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IMBER – Research for marine sustainability: Synthesis and the way forward

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ABSTRACT

The Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project aims at developing a comprehensive understanding of and accurate predictive capacity of ocean responses to accelerating global change and the consequent effects on the Earth system and human society. Understanding the changing ecology and biogeochemistry of marine ecosystems and their sensitivity and resilience to multiple drivers, pressures and stressors is critical to developing responses that will help reduce the vulnerability of marine-dependent human communities. This overview of the IMBER project provides a synthesis of project achievements and highlights the value of collaborative, interdisciplinary, integrated research approaches as developed and implemented through IMBER regional programs, working groups, project-wide activities, national contributions, and external partnerships. A perspective is provided on the way forward for the next 10 years of the IMBER project as the global environmental change research landscape evolves and as new areas of marine research emerge. IMBER science aims to foster collaborative, interdisciplinary and integrated research that addresses key ocean and social science issues and provides the understanding needed to propose innovative societal responses to changing marine systems.

1. Introduction

The marine realm, which includes coastal, continental margin, open ocean, and sea-ice covered systems and their interfaces with the atmosphere, land and ice, is an integral part of the Earth system through climate regulation and the provisioning of living and non-living resources, values and benefits. In the Anthropocene, it is experiencing unprecedented changes related to a complex mix of drivers and stressors that occur over a large range of space and time scales, which in turn affect the human communities that rely on its services and resources. Understanding and assessing both the individual and combined causes and effects of these complex changes at global to local space scales and short to long-term time scales is needed to project and predict future states and ultimately use these to improve options for governance, policy and management.

The recognition of the importance of the role of the ocean in the atmospheric carbon dioxide (CO_2) budget and hence climate change facilitated the development of an international marine biogeochemistry research framework with a focus on the carbon cycle and flux from the surface to the deep ocean. The ensuing research project, the Joint Global Ocean Flux Study (JGOFS, project duration 1987–2003), an International Geosphere-Biosphere Programme (IGBP) and Scientific Committee on Oceanic Research (SCOR) sponsored international ocean carbon project (Hanson et al., 2000; Fasham et al., 2001; Fasham, 2003), was designed to provide integrated and quantitative understanding and assessment of the biogeochemical

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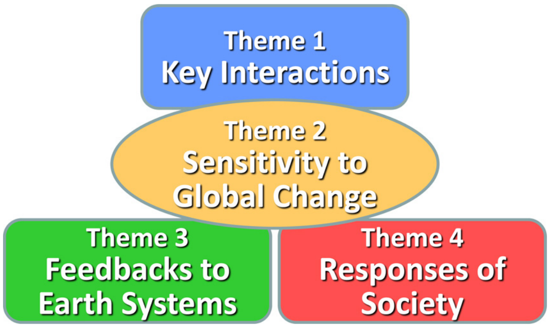

Fig. 1. Schematic of the four themes underpinning IMBER science. Details and rationale for each theme are given in IMBER (2005) and key results from each are highlighted in the text.

fluxes of carbon in the ocean and their role in the global carbon cycle. JGOFS research improved understanding of the marine carbon pump, particularly the phytoplankton capacity to assimilate and transform natural and anthropogenic CO_2 in the surface waters and transfer this to deeper waters and bottom sediments. Concurrent with JGOFS, a second international research initiative, the Global Ocean Ecosystem Dynamics (GLOBEC, project duration 1995–2010) project, which was sponsored by IGBP, SCOR and the Intergovernmental Oceanographic Commission (IOC), was developed as a response to the need to understand global change effects on the abundance, diversity and productivity of marine populations (from zooplankton to fish) and hence marine ecosystems. GLOBEC made important advances in understanding coupling of ocean physics and trophodynamics, with particular emphasis on zooplankton as a key mediator of the transfer of primary production to higher trophic levels (Perry et al., 2010; Barange et al., 2010). GLOBEC also initiated activities that focused on the role of humans as an integral component of marine food webs. JGOFS and GLOBEC significantly advanced understanding of controls, process and variability of marine biogeochemical cycles and food webs. However, this improved understanding highlighted knowledge gaps and limitations in the global research capacity for integrated approaches across multiple scales and key processes that were needed to understand global change effects on marine ecosystems.

The challenges to understand the interactions and relationships between biogeochemical cycles and food webs across multiple space-time scales, and to quantify and predict responses of the marine system to natural and anthropogenic forcings led to the development of the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER, www.imber.info) project with the central goal to provide "a comprehensive understanding of, and accurate predictive capacity for, ocean responses to accelerating global change and the consequent effects on the Earth system and human society". This goal has been pursued through science activities under four overarching and interlinked themes (Fig. 1) and international coordination, networking and capacity building activities developed through regional programs, working groups, national contributions, endorsed projects (Fig. 2), and integrative, project-wide activities (Table S1).

During its first 10 years (2005–2015), IMBER focused on in-depth regional and topical analyses and comprehensive comparisons of diverse marine ecosystems. The results from these activities provided new understanding about the potential effects of global environmental changes on biogeochemical cycling, food web dynamics, and impacts and linkages to human systems at multiple scales. The scientific achievements of IMBER include significant advances in key research areas, assessments of current scientific understanding, identification of gaps in understanding, and the interdisciplinary science required to address these knowledge gaps. Results accruing from IMBER activities are published in numerous peer-reviewed articles, special journal issues, and books, and are presented to the wider community through numerous special sessions convened at national and international meetings, workshops, symposia, and open science

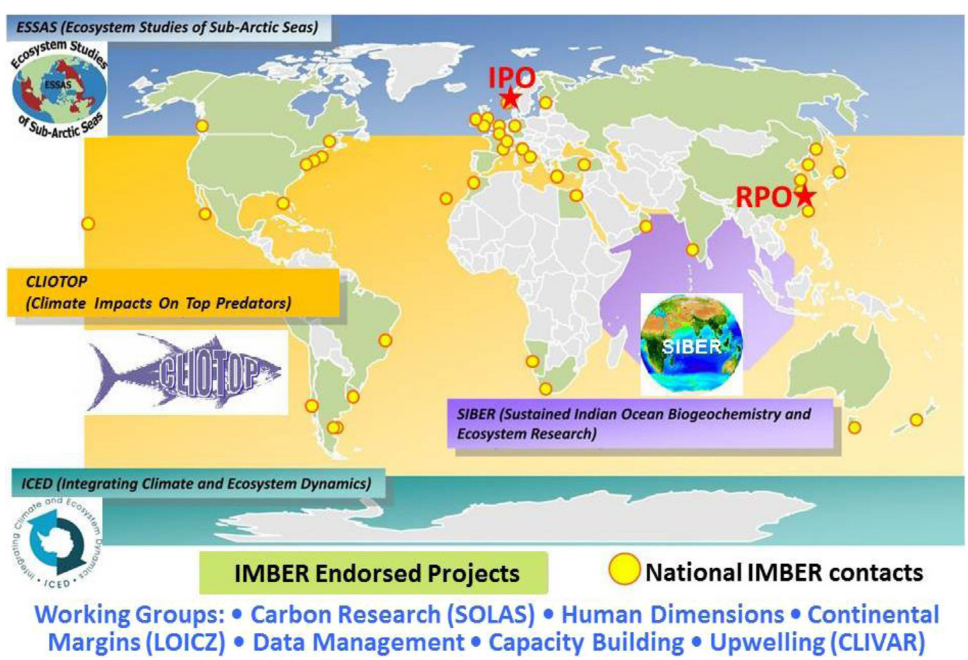

Fig. 2. IMBER science is implemented through four regional programs (CLIOTOP, ESSAS, ICED, SIBER), six working groups (three jointly sponsored with the Surface Ocean Lower Atmosphere Study (SOLAS), Land Ocean Interactions in the Coastal Zone (LOICZ), and Climate and Ocean) – Variability, Predictability, and Change (CLIVAR) projects and more than 35 national programs. An International Project Office (IPO) at the Institute of Marine Research, Bergen, Norway, and a Regional Project Office (RPO) at East China Normal University, Shanghai, China coordinate IMBER activities. In mid 2015 the ESSAS regional program changed its name to Ecosystem Studies of Sub-Arctic and Arctic Seas, which reflects its expanding interests in Arctic seas and retains the program acronym.

conferences. Specific products resulting from IMBER activities (e.g. Data Management Cookbook) and partnerships (Surface Ocean Carbon Atlas, SOCAT) provide important community resources, and capacity building activities, through summer schools and targeted meetings, have contributed to strengthening the global marine research community. Key highlights of these activities as well as a historical perspective, some key science achievements and a vision and a set of goals for the next decade of IMBER research are provided in the sections that follow.

2. IMBER history

In 2001 the IGBP and SCOR Ocean Futures Planning Committee initiated an activity to "identify the most important science issues related to biological and chemical aspects of the ocean's role in global change and effects of global change on the ocean, with emphasis on important issues that are not major components of existing international projects". This planning activity incorporated results from JGOFS. The recommendations from the Ocean Futures Planning Committee provided the basis for an international conference on ocean biogeochemistry and ecosystems in 2003 (Fig. 3) to gather inputs from the science community for the development of a science plan and implementation strategy (SPIS) and initial framework for the IMBER project (IMBER, 2005).

During its first five years (2005–2010) IMBER progressed in parallel and in collaboration with GLOBEC. Prior to the end of GLOBEC in 2010, IGBP and SCOR established a Transition Task Team (TTT) to recommend a post-GLOBEC strategy for IMBER (Field, 2009a,b). The TTT recommendations resulted in an updated IMBER SPIS (IMBER, 2010) that incorporated several of GLOBEC's continuing activities (Fig. 3) and proposed new or extended research directions based on emerging scientific issues. Important aspects were the expansion of IMBER's scope to strengthen integration of the human dimension into IMBER science, inclusion of research on new microbial metabolic and biogeochemical pathways, a better appreciation of thresholds and regime shifts, and an enhanced focus on comparative studies within and across regional programs, including ecosystem models that incorporate the human dimension. An important outcome of the updated SPIS was the addition of a Human Dimensions Working Group (HDWG, Fig. 2) in 2010 that built upon the GLOBEC human interactions focus group, and activities underway in the Land-Ocean Interactions in the Coastal Zone (LOICZ) project, IGBP and the International Human Dimensions Programme on Global Environmental Change (IHDP). The timeline for the updated science plan was five years (2010–2015).

At the time that IMBER was implementing this second five-year phase, the International Council for Science (ICSU) and the International Group of Funding Agencies for Global Change Research (IGFA-GCR), organizations that oversee international science coordination, were considering major changes in programmatic structure, function and funding, which had particular implications for the international global environmental change community. Plans were underway to replace the IGBP, IHDP, DIVERSITAS and the Earth System Science Partnership (ESSP) with a single overarching program, Future Earth, a 10-year international research initiative. With the implementation of Future Earth in late 2015, and the coincident end of the IGBP, IMBER aims to transition as a core project of Future Earth (Fig. 3) and continue as a large-scale research project of SCOR.

The IMBER Open Science Conference (OSC), '*Future Oceans – Research for marine sustainability: multiple stressors, drivers, challenges and solutions*', held in June 2014, provided a venue for the marine science community to present key findings of IMBER-relevant research and promote integrated syntheses of IMBER research. It also gave a planned opportunity to solicit and discuss approaches for updating the IMBER research agenda to guide future research into marine biogeochemistry, ecosystem structure and functioning, the human dimensions of global marine change, and interactions between them. As such, the OSC was an important forum to discuss and gather input from the IMBER community to define and plan its next 10-year phase of research.

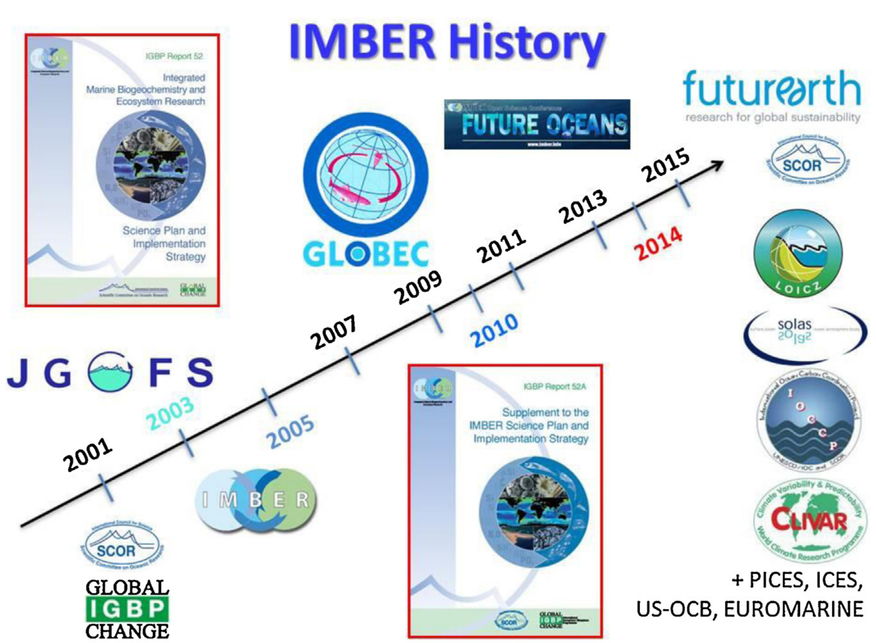

Fig. 3. Timeline of IMBER history. The JGOFS project ended in 2003 (cyan) and the IMBER science plan and implementation strategy (SPIS) was published in 2005 (light blue). GLOBEC ended in 2010, which coincided with the publication of a revised IMBER SPIS (dark blue). The IMBER Open Science Conference (OSC) was in 2014 (red). Beyond 2015, IMBER will transition to a core project of Future Earth and will continue as a SCOR large-scale research project under its new SPIS. IMBER partner projects and organizations (logos and list to right) are defined in the text.

3. IMBER data management and capacity building

3.1. Data management

From the outset, IMBER supported a Data Management Committee (DMC) to assist with establishing good marine data management practices, and developing, implementing and promoting an open data policy to provide guidance to all IMBER regional and endorsed projects. The DMC raised awareness of the need to establish data management procedures early in the research process, promoted the benefits of following good data management practices, and provided examples of these data management procedures as implemented in IMBER research projects. The DMC paid particular attention to training early career researchers and data scientists. For this purpose, the IMBER Data Management Cookbook (Pollard et al., 2011) was developed and the DMC convened three international workshops to provide hands-on training on data management, data preservation, and data publication (Table S1). The Cookbook is a compendium of recipes to make data management suitable for any project that gathers data and intends to make the data widely available. It provides planning, data organization and management tips and examples for projects involving a number of researchers from different disciplines, typical of but not limited to IMBER projects. The Data Management Cookbook has been widely distributed, translated into Spanish, and used to inform data management practices in other international marine research programs.

3.2. Capacity building

IMBER has been proactive in building and strengthening the scientific capacity of early to mid-career researchers, and scientists from developing countries. In partnerships or with support from a range of international organizations (e.g. SCOR, Asia Pacific Network for Global Change Research (APN), North Pacific Marine Science Organization (PICES), Climate and Ocean – Variability, Predictability, and Change (CLIVAR) project, the EUR-OCEANS Consortium, now EuroMarine), IMBER convened five summer schools (Table S1) training over 300 students and early career researchers from 43 countries. The summer school lectures are given by leading experts in their respective disciplines, indicating the level of commitment from the IMBER community to providing a unique and valuable experience for participants. Access to this wealth of knowledge and experience is expanded to a broader audience via live streaming of the summer school lectures, which are then available via the IMBER website for future viewing.

The IMBER national contributions and endorsed projects provide another important capacity building opportunity. These projects bring research communities together to address specific aspects of IMBER research questions in many and varied regions of the ocean, enabling comparative analyses across marine systems. Combined national efforts are important in the delivery and execution of the IMBER regional programs (e.g. ESSAS-NORCAN Project, Drinkwater and Pepin, 2013). As such these projects represent an important mechanism for implementing IMBER research and developing an international research community (Fig. 4) with a focus on IMBER science.

Most IMBER meetings, workshops and conferences include capacity building components that range from financial support for participants, to dedicated workshops, to individual mentoring of attendees. In addition, IMBER, with support from the APN, convened a workshop to evaluate the capacity development needs for integrated marine biogeochemistry and ecosystem research in the Asia-Pacific region and the effectiveness of capacity building activities of large marine research projects. The workshop results were used to recommend key activities to develop human capital for future international marine projects (Morrison et al., 2013). Specific capacity building in the Asia–Pacific region continues through organization and support of the biennial IMBER China–Japan–Korea symposia, which have a regional and a topical focus (Table S1). The establishment of the IMBER Regional Project Office (RPO) in 2010 at East China Normal University in Shanghai, P. R. China was an important development that facilitates dissemination of IMBER results and capacity building in the Asia–Pacific community.

IMBER has provided numerous opportunities for the marine science community to discuss, synthesize and integrate the dynamics of marine biogeochemical and ecosystem processes and their relations to human systems, thereby developing a community of interdisciplinary synthetic researchers. Key activities include the biennial IMBIZOs (the Zulu word for 'a gathering') that are interdisciplinary scientific meetings with about 120 participants (Table S1), and the 2014 OSC (about 500 participants, Table S1). The IMBIZO format (concurrent and interacting workshops) and small size is designed to provide an environment to foster discussion of interdisciplinary topics that are not typically included in more traditional workshops and symposia. Several key publications have resulted from IMBIZOs (e.g. Salihoğlu et al., 2013; Jiao et al., 2014; Refs. in Table S1). The IMBIZOs have been particularly successful in creating new collaborative research groups, which not only produce a collection of publications directly relevant to the meeting but also continue to work together after the IMBIZO on publications, conference organization and research grants. IMBER plans to continue OSCs, which are key to international capacity building, at three to four year intervals to highlight science achievements, look to the future, and continue development of a research community.

IMBER capacity building has also focused on activities that engage stakeholder and other communities. As an example, IMBER contributed to development of the International Ocean Acidification Reference Users Group (iOA RUG), which is successful at knowledge transfer across disciplines and in conveying science research results to non-scientific audiences and science end-users. IMBER was also instrumental in developing and securing funding for the Ocean Acidification International Coordination Centre (OA-ICC), located at the International Atomic Energy Agency Environment Laboratories in Monaco, a successful achievement in capacity building for a particular science focus.

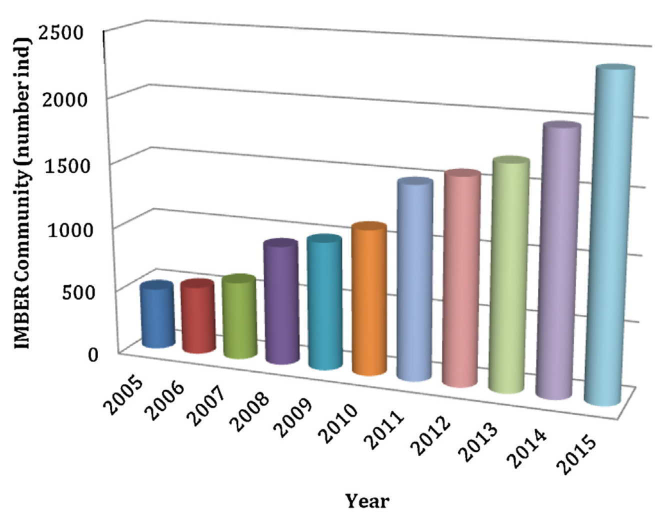

Fig. 4. Time history of development of the IMBER science community. Numbers are derived from project distribution lists and represent a conservative estimate of the size of the IMBER community.

4. IMBER scientific highlights and achievements

In the past 10 years, IMBER has made significant contributions that advanced the understanding of ecological and biogeochemical processes and functioning of the oceans, the dynamics of the interactions between ecology and biogeochemistry, the links to human society and the potential impacts of global change. Key highlights from each of the IMBER science themes (Fig. 1) are given in the following sections.

4.1. Theme 1: interactions between biogeochemical cycles and marine food webs

The interplay between ecological and biogeochemical processes in the mesopelagic and bathypelagic zones of the open ocean can have significant consequences for the efficiency of carbon sequestration. Yet, the deep sea remains the largest and least explored ecosystem on Earth. IMBER, recognizing this knowledge gap, facilitated synthesis (via IMBIZO I, Table S1) of existing knowledge about the diversity and distribution of microbes and metazoa (from viruses to fish) in relation to their impact on global biogeochemical cycles (Steinberg and Hansell, 2010). Robinson et al. (2010) highlighted the influence of the composition of dissolved and particulate organic matter exported from the euphotic zone on the efficiency of prokaryote remineralisation and zooplankton transformation of carbon in the mesopelagic zone. Nagata et al. (2010) showed that microbes in the bathypelagic ocean exhibit not only high diversity but also functional traits that are understood to be adaptations to the high pressure and low temperature conditions in the deep sea. The apparent mismatch between estimates of organic carbon supply to the meso- and bathypelagic zones and measurements of organic carbon utilization within these zones was reconciled by taking into account uncertainties in measurements, environmental variability and processes such as chemoautotrophic fixation of inorganic carbon by *Crenarchaeota* (Burd et al., 2010; Reinthaler et al., 2010).

Through its End-to-End (E2E) Food Webs Working Group and discussions at IMBIZO I (Table S1), a conceptual implementation framework was developed for linking biogeochemical cycles and food webs (Fig. 5, Moloney et al., 2011). The eight thematic areas of this conceptual framework illustrate the complexity of E2E food webs. Individual themes are connected from the level of nutrients or individuals to the level of the food web, and span small to large time and space scales. Connectivity between thematic areas happens at different levels and scales, and differs across environments. When, where and how these connections occur provide a guide for experimental, field and modeling studies (Murphy and Hofmann, 2012).

The E2E focus led to the development, particularly through the regional programs, of a series of studies of oceanic food webs and comparatives analyses of ecosystem structure and functioning (e.g. Link et al., 2012; Murphy et al., 2012). These studies demonstrated, across a range of ecosystems from the polar regions to the tropics, how differences in ocean physics and biogeochemistry relate to changes in the regional distribution of organisms and the structure of oceanic food webs. The IMBIZO II (Table S1) discussions resulted in development of a summary of the challenges associated with implementing E2E food web research and provided a conceptual approach for bridging marine ecosystem and biogeochemical research (Salihoğlu et al., 2013). Implementing this approach across marine systems through comparative studies (see methods and examples in Hood et al., 2013) provides new insights into fundamental interactions in E2E systems that are the basis for the development of models for projecting potential future states and predicting responses of present-day ecosystems. These studies also highlighted the importance of developing understanding and models of the specific processes that link biogeochemical cycles and food webs, such as the role of different zooplankton species in vertical carbon export flux from the upper ocean and the importance of mesopelagic food web interactions in the fate of carbon in the ocean interior.

An important unknown about ocean carbon storage is why so much dissolved organic carbon (DOC) is not used by microbes, despite their vast abundance and diversity. Addressing this issue was one focus of IMBIZO III (Table S1). Jiao et al. (2014) considered the biogeochemical and microbial controls of the recalcitrance of DOC to degradation, and how these mechanisms might be affected by changes in temperature, nutrient supply, acidification and hypoxia. They proposed two types of recalcitrant DOC, that which is recalcitrant in a given biogeochemical context and that which occurs at concentrations below the uptake thresholds of prokaryotes. The maintenance of this recalcitrance is critical to the magnitude of marine carbon sequestration. Using ultrahigh resolution mass spectrometry, Koch et al. (2014) determined that the molecular fingerprint of DOC produced after a 2-year seawater + glucose incubation experiment closely matched the molecular signature of deep-water recalcitrant DOC, and that higher substrate concentrations led to higher concentrations of refractory DOC. If applicable to the open ocean, this suggests that carbon sequestration is dependent on the magnitude of primary production. Recognizing the critical role of microbial diversity and activity in the production of recalcitrant DOC, Mitra et al. (2014a,b) show the importance of including mixotrophic protists in models of the functioning of the biological carbon pump, and Li et al. (2014) measured deep water production rates of carbon from viral lysis up to 2.3 μgC L^{-1} day^{-1} suggesting the important role that virioplankton play in deep water carbon cycling.

The interaction between biogeochemical cycles and marine food web dynamics at basin scales is being addressed by IMBER in the Indian Ocean through its Sustained Indian Ocean Biogeochemistry and Ecosystem Research regional program (SIBER, co-sponsored by the Indian Ocean Global Ocean Observing System,

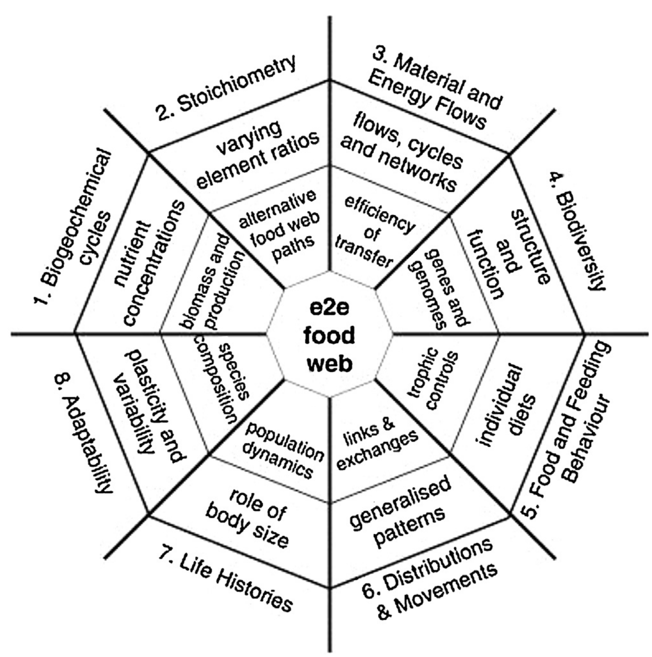

Fig. 5. A conceptual implementation framework for end-to-end food web research. Eight major thematic areas are shown, with threads spanning small to large time and space scales and dealing with issues across different levels of organization. Keywords illustrate processes; issues and approaches. From Moloney et al. (2011).

and in collaboration with CLIVAR's Indian Ocean Panel). The circulation of the Indian Ocean is strongly affected by atmospheric variability at seasonal (monsoon) and interannual (Indian Ocean Dipole) time scales, which imparts variability in nutrient supply and upper ocean structure that is reflected in basin-wide primary production and chlorophyll patterns (Wiggert et al., 2009). The Indonesian Throughflow (ITF) is a chokepoint in the upper ocean thermohaline circulation carrying Pacific waters through the strongly mixed Indonesian Sea and into the Indian Ocean (Ayers et al., 2014). This suggests that most of the ITF nutrient supply to the Indian Ocean goes into the thermocline waters, where it is likely to support new production and significantly impact Indian Ocean biogeochemical cycling. Elsewhere in the Indian Ocean studies have shown the Arabian Sea contains one of the world's most intense oxygen minimum zones (OMZ), the location and magnitude of which is affected by seasonal and interannual circulation changes (McCreary et al., 2013). These studies are supported by the open ocean and coastal observing systems being deployed throughout the Indian Ocean through an international collaborative effort (Hood et al., 2011; Yu et al., 2012).

4.2. Theme 2: sensitivity to global change

Acidification of the surface ocean and its consequent changes to the marine carbonate system has been shown to result in changes in biogeochemical cycles, food webs and their interactions (e.g. Doney et al., 2009; Riebesell and Tortell, 2011). Studies of the responses of individual species to ocean acidification (OA) and ecosystem community responses to multiple stressors (e.g. warming temperature, low oxygen) have been supported by IMBER, in collaboration with the Surface Ocean-Lower Atmosphere Study (SOLAS) (Gattuso and Hansson, 2011; Gattuso et al., 2015). An important component of this research topic has been the development of an OA research community and the dissemination of OA research results to marine science stakeholders and policy makers (e.g., Turley et al., 2010; Turley and Gattuso, 2012; Gattuso et al., 2013).

The CLimate Impacts on Oceanic TOp Predators (CLIOTOP) regional program has focused on identifying and quantifying the impact of climate variability and fishing on the structure and functioning of global open ocean pelagic ecosystems and their top-predator species. These results are being used to enhance predictive capability at individual or species levels. One example is an assessment of the vulnerability of the commercially important bluefin tuna to increasing ocean temperatures. Modeling studies of climate change scenarios suggested a decrease in productivity of this species through reduction in its spawning habitat (Muhling et al., 2011). Although progress has been made in observing and modeling the dynamics of optimum habitats for top predators, realistic predictions are hampered by, for example, the lack of a clear climate change signal in the El Niño-Southern Oscillation (ENSO) (Chiodi and Harrison, 2015). The limited quantitative knowledge of the process related to climate effects on marine ecosystems, (and thus limited modeling capabilities), raises the challenge of developing management systems that are robust to large uncertainties in predicting nature (Evans et al., 2015). The potential consequences of climate change on open ocean pelagic predators are linked to human systems can be understood and assessed through research frameworks that explicitly include ecological and societal systems and provide a basis for developing future scenarios and fisheries adaptation options (Hobday et al., 2013; Maury et al., 2013).

Documenting and understanding the processes linking ecosystem changes with climate variability in the Sub-Arctic and Arctic regions has been a major focus of the Ecosystem Studies of Sub-Arctic Seas (ESSAS, now Ecosystem Studies of Sub-Arctic and Arctic Seas) regional program. For example, comparisons of warm and cold years within the Bering Sea ecosystem led to the Oscillating Control Hypothesis that links climate, the timing of the sea ice retreat in spring, phytoplankton and zooplankton production, and the abundance of walleye pollock (Hunt et al., 2011; Hunt et al., 2013). In the Arctic, eddies along the shelf break were found to entrain shelf waters with their flora and fauna into the central basin, thereby increasing the productivity and enhancing the Arctic marine biological pump (Watanabe et al., 2012, 2014). Projections of the impacts of climate change on Sub-Arctic and Arctic marine ecosystems have included generally northward shifts in the distribution of zooplankton and fish (Mueter et al., 2011) as well as increased spawning in the north (Drinkwater and Pepin, 2013). The adaptive responses of zooplankton to future climate is considered to be a key factor in determining future fish populations and hence fisheries in the Arctic (McBride et al., 2014; Kristiansen et al., 2014). Examining multiple Sub-Arctic ecosystems revealed that in addition to climate, fishing and internal dynamics also influence fish production, with the dominant key driver tending to be system-specific (Link et al., 2012). Evidence that future ecosystem projections must at least consider human-natural science connections and interactions were shown in a comparative study of cod stocks off Norway and eastern Canada (Lilly et al., 2013). During the 1980s and 1990s, favorable environmental conditions combined with timely responses by fishery managers to restrict fishing when abundance levels were low allowed the stock off Norway to rebuild while the collapse of the cod stock off Newfoundland and Labrador was caused by an extended period of poor environmental conditions and a failure to respond by reducing fishing pressure when required.

Scaling-up regional studies to generate integrated, circumpolar analyses has been a focus for the Integrating Climate and Ecosystem Dynamics in the Southern Ocean (ICED) regional program. Comparative analyses and modeling studies have shown the importance of sea ice, iron (and resultant productivity), and connectivity (through advection and movement), in determining the structure and functioning of Southern Ocean ecosystems (Murphy et al., 2012, 2013), and highlighted different directions and magnitudes of ecological responses to sea ice changes (Constable et al., 2014; Melbourne-Thomas et al., 2013; Murphy et al., 2014). Observations of pelagic organisms in polar waters support predictions that the impact of ocean acidification on marine ecosystems and food webs may be significant (Bednarsek et al., 2012). Future scenarios and projections of the impacts of change (Kawaguchi et al., 2013; Smith et al., 2014) predict a 20% reduction in Antarctic krill (*Euphausia superba*) habitat by the end of the century (Hill et al., 2014). This is important for the development of procedures for sustainable harvesting of marine living resources in changing ecosystems by examining how human interactions and wider societal perspectives can be included when developing management objectives (Grant et al., 2013; Hill et al., 2014).

The SIBER regional program has as a primary focus on understanding and quantifying the complexes of the Indian Ocean and its role in the climate system. SIBER, in partnership with CLIVAR, IOGOOS (Indian Ocean Global Ocean Observing System), GEOTRACES (global survey of ocean isotopes and tracers), GO-SHIP (Global Ocean Ship-Based Hydrographic Investigations Program) and several national research programs, is launching the second International Indian Ocean Expedition (IIOE-2) (Hood et al., 2014). The IIOE-2 (planned for 2015–2020) will focus on geological, ocean and atmospheric processes of the Indian Ocean basin, extending to interactions with the Southern Ocean (Hood et al., 2014). All of the IIOE-2 research themes have aspects that are relevant to IMBER, but those focused on boundary current and monsoonal circulation variability, climate variability and change, and effects on biogeochemical cycles and food webs are of particular relevance.

Continental margin systems are undergoing rapid change forced by direct human activity, anthropogenic CO_2-induced climate change, and natural variability (Levin et al., 2015). The controls on marine continental margin ecosystems (including biogeochemical cycling) are dynamic, complex and include the combined and often simultaneous effect of top–down (often human) and bottom-up (natural or human) controls (Levin et al., 2015) acting at a range of space and time scales (Glavovic et al., 2015). Through collaborative activities with LOICZ, IMBER is developing priorities to guide integrated environmental, ecological and economic research of continental margin systems and develop projections of how these systems may change under different climate scenarios (Levin et al., 2015; Glavovic et al., 2015).

4.3. Theme 3: feedbacks to Earth systems

The most direct, and probably strongest, feedback from marine biogeochemistry and ecosystems to the Earth system is through oceanic regulation of atmospheric CO_2. Understanding the sources, sinks and transport of carbon along with gradients of atmospheric CO_2 was recognized by IMBER as critical to assessing changes in ocean uptake and storage capacity. The coordination and synthesis of IMBER ocean carbon research is done through working groups that focus on surface and interior ocean processes, as well as ocean acidification, as noted above.

SOCAT, developed by a collaborative working group between IMBER, SOLAS and the International Ocean Carbon Coordination Project (IOCCP), provides over 10 million quality-controlled surface ocean fCO_2 (fugacity of CO_2) values for the global oceans and coastal seas (Pfeil et al., 2013; Sabine et al., 2013; Bakker et al., 2014). The SOCAT data (Fig. 6) are used to assess the magnitude of the ocean carbon sink (Bakker et al., 2014; Landschützer et al., 2014; Rödenbeck et al., 2014), the extent of ocean acidification (Séférian et al., 2014; Tjiputra et al., 2014; Lauvset et al., 2015), and to evaluate and constrain ocean and climate carbon models.

The 2013 and 2014 global carbon budgets used SOCAT-based methods to assess variability in the ocean carbon sink and to evaluate uncertainties associated with outputs from global carbon models (Le Quéré et al., 2014a,b, 2015). These analyses indicate that the ocean uptake of atmospheric CO_2 in 2013 was 2.9 ± 0.5 GtC yr^{-1}, or about 30% of the CO_2 emissions from fossil-fuel combustion and cement production. SOCAT provides uniform and quality-controlled global surface CO_2 data that contribute to more rapid availability of ocean carbon data for synthesis products

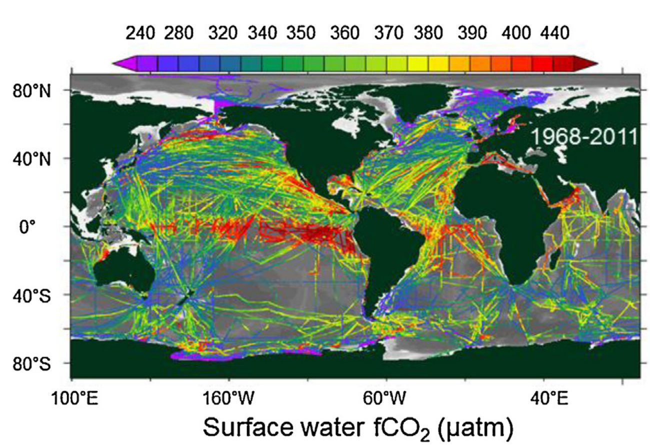

Fig. 6. Observations in the Surface Ocean CO_2 Atlas version 2 (from Bakker et al., 2014).

and policy-related regional and global assessments (Bakker et al., 2014; Le Quéré et al., 2015).

Quantifying the oceanic carbon and oxygen inventories and their variability is crucial for understanding the global carbon and oxygen cycles and their changes over times. However, estimating the storage of anthropogenic CO_2 in the ocean is a non-trivial task, not least because of the disparate nature of the available observations. The SOLAS/IMBER interior ocean carbon working group has therefore undertaken synthesis activities to collate, quality control and interpret available data on oceanic CO_2 (see SOCAT above) and oxygen (Frölicher et al., 2009; Helm et al., 2011; Stendardo and Gruber, 2012). Khatiwala et al. (2013) reviewed observation-based estimates of the global ocean inventory of anthropogenic CO_2, and found that they agreed to within the $\sim$20% uncertainty of the various methods, providing a 'best' estimate of 155 PgC. Future progress in reducing this uncertainty will depend on collecting and collating long-term spatially representative observations. The working group has promoted the development of sustainable observing systems including the addition of oxygen sensors to the international Argo float program (Argo-O_2; Gruber et al., 2010) and other Bio-optical Sensors on Argo Floats (Bio-Argo, e.g., Mignot et al., 2014; Xing et al., 2014). Dissolved oxygen responds to climate variability, making it an ideal parameter to detect and better understand the link between global warming and the resultant biogeochemical and physical changes in the ocean. By building a 50-year high-quality oxygen dataset for the North Atlantic, Stendardo and Gruber (2012) were able to estimate trends in dissolved oxygen over much longer time periods and much broader regions than had hitherto been possible. Their analysis strongly supports the suggestion that if anthropogenic climate change continues unabated, the ocean will deoxygenate, with poorly understood consequences for marine life. Members of the SOLAS/IMBER working group also contribute to a SCOR working group to develop consistent quality control procedures for oxygen and other biogeochemical sensors on floats and gliders (Johnson et al., 2009; Claustre et al., 2010).

4.4. Theme 4: responses to society

Marine ecosystems are subject to increasing multiple challenges from natural and anthropogenic stressors, the impacts of which alter the functioning of marine ecosystems and thus the provisioning of the goods and services on which the livelihood and well-being of human communities depends. Such global change issues are typically viewed as environmental issues, but in reality these are social and human issues that take place within broader, linked social and ecological systems (Perry et al., 2012). Because humans are both the main driver (together with natural climate variability) and the ultimate recipient of environmental change, it is necessary to engage humans, as individuals, communities and societies, in approaches that lead towards a sustainable future. To do so requires mechanisms that enable not only close interaction and cooperation between natural and social scientists, but also effective communication and public engagement. The IMBER HDWG, through research, strategic partnerships and outreach, has worked to further understand the multiple feedbacks and interactions between human and ocean systems and to explore the science-policy-society interface in order to clarify what human institutions can do, either to mitigate anthropogenic perturbations of the ocean system, or to adapt to such changes.

A major achievement of the HDWG was the development of an integrated assessment framework I(MBER)-ADApT (Assessment based on Description and responses, and Appraisal for a Typology) (Fig. 7) that builds on knowledge learned from past experience of responses to global change (Bundy et al., 2015). This framework is intended to enable decision makers, researchers, managers and local stakeholders to make more efficient decisions for marine sustainability, and evaluate where to most effectively allocate resources to reduce vulnerability and enhance resilience of coastal people and maritime communities to global change. I-ADApT is based on the development of a typology of case-studies that provide lessons on which natural, social and governance system responses to the global change worked, under what conditions, and why (Bundy et al., 2015). It has the potential to contribute to timely, cost-effective policy and governing decision-making and response and as such it represents an important advance in integrating human and natural systems. Currently, the HDWG is compiling and synthesizing 23 I-ADApT case studies from around the world for an edited book, and preparing a description of the use of I-ADApT to explore the response of shellfish fisheries to mass mortality events for publication. Recently, the Too Big To Ignore (TBTI) global research network, a partner with IMBER, adopted I-ADApT to analyze global change in small-scale fisheries.

The HDWG has also strived to promote consideration and further understanding of the human dimensions of marine global change throughout the IMBER project and in the marine research community more broadly. To this end, the HDWG has convened sessions at international meetings, IMBIZOs and the 2014 OSC that focused on aspects of sustainability, human-ocean interactions, and marine governance. The HDWG has encouraged other IMBER working groups and regional programs to include a focus on the relationships between humans and marine ecosystems, but interactions have been limited by SPISs for regional programs that were written prior to the establishment of the HDWG and by limited financial and personnel resources.

However, CLIOTOP has addressed the human dimensions of global change since its inception (outlined in its SPIS Maury and Lehodey, 2005) through its working group on socio-economic aspects and management strategies, which focuses on economics, management and policy (e.g., Miller et al., 2010, 2011; Maury et al., 2013). The ESSAS SPIS (Hunt and Drinkwater, 2005) included the introduction of human dimension activities. At each of the ESSAS Open Science Conferences (2005 and 2011), sessions were held that focused upon human dimension aspects including fisheries, fisheries management and fisheries economics; an ESSAS Human Dimensions working group was formed recently. Unique within IMBER, ESSAS has a Paleo-Ecology of Sub-Arctic Seas working group that is exploring the relationship between human settlements and the changes in their population levels with variability in marine productivity on time scales of centuries to millennium. For the Southern Ocean, ICED, together with the British Antarctic Survey and World Wildlife Federation, convened a workshop focused on Antarctic krill fishing conservation that involved participants from the science, conservation and fishing industry sectors. Through the IIOE-2 research theme on Anthropogenic impacts (Hood et al., 2014), SIBER is developing an initiative that considers how human-induced stressors (e.g. warming, ocean acidification) affect the ocean and how this impacts human populations in the Indian Ocean rim nations.

The HDWG contributed to a series of papers (Perry et al., 2012) that explore the roles of marine biogeochemical processes, how they are affected by environmental and human social changes, and the implications for sustainable human livelihoods (including governance and policy aspects). The papers provide reviews that assess a broad suite of multiple stressors on marine systems; explore how these stressors and their impacts on marine social–ecological systems can be observed and suitable indices developed, and discuss what to do in terms of management and governance of these stressors and changes.

5. Links to broader Earth system

IMBER's science objectives are broad and interdisciplinary because these build upon previous global enviornmental change projects and decades of marine science advances, and international networking and collaborations. As such, these objectives lend

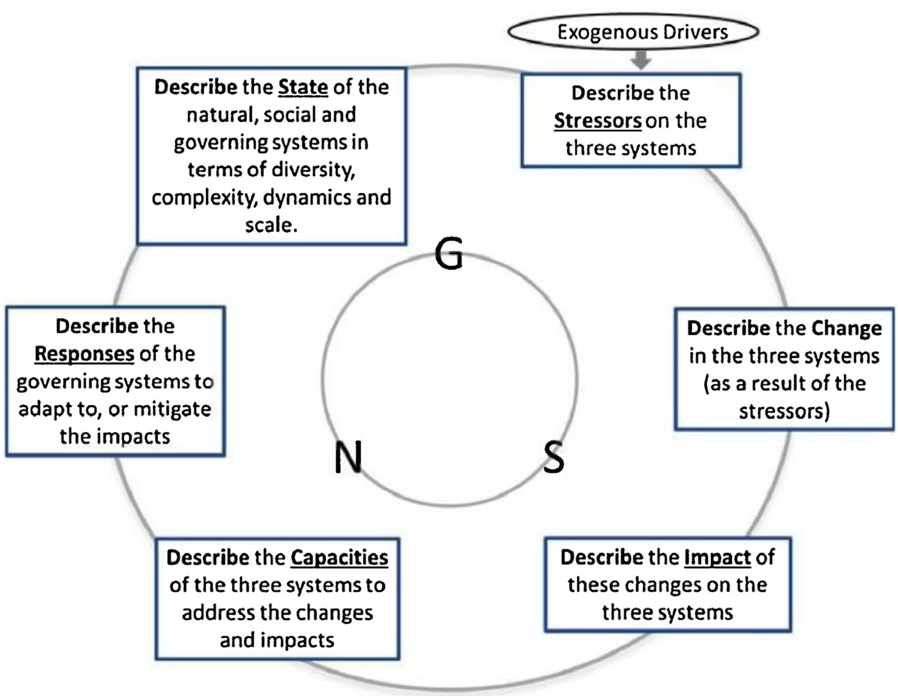

Fig. 7. The Description and response component of I(MBER)-ADApT, which includes the Natural (N), Social (S) and Governing Systems (G). The outer circle represents a continuous cycle, which can be entered at any point, and the inner circle indicates that each component of the Description should be applied to the natural, social and governing systems. From Bundy et al. (2015).

themselves to collaboration with other global environmental change projects and organizations. As a result, IMBER has engaged with organizations that represent academia, intergovernmental arenas, industry and private philanthropic foundations. These collaborations and partnerships are critical to securing the best evidence-based knowledge that is needed by society and policy advisory groups, including the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES). Many IMBER-related researchers have contributed to the activities of these groups and organizations.

IMBER has engaged in partnerships and collaborations through its working groups. The SOLAS/IMBER Carbon Working Groups, established to coordinate and synthesise ocean carbon research, has strong links to IOCCP and the Global Carbon Project (GCP). The IMBER/LOICZ Continental Margins Working Group was established to integrate and synthesise research at national and regional levels, and develop new research activities to facilitate sustainable use of continental margins. IMBER recently formed a working group with CLIVAR, SOLAS and IOC to explore climate processes in upwelling regions and their effects on biogeochemistry, plankton and fish populations.

IMBER activities have benefited from co-sponsorship from several international and national organizations and in turn IMBER sponsors science events of other organizations. The IMBER partnership with PICES has supported many activities, and future collaboration opportunities are planned with the PICES 'Forecasting and Understanding Trends, Uncertainty and Responses of North Pacific Marine Ecosystems' (FUTURE) scientific program. Joint sponsorship of working group activities and science meetings, such as ESSAS annual science meetings, have benefitted from collaborations with ICES and PICES. These collaborative opportunities strengthen and extend IMBER science and its impacts.

Recognizing the vulnerability of coastal communities to global change, especially those dependent on fisheries for food safety and security and employment, IMBER partnered with TBTI and the project, Indicators for the Sea (IndiSeas). TBTI is addressing issues related to the social, economic and political marginalization of small-scale fishing around the world, through the development of information systems and research and governance capacity. IndiSeas evaluates the effects of fishing on the health status of marine ecosystems using a panel of indicators that characterize the enviornmenal and goverance drivers, the ecological and biodiversity status of exploited resources, and the human dimension of fisheries (Shin et al., 2012; Bundy et al., 2012).

6. Perspective and future

IMBER is part of a larger global research community studying global change and variability and responses of marine ecosystems and society at local, national, regional and global levels. IMBER provides a focal point for linking these research initiatives to a larger community, thereby enabling comparisons and cross-fertilization of new ideas, paradigms and approaches across scientific disciplines, countries, regions, existing and developing programs and research-supporting organizations. Such comparisons and sharing of knowledge are essential when addressing complex, multi-scale issues across natural and human systems. Partnerships with international (e.g. GEOTRACES, ICES, LOICZ, PICES, SOLAS) and national (e.g. U.S. Ocean Carbon Biogeochemistry) projects and programs provide additional dimensions and expertise for IMBER activities. In this regard, IMBER facilitates integration of the intellectual advances from many research initiatives to develop new and important research questions that focus on understanding global environmental change effects on marine ecosystems. This synergy strengthens research at all levels, builds capacity, and provides leverage that allows science to advance at individual, institutional, national, regional and global levels.

IMBER, by design, has a broad scientific mandate. This has worked to IMBER's advantage in that it allowed development of research agendas that cross non-traditional boundaries (i.e. human–ocean) while maintaining focus on marine biogeochemistry and ecosystem research, with special emphasis on biogeochemistry and food webs and their linkages. This wider perspective allows IMBER to contribute to the development of a community that extends into the social dimensions of global change effects on ocean systems through targeted capacity building activities (Table S1). Reaching and engaging this wider community of researchers depends on linkages to ongoing and planned research initiatives, partnerships with national and international organizations, and recruitment of experts from the social sciences and humanities.

IMBER-sponsored activities have advanced progress and understanding of science issues associated with its four research themes (e.g. end-to-end food webs, ocean acidification, mesopelagic ecology, human dimension of marine ecosystems, importance of polar regions) and contributed to research capacity (e.g. data management, human dimensions, community development). The long-term impact of international research projects can be measured in terms of development of new research communities and research programs, enabling changes in science focus, and development of new areas of science. The contributions made by IMBER in these areas will become apparent over the next 5–10 years, and will be measured in part by new and emerging science in individual, national and regional research programs. Tracking scientific evidence-based decision-making outcomes in local, regional and international management, governance and policy is a more challenging endeavour, and the Future Earth framework can provide the ability to assess impacts in these areas.

In addition to curiosity-driven research to understand the dynamics of marine ecosystems, IMBER is continuing, through regional programs, working groups, national and endorsed projects, and partnerships, to foster collaborative, disciplinary, interdisciplinary and integrated research that addresses key ocean science issues generated by and/or impacting society. The intent is to provide evidence-based knowledge and guidance for policy decision makers, managers and marine-related communities in order to secure or transition towards sustainability of the marine realm under global change. This underlies a new IMBER vision to guide the next decade of research, which focuses on ocean sustainability under global change for the benefit of society.

Recognizing that the evolution of marine ecosystems (including biogeochemical cycles and human systems) is linked to natural and anthropogenic drivers and stressors, the proposed IMBER research goal for the next decade is to: Understand, quantify and compare historic and present structure and functioning of linked ocean and human systems to predict and project the changes including developing scenarios and options for securing or transitioning towards ocean sustainability.

The IMBER integrated research agenda for the next decade supports its new vision and goal and is based on grand challenges that focus on climate variability, global change and human drivers and stressors and innovation challenges that focus on new areas for IMBER where research is needed and where it is believed that major achievements can be made within 3–5 years. With this research agenda, IMBER will maintain its strong commitment to basic, curiosity-driven marine science and expand into new areas of problem-driven, policy-relevant interdisciplinary marine research. The established IMBER research community and its partners are in a lead position to integrate marine science into the evolving global environmental change research landscape (e.g.

Rudd and Fleishman, 2014; Duarte, 2014; Rudd, 2015; Steffen et al., 2015) and science-policy arena (e.g. IOC, 2011; UNEP, 2012; United Nations, 2014a,b; Diaz et al., 2015). Exciting changes and challenges are facing the marine research community, and dealing with these in a proactive, forward-thinking manner is key, both for now and the future.

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The ideas and results presented in this paper are based on numerous discussions with the international IMBER science community.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ancene.2015.
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