dynamics (WGHABD, Eileen Bresnan), the IOC International Panel on Harmful Algal Blooms (IPHAB, Gires Usup), the North Pacific Marine Science Organization (PICES, Vera Trainer) HAB Section, the International Society for the Study of Harmful Algae (ISSHA, Vera Trainer), the GOOS Biology and Ecosystems Panel (Raphe Kudela) and representatives of the sponsoring organizations, Henrik Enevoldsen from IOC and Ed Urban from SCOR.

The main objective of this meeting was to design the general plan of the program over the next decade and to map out specific activities for the next three years. In particular, the meeting focused on the definition of the Mission and Goals of GlobalHAB, the development of a *GlobalHAB Science and Implementation Plan*, the identification of approaches for collaboration with other international entities, and addressing logistic and structural questions of the programme. The main outcomes of the meeting are summarized below.

1.a. GlobalHAB Goal and Mission statements

GOAL: To improve understanding, prediction, management and mitigation of HABs in aquatic ecosystems.

MISSION: GlobalHAB will

- Address the scientific and societal challenges of HABs, including the environmental, human health and economic impacts, in a rapidly changing world.
- Consolidate linkages with broader scientific fields and other regional and international initiatives relevant to HABs.
- Foster the development and adoption of advanced 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.

1.b. Science and Implementation Plans

The Scientific Plan (SP) of GlobalHAB follows the legacy of the former GEOHAB programme, but will incorporate new themes. It will be augmented by a new Implementation Plan (IP) for the coming 10 years. The international scientific community at the GEOHAB Open Science Meeting (OSM) in Paris, April 2013 (GEOHAB 2014), recommended this approach.

During the meeting in Oban, the GlobalHAB SSC members analyzed the Programme Elements that structured GEOHAB to identify the relevant aspects still valid for GlobalHAB, as well as the new themes identified at the OSM in 2013. Before the meeting, several documents were developed by GlobalHAB SSC members in order to facilitate the meeting discussions.

It was decided to carry forward the 5 GEOHAB Program Elements (Biodiversity and Biogeography; Eutrophication; Adaptive Strategies; Comparative Approach; Modeling, Observation and Prediction) and to define new Topics: Benthic HABs; HABs in Freshwater Systems and cyanobacterial HABs; Toxins; HABs and Aquaculture; Health; Economy; and Climate Change. Based on the GEOHAB SP, the addendum will be more synthetic and merged with the new Implementation Plan in a single 20-25-page document.

1.c. Collaboration with other international bodies

Several Terms of Reference of GlobalHAB (presented at the SCOR Annual Meeting in 2014 and the 2015 XII Session IOC/IPHAB) specify the essential link of GlobalHAB with other international entities that have HABs among their scientific research interests (Figure 1). At the first GlobalHAB SSC meeting, some of these entities (GEO/Blue Planet, GOOS/EuroGOOS, IAEA, ICES, IOCCG, IPHAB, ISSHA, PICES) were already represented by their liaisons that indicated possible collaborations.

After the meeting, the SSC has been working on the elaboration of the *Science and Implementation Plan of GlobalHAB*. Draft versions of the Plan were presented at SCOR and during the ICHA meeting (see next). In January 2017, the first complete draft of the Plan was sent for evaluation by a 9 experts external panel. In parallel the SSC has worked on the development of the webpage (to be active in mid 2017 at www.globalhab.info).

I.2. September 5-7, 2016. Presentation of the GlobalHAB program at the SCOR Annual General Meeting in Sopot, Poland

Elisa Berdalet attended this meeting and acknowledged financial and logistic support from SCOR. In this meeting, the first draft of the *Science and Implementation Plan of GlobalHAB* was presented. It was very well received by the SCOR Annual Meeting.

I.3. October 12, 2016. Presentation of the GlobalHAB program at the Town Hall held within the International Conference on Harmful Algae, Florianópolis, Brazil.

This venue (http://icha2016.com/about/), with attendance of most members of the GlobalHAB SSC, allowed formally initiate GlobalHAB and invite the international community to actively participate in the programme. A Town Hall session devoted to GlobalHAB was held in October 12, 2016, announced also in Harmful Algal News N. 53. The draft of the *Science and Implementation Plan of GlobalHAB* and the preliminary webpage setup were presented. The meeting facilitated a fluent communication with the international community studying HABs and some implementation initiatives were presented and discussed by the attendants.

I.4. March 28-30, 2017. Second meeting of the GlobalHAB Scientific Steering Committee.

The GlobalHAB SSC held its second meeting at the Stazione Zoologica di Napoli (SZN) in Naples (Italy) on March 28-30, 2017. A main objective of this meeting was to elaborate the final version of the *Science and Implementation Plan of GlobalHAB* taking into consideration the evaluation by an external panel. The SSC thanks the panel that provided relevant contributions for improving the *Plan*. The conceptual scheme of the Themes addressed in GlobalHAB is presented in Figure 1.

A summary of the objectives of the different Themes to be covered by GlobalHAB and some of the implementation activities are presented in Annex I.

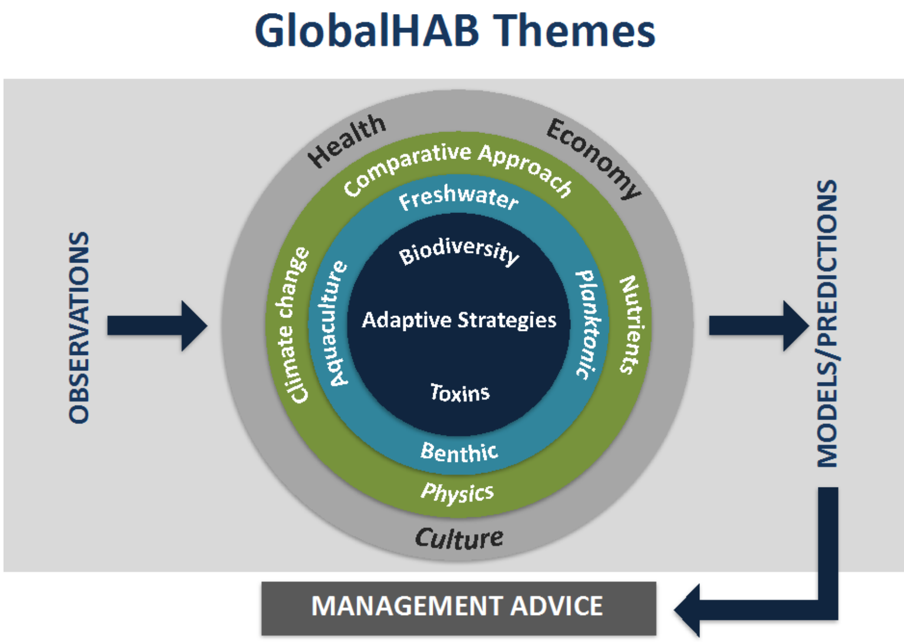

Figure 1. Themes integrated in GlobalHAB. Note that the terms "Physics", "Planktonic" and "Culture" refer to general aspects developed within the different Themes, and are included in the scheme to emphasize the multidisciplinary aspects integrated in GlobalHAB.

I.5. Presentation of GlobalHAB at different national and international events.
Information about the program has been provided by:

- E. Berdalet at OCEANEXT: Interdisciplinary Conference, Nantes, France, 8-10 June, 2016; "Multidisciplinary and coordinating initiatives to prevent and mitigate the impacts of HABs".

- P. T. Lim at the WESTPAC workshop on the development of a research strategy for HABs, Institute of Oceanography, Nha Trang, Vietnam, 19-21 Dec 2016, and at the IOC WESTPAC-HAB Workshop, 10th IOC WESTPAC Conference in QingDao, China, from 17-20 April 2017.

II. Funding considerations/future funding plans/Donors

The scientific meetings of the SSC have been funded by IOC/UNESCO and SCOR (with funding from the U.S. National Science Foundation), and by in-kind contributions from ICES, PICES and IPHAB.

III. Future work-plan and budget for 2017-2019

Some of the activities to be conducted in the 2017-2019 period include:

1) Review paper to identify the knowledge gain and existing gaps on the biogeography and biodiversity of selected taxa. Leader: M. Montresor.

2) Session on HAB biogeography at the 18th International Conference on Harmful Algae (ICHA), Nantes (France) 2018. In collaboration with ISSHA and ICHA organizers. Contact person: M. Montresor.

3) 3) Coordination with the IPHAB Task Team to implement the multi-agency IOC-IAEA-FAO- WHO "Global Ciguatera Strategy". Nexus persons: E: Berdalet, H. Enevoldsen. Contact people: P. Hess, M. Chinain, P. Tester and Marie-Yasmine Dechraoui Bottein (IAEA)..

4) Workshop about the mode of action of fish-killing microalgae (and other related issues), in coordination with the Task team on "Fish-killing HABs". Contact person: A. Cembella, P.J. Hansen.

5) Endorsement of the inter-laboratory validation study on mass spectrometry methods of PSP-toxin analysis. Leader: L. Mackenzie, CEFAS-Cawthron activity.

6) Special issue on "Harmful Algae and Climate Change", in *Harmful Algae*, by 2019.

7) Good-practices manual. Nexus person: E: Berdalet. Leader: M. Wells.

8) Co-organization and participation in the activities of the IOC GO2NE network. Nexus: R. Kudela. Leader: G. Pitcher.

9) Establish a Working Group on Macroalgal Blooms (*Sargassum, Ulva*). Contact people: C. Gobler, K. Yin. Leader: B. Lapointe.

10) Development of the GOOS Phytoplankton EOV (Essential Ocean Variable), which includes HABs,
http://goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114.
Contact person: R. Kudela

IV. Follow up on GEOHAB Synthesis Products

At the official end of GEOHAB, some synthesis products were still in progress and GlobalHAB has taken responsibility to see them completed. These products include the following:

IV.1. Scientific summary for policy makers

R.M. Kudela, **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, Ed Urban. (2015) *Harmful Algal Blooms - A scientific summary for policy makers.* IOC/UNESCO, Paris IOC/INF-1320
http://www.unesco.org/new/en/media-services/single-view/news/new_publication_on_harmful_algal_blooms_for_policy_makers/#.VfSqDngdzsI.

IV.2. A special issue published in *Oceanography* magazine (The Oceanographic Society)
Volume 30, March 2017: https://tos.org/oceanography/issue/volume-30-issue-01
Title: ***International Cooperation in Harmful Algal Blooms Science***
Guest Editors: Raphael Kudela, Henrik Enevoldsen and Ed Urban
Sponsors: Grant OCE-1243377 from the U.S. National Science Foundation to the Scientific Committee on Oceanic Research for GEOHAB activities; the Intergovernmental Oceanographic Commission of UNESCO; and the University of Copenhagen. Additional funds were provided by the Ida Benson Lynn Endowment, University of California Santa Cruz.

Papers:
GEOHAB–The Global Ecology and Oceanography of Harmful Algal Blooms Program: Motivation, Goals, and Legacy
Kudela, R.M., E. Berdalet, H. Enevoldsen, G. Pitcher, R. Raine, and E. Urban. 2017. GEOHAB–The Global Ecology and Oceanography of Harmful Algal Blooms Program: Motivation, goals, and legacy. *Oceanography* 30(1):12–21, https://doi.org/10.5670/oceanog.2017.106.

Harmful Algal Blooms in Eastern Boundary Upwelling Systems: A GEOHAB Core Research Project
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(1):22–35, https://doi.org/10.5670/oceanog.2017.107.

Harmful Algal Blooms in Benthic Systems: Recent Progress and Future Research
Berdalet, E., P.A. Tester, M. Chinain, S. Fraga, R. Lemée, W. Litaker, A. Penna, G. Usup, M. Vila, and A. Zingone. 2017. Harmful algal blooms in benthic systems: Recent progress and future research. *Oceanography* 30(1):36–45, https://doi.org/10.5670/oceanog.2017.108.

Harmful Algal Blooms in Fjords, Coastal Embayments, and Stratified Systems: Recent Progress and Future Research
Berdalet, E., M. Montresor, B. Reguera, S. Roy, H. Yamazaki, A. Cembella, and R. Raine. 2017. Harmful algal blooms in fjords, coastal embayments, and stratified systems: Recent progress and future research. *Oceanography* 30(1):46–57, https://doi.org/10.5670/oceanog.2017.109.

Globally Changing Nutrient Loads and Harmful Algal Blooms: Recent Advances, New Paradigms, and Continuing Challenges
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(1):58–69, https://doi.org/10.5670/oceanog.2017.110.

GlobalHAB: A New Program to Promote International Research, Observations, and Modeling of Harmful Algal Blooms in Aquatic Systems
Berdalet, E., R. Kudela, E. Urban, H. Enevoldsen, N.S. Banas, E. Bresnan, M. Burford, K. Davidson, C.J. Gobler, B. Karlson, P.T. Lim, L. Mackenzie, M. Montresor, V.L. Trainer, G. Usup, and K. Yin. 2017. GlobalHAB: A new program to promote international research, observations, and modeling of harmful algal blooms in aquatic systems. *Oceanography* 30(1):70–81, https://doi.org/10.5670/oceanog.2017.111.

IV.3. A monograph on the application of Ocean Colour satellite techniques for the study of HABs. It is planned for publication in the *IOCCG Report* series. This book is the result of the collaboration between GEOHAB and the International Ocean Colour Coordination Group

(IOCCG), with Steward Bernard, Raphael Kudela and Grant Picher as editors. The document will be structured around several representative case studies of HABs. Expected publication in 2017.

IV.4. A book published by Elsevier, under their *Ecological Studies* series.

Editors: Pat Glibert, Elisa Berdalet, Michele Burford, Grant Pitcher and Mingjiang Zhou.
Expected date of publication: Mid 2017 (to be send to the published on May 2017).
Chapters (updated list on March 2017):

	Chapter title	Authors
1	Preface	Glibert, Berdalet, Burford, Pitcher, Zhou
2	Harmful Algal Blooms: What they are, why they are harmful, where they are occurring, and the importance of understanding their ecology and oceanography	Glibert, Berdalet, Burford, Pitcher, Zhou
3	Introduction to the GEOHAB Program	Kudela, Berdalet, Enevoldsen, Pitcher, Raine, Urban
4	Harmful algal bloom expansion in concert with a sea of other global changes	Glibert et al.
5	Harmful algal blooms in a changing ocean	Wells and Karlson
6	The role of life cycle characteristics on harmful algal bloom dynamics	Azanza, Brosnahan, Anderson, Hense, Montresor
7	Mixotrophy in HABs: Who, When, Why, Web interactions, and What Next	Flynn, Mitra, Glibert, Burkholder
8	Nutrients and HABs: Resource availability, substrate ratios, dynamic kinetics and flexible nutrition	Glibert, Heil, Wilkerson, Dugdale
9	Key questions and recent advances on HABs in upwelling systems	Pitcher, Figueiras, Kudela, Moita, Reguera, Ruiz-Villareal
10	Key questions and recent advances on HABs in eutrophic systems	Glibert, Allen, Bouwman, Burford, Zhou
11	Key questions and recent advances on HABs in fjords and coastal embayments	Roy, Montresor And Cembella
12	Key questions and recent advances on HABs in stratified systems	Berdalet, Reguera, Yamazaki, Jenkinson, Raine
13	Key questions and recent advances on HABs in benthic systems	Berdalet and Tester
14	Overview of harmful algal blooms in Asia	Furuya, Iwataki, Lim,Lu, Azanza, Kim, Fukuyo
15	Harmful algal blooms in the coastal waters of China	Yu, Lu, And Liang
16	Green tides of the Yellow Sea: massive free-floating blooms of *Ulva prolifera*	Dongyan Liu, Mingjiang Zhou
17	*Noctiluca* blooms in the Arabian Sea and Gulf of Thailand	Goes et al.
18	Recent Advances in Modeling of Harmful Algal Blooms	Peter J.S. Franks
19	Advancements in observing systems, instrumentation and operational tools for HABs	Glibert et al.
20	Emerging HAB research issues in freshwater environments	Burford, Hamilton, Wood
21	Mitigation and Control of HABs	Zhiming Yu, Xiuxian Song, Xihua Cao, Yang Liu
22	GlobalHAB	Berdalet, Kudela, Urban, Enevoldsen, Banas, Bresnan, Burford, Davidson, Gobler, Karlson, Lim, Mackenzie, Montresor, Trainer, Usup, Yin

Annex I. Brief presentation of the Themes included in GlobalHAB. Extract of Berdalet et al. *in press.* In *Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB)*, Glibert PM, Berdalet E, Burford M, Pitcher G, Zhou M (eds) Ecological Studies Series, Springer.

1. Biodiversity and Biogeography—The overall objective of this Theme is to identify the factors that determine the changing biogeographical distribution of HAB species (including potential trends associated with climate change), their genetic variability, and the biodiversity of HAB-associated communities, including diversity of toxins. Understanding the biodiversity and biogeography of harmful organisms and their toxins is fundamental to identify trends in HAB occurrence, enable their prediction, and design management and, when possible, mitigate their impacts.

Correct taxonomic identification of harmful species is crucial to achieve this objective. New molecular technologies with progressively reduced cost (e.g., qPCR, fluorescent *in situ* hybridization, High Throughput Sequencing, HTS) are helping to refine species descriptions and to identify cryptic and pseudo-cryptic diversity among HAB species formerly defined based on morphological characters (Lelong et al. 2012; Kremp et al. 2014). In this sense, a priority is educating a future generation of taxonomists worldwide who will bridge the morphological and molecular identification techniques. Other related challenges are establishing reference sequences to interpret molecular data and achieve identification at the species level, and defining standardized protocols for physiological investigations (including e.g., toxin composition, physiology, life cycle).

To implement the objectives for this theme, GlobalHAB will collaborate with other projects and organizations to maintain and reinforce taxonomic training initiatives for the identification of microalgae, and support the establishment of a database for reference sequences of HAB species. Furthermore, GlobalHAB will align with the Global HAB Status Report and HAEDAT-HABMAP initiatives, to create a baseline of biogeographic species distribution and will support long time series, such as the ones considered within the recently finished "Phytoplankton Time Series and Ocean Observing sites" (SCOR WG 137 http://wg137.net/time-series/time-series-map) and the new IOC WG TrendsPO, where biological data are collected.

2. Adaptive Strategies— The overall objective of this Theme is to determine the adaptations of HAB species and how these adaptations help to explain their proliferation or harmful effects. Detecting unique characteristics and adaptations of HAB species in particular environments will contribute to the development of predictive models.

Under GEOHAB, significant effort was devoted to identifying harmful species uniquely associated with particular habitats. However, cosmopolitan rather than unique species thrive in upwelling systems (Smayda 2010a,b) and no unique taxa have been identified in fjords and coastal embayments (Roy et al. 2017). The only habitat-specific example identified was the pelagophytes *Aureococcus* and *Aureoumbra* that cause persistent brown tides in coastal eutrophied embayments (Gobler and Sunda 2012).

Still, it is likely that particular adaptive strategies play a role in the dynamics of harmful blooms. Understanding and characterizing these strategies in detail and, if possible, parameterizing the involved processes (especially under natural conditions), are main challenges to understand and predict HAB events. Examples include dinoflagellate life history strategies (e.g., encystment and excystment processes, sexual reproduction, vertical migration), which may explain the recurrence of the blooms in certain areas (see Azanza et al. 2017 for a review); the production of allelopathic compounds (biologically active compounds that elicit specific responses in competitors or predators, e.g., Ianora et al. 2011, Selander et al. 2015), and intrinsic chemical or life-form defenses against parasites (viruses, protists; e.g., Chambouvet et al. 2008), which can provide competitive advantages under certain conditions. In the case of cyanobacteria, buoyancy regulation to access light and nutrients, cyst formation under adverse conditions, superior nutrient scavenging physiology, genetic variability among strains within populations and over time, capacity to fix atmospheric nitrogen and synthesize secondary metabolites (O'Neil et al. 2012) appear as some of the particular adaptive strategies used by organisms in this group. Finally, the intrinsic capacity of attaching to surfaces (including plastics, e.g., Masó et al. 2003) exhibited by benthic dinoflagellates and macrophytes, potentially constituting a major adaptive mechanism to colonize and disperse into new habitats, requires further investigation.

Some of these adaptive strategies can be strain- and species-specific, and may make it difficult to establish general models. However, trait-based approaches (i.e., identification of common traits across HAB species) would facilitate integration of the outcomes from this Theme into new modeling approaches. The new *in situ* observation technologies and cutting-edge methodologies (metabolomics, proteomics, etc.) offer new possibilities for progress.

***3. HAB Toxins*—**The overall objective of this Theme is 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. Toxins are a cross-cutting subject and a common concern through all the GlobalHAB research topics.

To obtain better understanding of toxin biosynthesis pathways and the genes involved constitutes a fundamental challenge. Knowledge of the genetic basis of toxin production could reveal the existence of suitable target genes for the identification of toxic species. Furthermore, a better comprehension of environmental controls of toxin production is necessary for better prediction of the probable impact of changes in marine habitats on the toxicity of HAB species. Significant progress on the environmental controls on paralytic shellfish-poisoning (PSP) toxin (saxitoxins) synthesis (see review in Krüger et al. 2010) stimulates analogous research on other phycotoxins such as domoic acid (e.g., Jeffery et al. 2004), ciguatoxins, okadaic acid, and emerging toxins.

Identifying and characterizing the modes of action of fish-killing microalgal toxins—such as the ones produced by *Cochlodinium polykrikoides, Chattonella* spp., *Heterosigma akashiwo,* and *Karlodinium australe* (e.g. Black et al. 1991; Van Wagoner et al. 2008; Lim et al. 2014) and of other cytotoxic species affecting other cultured marine organisms (e.g., shrimp)—is still a challenging issue. This information is particularly relevant for development of effective strategies to protect the marine aquaculture industry from massive mortality episodes of farmed seafood products caused by microalgal blooms. Emerging toxins in marine and freshwater environments will require similar approaches.

Sustainability of marine aquaculture (as explained below) and the protection of public health and food security also require sensitive, accurate, fast and cost-effective means of microalgal toxin detection and analysis. Recent advances in analytical techniques, and cell-based and functional assays, are contributing to this progress (e.g., Yogi et al. 2011; Turner et al. 2015). However, official and reliable regulatory methods that are used for human health protection are still not available for routine analysis of some toxins, with ciguatoxin being the most notable. The role of different (marine and freshwater) toxin analogues and their bio-stability also require further attention (Pearson et al. 2016).

Within this theme GlobalHAB will foster, for instance, workshops focused on the genetic and environmental basis of toxicity (especially focused on domoic acid and PSP), and the mode of action of fish-killing phycotoxins, and will endorse inter-laboratory toxin analysis method validation, such as the ongoing validation for the Paralytic Shellfish Poisoning (PSP) toxin methods.

4. Nutrients and Eutrophication— This Theme continues to focus on the links between nutrient supply, eutrophication and on the occurrence of HABs. Nutrient pollution, typically driving eutrophication, is often considered to be a main driver responsible for the increased number of high-biomass HABs in marine, brackish and fresh waters (Paerl et al. 2001, Heisler et al. 2008). Important advances were achieved by GEOHAB on this research topic (see Glibert and Burford 2017, Glibert et al. 2017), which contributed, for instance, to the implementation of policies limiting nutrient (N and P) inputs and proved useful to prevent HABs in certain coastal and freshwater areas. However, the relationship between nutrient pollution and HABs is more complex than previously thought.

New challenges include understanding the role of organic nutrient availability and ratios on some HAB events, as well as in the modulation of HAB toxin production (Glibert and Burford 2017), and unveiling the mixotrophic capacities of HAB species (Burkholder et al. 2008). Furthermore, modifications in nutrient supply to aquatic systems may accompany climate change and other anthropogenic forcing factors. These questions are fundamental for both planktonic (e.g., *Pseudo-nitzschia*, *Alexandrium*) and benthic (e.g., *Gambierdiscus*, *Ostreopsis*) HAB taxa, macroalgal (e.g., *Sargassum*, *Enteromorpha*) blooms, and harmful freshwater and cyanobacteria species. GlobalHAB will also investigate the links of aquaculture-related nutrients and HAB occurrence and toxicity, and deoxygenation and anoxia processes resulting from high-biomass HABs.

5. HABs in freshwater systems and Cyanobacterial HABs (cyanoHABs)—The overall objective of this Theme is to develop a global perspective on the science and management of freshwater HABs, and cyanobacterial HABs in marine, brackish, and freshwater habitats.

Some eukaryotic groups and a range of cyanobacterial species (cyanoHABs, including *Microcystis*, *Cylindrospermopsis*, *Dolichospermum*, *Aphanizomenon*, *Planktothrix*, *Lyngbya*, *Phormidium*) are responsible for harmful events in freshwater systems and brackish areas (e.g., *Nodularia* in the Baltic Sea). In marine ecosystems, toxic filamentous cyanobacteria such as *Lyngbya* and *Moorea* have been more recently associated with harmful proliferation in tropical regions. Overall, these species produce a wide range of toxins, including microcystins, cylindrospermopsins, anatoxins, nodularins, saxitoxins, aplysiatoxins and lyngbyatoxins.

HABs in freshwater systems (especially drinking water reservoirs) and cyanoHABs have major economic, social, and environmental impacts, with millions of dollars spent annually testing water supplies and mitigating cyanoHAB effects (Hamilton et al. 2014). Under global warming scenarios, these events are expected to increase, although the picture is still not clear. In addition to fostering research to clarify potential trends (in coordination with activities to implement Theme 12), GlobalHAB's distinctive role on this Theme will be to bridge the gap between freshwater and marine HAB researchers to share knowledge, techniques, and approaches and to facilitate more effective communication between HAB scientists and policymakers internationally. A final aim will be to determine the current state of knowledge and potential approaches to managing, mitigating, and predicting cyanoHABs in freshwater, brackish, and marine habitats. Cross-cutting objectives concerning specific adaptive strategies of cyanoHAB species, genetic and environmental control of toxin production, modulation of the events by nutrient availability, and modeling (see review by Burford et al. 2017) are also included in this Theme and will take into account the activities to implement the Themes described in subsections 2, 3, 4 and 9.

6. HABs and Marine Aquaculture—The objectives of this Theme are to determine the links between marine aquaculture and HAB occurrence and to find efficient methods to protect farmed seafood products from HAB impacts in different regions.

Aquaculture of shellfish and finfish has many benefits, including the creation of nutritious high-protein food, reducing the pressure on natural resources and supporting sustainable economic development and employment. Unfortunately, contamination of seafood by phycotoxins and mass mortalities of cultured animals caused by harmful microalgae (raphidophytes, dictyochophytes, haptophytes, dinoflagellates) have devastating impacts on aquaculture operations in certain areas. Improved awareness and identification of HAB events have coincided with increases in aquaculture development, raising concern about the direct implication of aquaculture on the (increased) incidence and intensity of HABs (Price et al. 2015). Through focused studies and improved observational methods, this Theme will seek to provide fresh perspectives for assessing the potential effects of nutrients, shifting nutrient ratios, organic matter, and fish/shellfish transfer from aquaculture activities on the promotion of HABs in different areas of the planet. Progress in modelling (hydrodynamic and coupled biogeochemical models) and technology can notably contribute to improve early warning and mitigation methods, appropriately designed to the specific aquaculture sites.

On another hand, there is a need to find efficient methods to protect farmed seafood products from HAB impacts. Basic research issues include clarification of the deleterious effects of some fish-killing algae (as indicated in Theme 3), as well as other emergent toxins and mechanisms of harm in cultured seafood (e.g., Borcier et al. 2017), the ecophysiology and ecology of fish-killing algae, and the global extent of these blooms. Advances in technology (e.g., high-tech, autonomous, *in situ* molecular and imaging flow cytometry methods) are offering new possibilities for early warning and real-time sensing of impending blooms, although some refinement and field trials are still required. In turn, detection of organisms and toxins in waters and shellfish through rapid test kits is becoming more feasible, expected to cover wider range of targets, and to be validated in the near future.

GlobalHAB will endorse and seek to promote activities in this important field of both fundamental and applied research to provide reliable, mature, cost-effective solutions for the prevention and mitigation of the impacts of HABs on aquaculture.

7. Benthic HABs (BHABs)—The overall objective of this Theme is 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. This Theme is a direct continuation of the GEOHAB CRP on HABs in Benthic Systems (GEOHAB 2012) established in response to more frequent events and geographic expansion of BHABs, especially those caused by the toxic benthic dinoflagellate genera, *Gambierdiscus* and *Ostreopsis*. Ciguatoxins produced by *Gambierdiscus* species are bioaccumulated in reef fish, causing ciguatera fish poisoning (CFP) in humans when eaten. CFP, the most frequent HAB-related illness in the world, often with significant long-term health effects (Friedman et al. 2017), is endemic in tropical areas and is also expanding to temperate latitudes (e.g., Boada et al. 2010). *Ostreopsis* produces palytoxins and analogues, associated with dramatic seafood intoxications in the tropics. *Ostreopsis* blooms have become more frequent and intense, especially in temperate waters, where some outbreaks have been related to sporadic acute respiratory irritations in humans exposed to marine aerosols and massive benthic faunal damage (see references in Berdalet et al. 2017a, Berdalet and Tester 2017).

The objectives and questions formulated in GEOHAB (2012) are still valid, and significant progress was achieved in a relatively short time (reviewed in Berdalet et al. 2017a), in part due to the cooperative international research and capacity building fostered by GEOHAB.

GlobalHAB will continue the lines of research indicated in GEOHAB (2012) to improve knowledge of the ecology, physiology, and toxin-transfer mechanisms through marine food webs, and to determine fundamental parameters to develop predictive models on BHAB dynamics. This Theme is not only focused on *Gambierdiscus* and *Ostreopsis*, but also on other BHAB taxa as well. The impacts of BHABs in marine organisms and ecosystems, and the modulation of BHAB dynamics by climate change should be investigated as well.

GlobalHAB will be directly involved in regional and international initiatives focused on multidisciplinary research on CFP (including ecology, toxicology, medicine and epidemiology), especially in the most affected tropical and subtropical areas, such as the "Global Ciguatera Strategy" (http://hab.ioc-unesco.org/) adopted by IOC, WHO, IAEA and FAO in 2015 (see also Theme 10). Emphasis will be put in the standardization of sampling methods for BHAB organisms (e.g., Tester et al. 2014; Jauzein et al. 2016; Mangialajo et al. 2017) and to use common databases on organisms' biogeography and harmful events. GlobalHAB will facilitate interactions among public health, social, economy experts, stakeholders, and people directly suffering BHAB impacts, through transdisciplinary meetings (see also 'Health' and 'Economy' Themes).

***8. Comparative Ecosystems*—**The overall objective of this Theme is to determine the extent to which HAB species, their population dynamics, and community interactions respond similarly within comparable ecosystem types. The GEOHAB program adopted the comparative approach (GEOHAB 2001, Anderson et al. 2005), from the cellular to the ecosystem level (namely, in upwelling and stratified systems, embayments and fjords levels) (Trainer et al. 2010; Berdalet et al. 2017b; Kudela et al. 2010a, b; Kudela et al. 2017a, b; Pitcher et al. 2017a, b). This approach is based on the view that the ecology and oceanography of HABs can be best understood through the study of the causative organisms and affected systems in relation to comparable organisms and systems. Improved generalizations about the causes and consequences of HABs would be particularly useful in modeling HABs, and management and mitigation of their effects.

GlobalHAB will also adopt a comparative approach, and extend it to comparisons within marine, brackish and freshwater ecosystem types and, if possible, among the different aquatic systems as well. Case studies where the comparative approach can provide useful insights and progress include comparisons of *Gambierdiscus* dynamics in the main affected areas (the Pacific Ocean and Caribbean Sea); comparison of the dynamics of *Ostreopsis* and *Gambierdiscus* (the main benthic HAB taxa); comparison of the dramatic impacts of *Pseudo-nitzschia* in the eastern, but not the western Pacific (Trainer and Kameneva 2017); or the blooms of *Pseudochattonella* species (Dictyochophyceae) that caused fish mortalities in northern Europe at the end of the 20th Century, as well as in Japan (e.g., Dahl and Tangen 1993; Fukuyo et al. 2003) and more recently in South America (Clement et al. 2016; in this case also followed by exceptional *Alexandrium catenella* blooms, Hernández et al. 2016). By studying conditions leading to blooms at different latitudes and under different environmental conditions, an increased understanding in bloom formation and effects of climate change on cyanobacteria blooms may also be achieved.

The comparative ecosystem approach is expected to be central to many of the GlobalHAB implementation activities. Another key example of implementation is through participation and support of partner efforts, such as the North Pacific Marine Science Organization (PICES) workshops comparing similar HAB species and events from the eastern and western Pacific.

***9. Observation, Modelling, and Prediction*—**The overall objective of this Theme is to improve the detection and prediction of HABs by developing new capabilities in observation and modeling.

Understanding and describing HAB dynamics requires highly resolved observations of biological, chemical, and physical processes that interplay from cell to ecosystem scales. Parametrization of the different processes are fundamental for development and validation of short-term, regional forecasting as well as long-term or large-scale projections of HABs.

Technical progress has favored improved visualization and/or characterization of small (cellular) and fine-scale processes (e.g., thin layers in stratified systems) (see review in Berdalet et al. 2014, 2017b). Examples include the FlowCytobot and the Imaging Flow Cytobot (Campbell et al., 2010; Brosnahan et al., 2015), the underwater long working distance microscope (Jaffe et al. 2013), the fine-scale sampler (FSS) and the high-resolution IFREMER Particle Size Analyzer Profiler (IPSAP) (Lunven et al. 2016); tow-body systems such as Acrobat (SeaSciences; Timmerman et al. 2014) and autonomous underwater vehicles like the MBARI Dorado (Ryan et al. 2010); the free-glidering quasi-horizontal profiler (TurboMAP-G, Foloni-Neto et al. 2014), and the Environmental Sample

Processor (e.g., Greenfield et al. 2008). Furthermore, long-term coordinated and multi-parameter observation systems are valuable tools for early warnings and predictions. Recent examples of projects effectively merging observation and modeling to inform prediction at a regional scale include the ASIMUTH project (Davidson et al. 2016), and the development of predictive models for *Alexandrium* (Anderson et al. 2014) and *Pseudo-nitzschia* (Anderson et al. 2016).

GlobalHAB will follow on GEOHAB (see e.g., HABWATCH 2004, with lectures and tutorials available at http://HABWatch.obs-vlfr.fr; GEOHAB 2011, 2013; Berdalet et al. 2014) co-sponsoring initiatives such as specific technical and modeling workshops. GlobalHAB will also coordinate with the Global Ocean Observing System (GOOS), the International Council for the Exploration of the Sea (ICES), and the International Ocean-Colour Coordination Group (IOCCG) to identify and provide justification for long-term HAB sentinel sites, recently included as an Essential Ocean Variable in GOOS.

10. HABs and Human and Environmental Health—The overall objective of this Theme is to increase collaborations among HAB scientists with medical, veterinary, public health, and social science experts to help minimize the risk of HAB impacts to human and animal health.

In the case of CFP, there is a solid background of medical and public health information, including methods of risk communication (Friedman et al. 2017). In the most affected areas, public health and HAB specialists have begun to establish systems for compiling multidisciplinary environmental and human health data. This is the case both for *One Health Harmful Algal Bloom System* (OHHABS) launched in June 2016 by the U.S. Centers for Disease Control and Prevention (CDC) (http://www.cdc.gov/habs/ohhabs.html), and for the platform at the Institute Louis Malardé (http://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. Importantly, at the international level, the coordinated IOC-IAEA-FAO-WHO "Global Ciguatera Strategy" was adopted in 2015 (http://hab.ioc-unesco.org/) for improved research and management. GlobalHAB has been aligned with this initiative since its inception, actively collaborating with the task team established to implement the strategy.

Furthermore, the need for an integrated understanding of the health and environmental characteristics of the ocean is progressively getting visibility in Europe (e.g., Moore et al. 2013; www.ecehh.org/events/oceans-human-health/) and the United States. This includes HABs at the core of both ocean and human health. Information on HAB-related illnesses in animals and humans, and on certain environmental characteristics of the blooms are collected by OHHABs. Information about HAB-related illnesses is also registered by the CDC through the National Outbreak Reporting System (NORS) (www.cdc.gov/). GlobalHAB will align with these initiatives facilitating, for instance, joint transdisciplinary meetings among HAB and non-HAB specialists.

11. Economy—The overall objective of this Theme is to develop cross-community understanding of the economic impacts of HABs and to define methods and criteria capable of robustly assessing (at both regional and national levels) the economic costs of HABs, the full costs associated with monitoring, predicting, and mitigating HABs, and the economic value of minimizing HAB impacts.

Hoagland et al. (2002) estimated the economic effects of HABs in the United States to be $50 million per year (between 1987 and 1992, at the 2002 value of the dollar). Multiyear losses in farmed fish and shellfish production was estimated as about US$94.0 million for Korea, Japan and China from 2006 to 2012 (Trainer and Yoshida 2014). In Washington State, USA, a year-long closure of the recreational razor clam harvest resulted in almost US$25 million in lost income, including over 400 jobs, as well as lost wages and spending during trips to the coast on hotels, groceries, camping, and restaurants (Dyson and Huppert 2010). 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). However, there is a general consensus that many studies on the negative economic impacts of HABs have employed relatively crude measures and methodologies, the results of which often are difficult to compare (Davidson et al. 2014). Revision of regional estimates with more modern environmental economic methods is required, as are more local evaluations in regions of particular concern or economic value. The economic effects of HABs arise from public health costs, commercial fishery 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. Environmental evaluation of HABs also needs to be extended to ensure that the less tangible benefits of HAB mitigation are included, for example, the value in terms of health and wellbeing of eating seafood and of maintaining sustainable employment in remote regions to foster sustainable development.

This is a complex and transdisciplinary Theme to address. The main contribution of GlobalHAB will be to bring together natural scientists with economists, and to serve as a catalyst for further advances between these communities.

***12. Climate Change and HABs*—**The overall objective of this topic is to understand global patterns in HAB responses to common drivers (thermal windows, stratification, changing levels of CO_2) associated with climate change.

Concern about the potential impacts of long-term climate change on HAB dynamics was already noted in the *GEOHAB Science Plan* (2001). Towards the end of the program, a workshop (Wells et al. 2015) and a symposium (Wells and Trainer 2016; https://pices.int/meetings/international_symposia/2015/2015-HAB/scope.aspx) on HABs were organized in cooperation with ICES, PICES and FORMAS.

Scientific data obtained in the last twenty years suggest that the main factors controlling microalgal populations (surface water temperature, ocean stratification, wind and water circulation patterns, precipitation-linked nutrient inputs, and salinity in marine and brackish waters) are changing in ways that could foster the geographic expansion and increase the impacts of HABs (e.g., Hallegraeff 2010; Wells et al. 2015). Alteration of marine habitats is another global change that is affecting HAB occurrences, and surface water acidification may have a potential influence as well. A fundamental question is whether the environmental windows of opportunity for HAB species are expanding (e.g., Moore et al. 2015), or simply shifting geographically and seasonally.

GlobalHAB has identified different levels of research to address this Theme, from experimental work on climate effects on HAB organisms using laboratory and mesocosms experiments as a base for predictions of climate change effects on HABs, to the development of comprehensive, region-specific studies integrating biological process data with downscaled climate projections. To reach a global comprehension requires adoption of good practices in lab and field approaches to investigate HAB responses to climate-linked drivers (see Wells et al. 2015), a Manual that will be fostered by GlobalHAB.

Interest in this Theme is shared by several international organizations and initiatives as indicated earlier (see Theme 1). For instance, GlobalHAB will work with GOOS to identify the best sites for time-series observations of HABs and related oceanographic parameters (EOVs, essential ocean variables) to track the potential impact of climate change on HABs. GlobalHAB will also cooperate with other international groups (particularly the IOC Global Ocean Oxygen Network, GO_2NE) to investigate ocean deoxygenation in response to climate change and eutrophication, with a specific focus on HABs.

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