IMBeR
Integrated Marine Biosphere Research

IMBeR into the future

Science Plan and Implementation Strategy

2016 - 2025

International Council for Science
SCOR
Scientific Committee on Oceanic Research

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research for global sustainability

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Integrated Marine Biosphere Research (IMBeR)

Science Plan and Implementation Strategy

Developed by

The IMBeR Community

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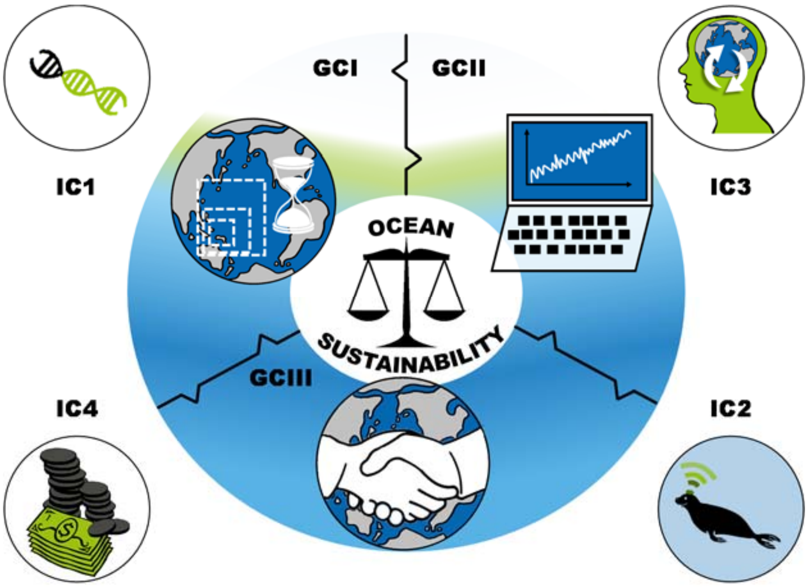
EXECUTIVE SUMMARY

The Integrated Marine Biosphere Research (IMBeR) project, formerly the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER[1]) project, is a global environmental change research initiative. Since its start in 2005, IMBeR has advanced understanding about potential marine environmental effects of global change, and the impacts and linkages to human systems at multiple scales. It is apparent that complex environmental issues and associated societal/sustainability choices operate at and across the interfaces of natural and social sciences and the humanities, and require both basic, curiosity-driven research and problem-driven, policy-relevant research. Collaborative, disciplinary, interdisciplinary, transdisciplinary and integrated research that addresses key ocean science issues generated by and/or impacting society is required to provide evidence-based knowledge and guidance, along with options for policy-makers, managers and marine-related communities, to help achieve sustainability of the marine realm under global change. This recognition underlies a new vision, "***Ocean sustainability under global change for the benefit of society***", to guide IMBeR research for the next decade (2016-2025).

This vision recognises that the evolution of marine ecosystems (including biogeochemical cycles and human systems) is linked to natural and anthropogenic drivers and stressors, as articulated in the new IMBeR research goal to, *"**Understand, quantify and compare historic and present structure and functioning of linked ocean and human systems to predict and project changes including developing scenarios and options for securing or transitioning towards ocean sustainability**"*. To implement its new vision and goal in the next decade, IMBeR's mission is to, *"**Promote integrated marine research and enable capabilities for developing and implementing ocean sustainability options within and across the natural and social sciences, and communicate relevant information and knowledge needed by society to secure sustainable, productive and healthy oceans**"*.

This *Science Plan and Implementation Strategy* provides a 10-year (2016-2025) marine research agenda for IMBeR. It is developed around three Grand Challenges (GC, see Graphical Executive Summary) focusing on climate variability, global change and drivers and stressors. The qualitative and quantitative understanding of historic and present ocean variability and change (Grand Challenge I) are the basis for scenarios, projections and predictions of the future (Grand Challenge II). These are linked in Grand Challenge III to understand how humans are causing the variability and changes, and how they, in turn, are impacted by these changes, including feedbacks between the human and ocean systems. Priority research areas with overarching and specific research questions are identified for each Grand Challenge. The Grand Challenges are supplemented with Innovation Challenges (IC, see graphical executive summary) that focus on new topics for IMBeR where research is needed and where it is believed that major achievements can be made within three to five years. The Innovation Challenges also provide a means for IMBeR to adjust its focus as major science discoveries are made and new priorities arise, especially regarding scientific innovations.

[1] The project name was changed to reflect the broadening of scope outlined in this *Science Plan and Implementation Strategy*.



Graphical Executive Summary

Grand Challenge I: *Understanding and quantifying the state and variability of marine ecosystems*

The Challenge: To develop whole system-level understanding of ecosystems, including complex biogeochemical cycles and human interactions, together with understanding of the scales of spatial and temporal variability of their structure and functioning.

Grand Challenge I (GCI) is directed at using a whole-ecosystem approach to understand, detect, and quantify the effects of natural and anthropogenic change on marine ecosystems. The two priority research areas address (i) linkages between food webs and biogeochemical cycles, with focus on the processes that affect ecosystem structure and functioning and responses to change; and (ii) the range of time and space scales over which these processes and responses operate.

Grand Challenge II: *Improving scenarios, predictions and projections of future ocean-human systems at multiple scales*

The Challenge: To incorporate understanding of the drivers and consequences of global change on marine ecosystems and human societies at multiple scales into models to project and predict future states.

Grand Challenge II (GCII) focuses on distinguishing and attributing causes and effects of anthropogenic processes to biogeochemical changes to inform projections and predictions of future ecosystem conditions, including scenarios and estimates of potential human interference. The priority research areas for this Grand Challenge are to advance the understanding gained from Grand Challenge I to estimate probable future states of marine ecosystems and representative marine species, and to assess the impact of those changes for human well-being and livelihoods.

Grand Challenge III: *Improving and achieving sustainable ocean governance*

The Challenge: To improve communication and understanding between IMBeR science, policy and society to achieve better governance, adaptation to and mitigation of global change, and transition towards ocean sustainability.

Grand Challenge III (GCIII) focuses on marine governance, including the acquisition, mobilization and provision of evidence-based advice for marine managers, policy-makers, and other research end-users. This Grand Challenge integrates the science from Grand Challenges I and II to support development of mechanisms that (a) enable interdisciplinary research and cooperation between natural and social scientists and researchers in humanities, and (b) effective communication and public engagement at local and regional scales.

Innovation Challenges

Four Innovation Challenges are proposed for new research where IMBeR can make progress in the next three to five years. These Challenges focus on enhanced understanding of the role of metabolic diversity and evolution in marine biogeochemical cycling and ocean ecosystem processes (IC1); contributions to the development of a global ocean ecosystem observational and modelling network that provides "ecosystem essential ocean variables" and improvements to marine data and information management (IC2); advancing understanding of ecological feedbacks in the Earth System (IC3); and advancing and improving the use of social science data for ocean management, decision making and policy development (IC4). Priority research questions are provided for each Innovation Challenge, and the outputs of each Innovation Challenge feed into one or more of the Grand Challenges.

Implementation

Activities undertaken by IMBeR's existing regional programmes, working groups, task teams, regular symposia and summer schools will address the knowledge gaps and research questions identified in the Grand Challenges and Innovation Challenges. These activities will be supported by a network of more than 2,000 scientists from about 80 countries, endorsed projects, and other core research projects and science organisations. IMBeR's existing structure will evolve through the creation of new working groups, regional studies, and activities, as needed, to advance the Challenges. IMBeR science will be strengthened and its impacts extended through on-going and new partnerships and collaborations with international and national organisations, including the International Council for Science (ICSU), the Scientific Committee on Oceanic Research (SCOR), Future Earth, the World Climate Research Programme (WCRP), and the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO) which sponsors the Global Ocean Observing System (GOOS) and co-sponsors the International Ocean Carbon Co-ordination Project (IOCCP) with SCOR. IMBeR science is relevant for addressing several of the United Nations' Sustainable Development Goals (SDGs), especially SDG14 Life Below Water.

CONTENTS

1. IMBeR – Looking to the Future

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 provisioning of living and non-living resources. In the Anthropocene, it is experiencing unprecedented changes resulting from a complex mix of drivers, stressors and processes that occur over a large range of space and time scales which, in turn, affect the human communities that rely on the oceans' services and resources. Sustainable management of the oceans requires scientific evidence-based information and knowledge that allows both the individual and combined effects of these complex changes at global to local scales and short to long-term time scales to be understood, assessed, projected, and predicted, and linked to options for improved governance, policy and management.

The Integrated Marine Biogeochemical and Ecosystem Research (IMBER) project started in 2005 as a global environmental change research initiative "*to investigate the sensitivity of marine biogeochemical cycles and ecosystems to global change, on time scales ranging from years to decades*". During the past decade IMBER contributed new understanding that advanced this original goal through individual and integrated studies of complex marine ecosystems, consisting of linked natural, human, and governance subsystems and in-depth exploration of multiple dimensions and scales of their structure, functioning and values (Hofmann et al., 2015).

The complex environmental issues and associated societal/sustainability choices, particularly those relating to global environmental change, operate at and across the interfaces of natural and social sciences and the humanities, and require both basic, curiosity-driven research and problem-driven, policy-relevant research (Duarte, 2014; Rudd, 2014; Diaz et al., 2015; Steffen et al., 2015). Collaborative, disciplinary, interdisciplinary and integrated research that addresses key ocean science issues generated by and/or impacting society is required to provide evidence-based knowledge and guidance (Steffen et al., 2015). Designing the approaches to be undertaken in cooperation with users will ensure development of useable options for policy decision makers, managers and marine-related communities for securing or transitioning towards sustainability of the marine realm under global change in the Anthropocene. This broadening of scope and impact underlies a new vision to guide the next decade of research for the Integrated Marine Biosphere Research (IMBeR) project:

"Ocean sustainability under global change for the benefit of society".

Recognising that the evolution of marine ecosystems (including biogeochemical cycles and human systems) is linked to natural and anthropogenic drivers and stressors, the 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 changes including developing scenarios and options for securing or transitioning towards ocean sustainability."***

This goal will be addressed by engaging the IMBeR community and additional relevant stakeholders in a scientific endeavour that will:

> ***"Promote integrated marine research and enable capabilities for developing and implementing ocean sustainability options within and across the natural and social sciences, and communicate relevant information and knowledge needed by society to secure sustainable, productive and healthy oceans".***

The integrated research agenda outlined in this *Science Plan and Implementation Strategy* (SPIS), and developed by the IMBeR community, supports this new vision and goal. It is developed around Grand Challenges (Section 2) that focus on climate variability, global change, and human drivers and stressors (**Fig. 1**). The Grand Challenges are supplemented with Innovation Challenges (Section 3) that focus

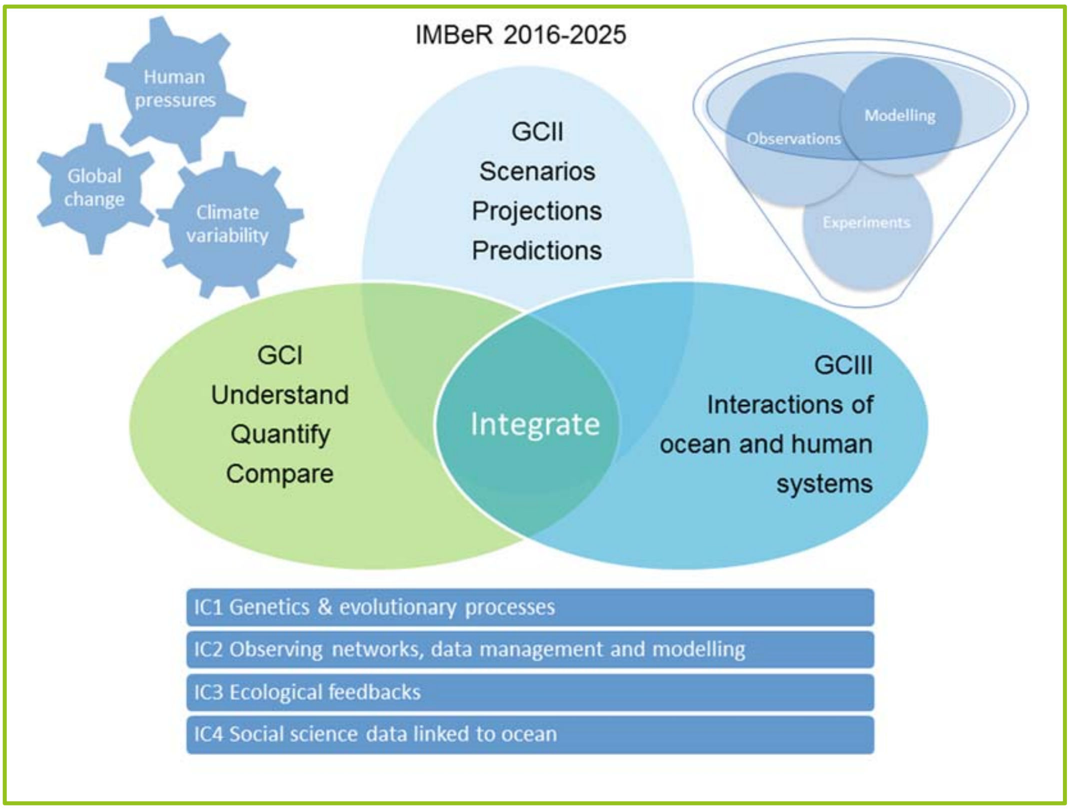


Figure 1. Integrative structure of IMBeR Grand Challenges (GC) and Innovative Challenges (IC). Marine ecosystems are responding to major pressures (upper left) that operate at a range of scales. Understanding, quantifying and predicting responses of marine ecosystems to these pressures requires integrated observational, experimental and modelling programmes (upper right).

on new areas for IMBeR where research is needed and where it is believed that major achievements can be made in three to five years.

IMBeR, as an international, integrated global environmental change research project enables global comparisons of regional studies and the cross-fertilisation of new ideas, paradigms and approaches between scientific disciplines, countries, regions, existing and developing programmes and research-supporting organisations (**FIG. 2**). These comparisons and cross-fertilisations are essential when addressing complex, multi-scale issues across natural and human systems (Diaz et al., 2015; Steffen et al., 2015). IMBeR will continue to provide a platform for discussion about mitigation of and adaptation to global environmental change in marine ecosystems and will promote capacity development and knowledge transfer to help strengthen research, governance, policy, and management. Important changes and challenges confront the marine research community and addressing these in a proactive, forward-thinking manner is key, both for now and in the future.

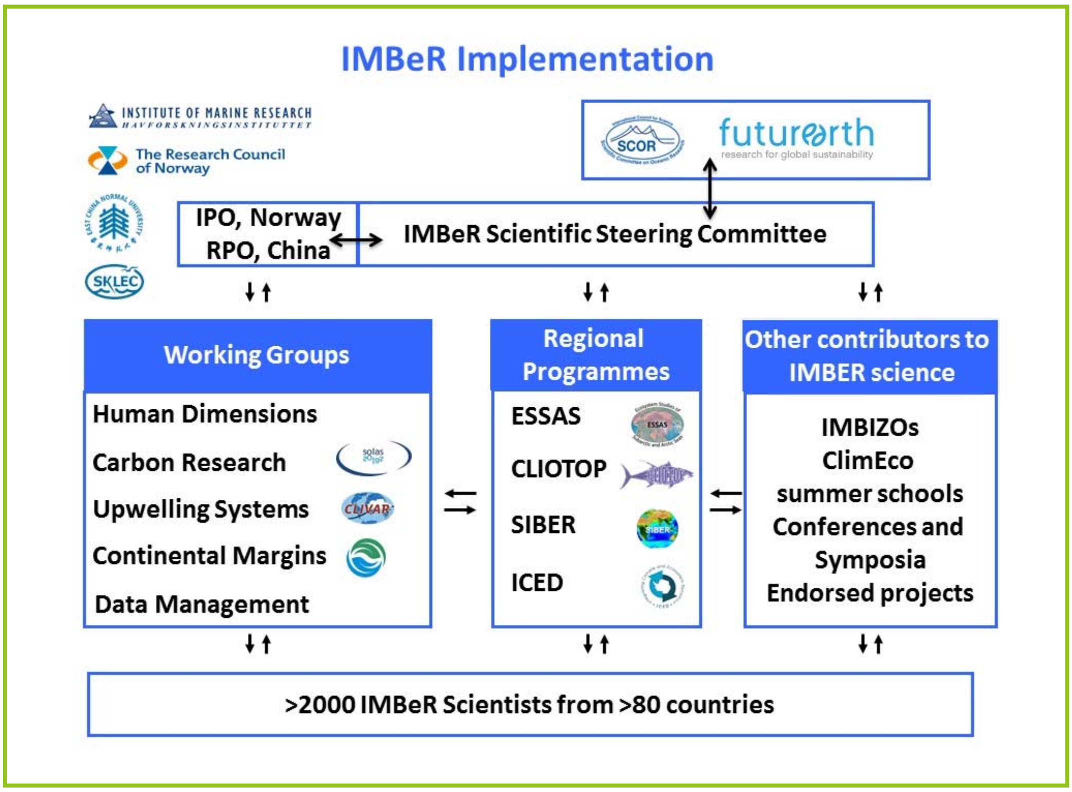


FIGURE 2. IMBeR Project organisation and implementation. Coordination of IMBeR activities is through the International Project Office (IPO), the Regional Project Office (RPO) and the Scientific Steering Committee (SSC). Implementation of IMBeR's research agenda is through working groups, regional programmes, across-project activities such as IMBIZOs and ClimEco summer schools, and endorsed projects.

2. Grand Challenges and Research Priorities

Three Grand Challenges form the basis to guide IMBeR research for the next decade. These consider understanding and quantifying marine ecosystems, developing scenarios and projections and predictions of future states of marine and human systems at multiple scales, and fostering successful and sustainable ocean governance. For each Grand Challenge, priority research areas are identified, along with overarching and specific research questions.

2.1 Grand Challenge I – understanding and quantifying the state and variability of marine ecosystems

The Challenge: *To develop whole system-level understanding of ecosystems, including complex biogeochemical cycles and human interactions, and understanding the scales of spatial and temporal variability of their structure and functioning*

Rationale: The global changes affecting marine ecosystems have variable physical, ecological and anthropogenic drivers and impacts (Rosenzweig et al., 2008; Hoegh-Guldberg and Bruno, 2010; Doney et al., 2012; Gattuso et al., 2015). Food web structure and functioning and feedbacks with biogeochemical cycles are key aspects that can be used to evaluate how the ecosystem as a whole might respond to change, and the consequences of such changes for human systems. Knowledge is needed to assess these responses across a range of biogeochemical, physiological, trophic, spatial, and temporal scales (e.g., from molecules to individuals to whole ecosystems, from local to global, and from seasons to centuries) (Rose et al., 2010; Moloney et al., 2011; Murphy et al., 2012).

Drivers and stressors (e.g., ocean acidification, coastal hypoxia, warming, decreases in oceanic oxygen concentrations, fishing, eutrophication, pollution) do not occur in isolation (Halpern et al., 2008; Bopp et al., 2013). Their complex, multi-scale linkages create significant challenges for marine ecosystems and dependent human communities. Many of the processes that may alter marine biogeochemical cycling and food webs are partially known, but better quantitative understanding is needed to usefully predict or project changes due to individual stresses, the combined effect of multiple drivers and stressors, and the resulting impacts on society

(Crain et al., 2008; Perry et al., 2010a).
Identifying and evaluating the role of multiple drivers and stressors in determining thresholds, tipping points, and bifurcation points in marine ecosystems and their impacts on human systems is critical (Perry et al., 2010b).
Grand Challenge I is directed at using a whole system approach to understand, detect and quantify the effects of natural and anthropogenic change on marine ecosystems (**FIG. 3**). It includes two priority research areas that address linkages between food webs and biogeochemical cycles, with particular attention paid to the drivers and stressors that affect ecosystem structure and functioning and responses to change (**TEXT BOX 1**) and the scales over which these operate (**TEXT BOX 2**).

Knowledge Gaps: The dependencies of human systems on, and the scales at which these are linked and feed back to, marine ecosystems are central to addressing the research questions posed under Grand Challenge I. Approaches that recognise and define the interdependence of marine ecosystems and human systems at a

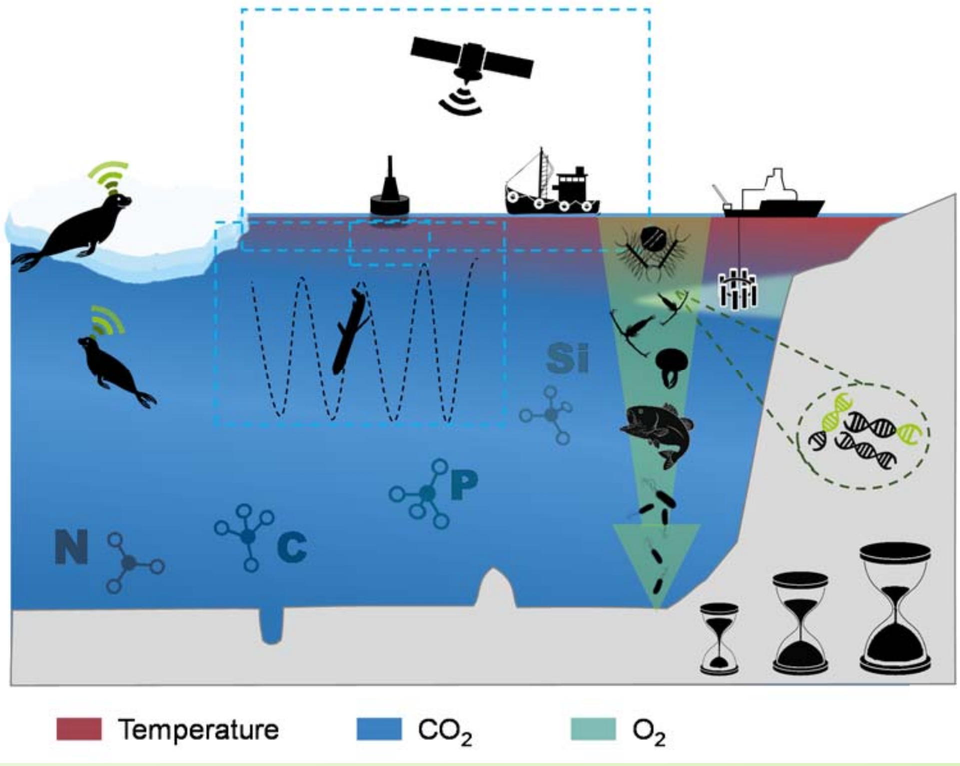


FIGURE 3. Infographic illustrating Grand Challenge I. The time-varying and spatial scale-relevant interactions recognize multiple stresses, such as temperature, carbon dioxide (CO_2), oxygen (O_2), and fishing on marine biogeochemistry, food webs and human systems. Adaptation of marine organisms through evolution and metabolic diversity provides potential for ecosystem responses to changes. Advances in understanding are made through innovative data collection mechanisms such as autonomous animal profilers, underwater gliders, and fishing vessel global positioning systems. Understanding of the structure and function of ecosystems across multiple scales requires analyses of local, regional and ocean/global scale processes and integration through coupled modelling systems.

range of scales are being developed (Perry and Ommer, 2003; Brander, 2007; Perry et al., 2010a,b), but application of these beyond fisheries is needed. Also, defining scale dependencies of human systems has been focused on local scales, and approaches to scale these up are critical for the development of integrated observing and modelling systems for the full social–ecological system (Perry et al., 2010a; Barange et al., 2014). Further, the scales over which non-climate stresses (e.g., fishing) interact with climate change and marine ecosystems is an important unknown that affects interactions and linkages in the social-ecological system (Brander, 2007; Perry et al., 2010a,b).

The focus of Grand Challenge I on whole-ecosystem understanding requires addressing little-known and/or poorly studied aspects of marine food webs (Text Box 1). Within the many unknowns of food webs, mid-trophic levels (e.g., mixotrophs, zooplankton, forage fish, mesopelagic fish, cephalopods) are recognised as providing critical linkages in the transfer of matter and energy between lower and higher trophic levels, which mediate feedbacks to biogeochemical cycles (Link et al., 2005; Frank et al., 2006; Murphy et al., 2012, 2016). However, sampling and quantification of mid-trophic levels is often insufficient to fully estimate these important linkages, and at present there are increasing interests in fishing at these levels (Murphy et al., 2016; St. John et al., 2016). Improved experimental, observational and modelling studies that describe, define and quantify the role of mid-trophic levels and associated transfer rates within the context of food webs are needed.

The environment and ecosystems of the Arctic and Antarctic are particularly sensitive to changing climate. Reductions in sea ice cover, warming, and consequent changes in upper ocean mixing and light environments are already affecting biogeochemical cycling, and primary and secondary production in both systems (Smetacek and Nicol, 2005; Trembley and Gagnon, 2009: Wassmann et al., 2011; Duarte et al., 2012a,b; Constable et al., 2014). Boreal planktivorous species in high-latitude environments are adapted to cycles of hibernation and diapause during the dark winter, and a rapid growth period and bloom during the

Text Box 1

Grand Challenge I Priority Research Area
Natural and anthropogenic global and marine change

Overarching Research Question

What are the respective effects, impacts, and mechanisms of natural climate variability and anthropogenic global change on marine biogeochemical cycles, ecosystems, and human well-being and livelihoods?

Related Questions

How are anthropogenic impacts on biogeochemistry transmitted to the ecosystem and human society, and vice versa?

What are the major linkages, interactions and dependencies between human and ocean systems, and how are they affected by global change?

At what spatial and temporal scales do different stressors and drivers operate?

How do multiple drivers and stressors interact to affect structure, functioning and response to change?

How can cumulative and synergistic effects of multiple drivers be identified, quantified, and modelled?

How can regime shifts, tipping or bifurcation points and critical thresholds be identified, quantified, and modelled?

Text Box 2

Grand Challenge I Priority Research Area
Interactions across space and time scales

Overarching Research Question

What is the role of interactions at different space and time scales in the response of marine biogeochemistry and food webs to climate variability and change?

Related Questions

How do biogeochemical and ecological processes over different scales interact to determine ecosystem structure, functioning and responses to change and how do these affect human well-being and livelihoods?

How do the social and governing systems operate and interact over different scales to determine human response to change and how does this link back to ecosystem structure and functioning?

How can end-to-end ecosystem processes be further identified, quantified, and modelled over multiple scales?

How can human-ecosystem interactions be matched and modelled over different scales?

spring and summer when temperatures are higher and light is abundant (Murphy et al., 2016). The ability of temperate plankton and fish species to adapt to a high-latitude seasonal life cycle has important implications for the establishment of new species at high latitudes as the oceans warm. Moreover, the ecological productivity of high-latitude systems will be altered as new combinations of temperature, light and nutrient availability occur (Wassmann et al., 2010: Slagstad et al., 2011; Murphy et al., 2016). The consequences of these changes for habitat suitability, biogeochemical cycling and food web structure and function, and dependent human societies are largely unknown. Integrated, quantitative descriptions of food webs at local, regional and circumpolar scales are needed to project and predict system responses to changing environmental conditions (Carmack and Wassmann 2006; Murphy et al., 2012).

Understanding interactions and coupling across scales is integral to Grand Challenge I (Text Box 2). Mesoscale and sub-mesoscale processes are important controls of biogeochemical cycling, ecosystem productivity, and variability (e.g., Lévy et al., 2012; Mahadevan et al., 2012) and as such are important controls on energy flow to higher trophic levels (Godø et al., 2012; Bertrand et al., 2014). Approaches that allow representation of coupling across this physical continuum to food web processes in marine ecosystem models are still to be developed and are needed for predictions of future states of marine ecosystems.

The deep ocean below 1000 m (about 88% of the ocean volume) is one of the great unexplored realms and the scales over which the mechanisms mediating surface to deep connections of carbon and nutrients operate and the processes that determine the variability in the transfer of matter and energy are poorly understood (Burd et al., 2010). The solubility and biological pumps connect surface processes to the deepest ocean layers, where biological processes occur at much lower rates relative to the upper ocean (Koppelmann and Frost, 2008, and references cited therein). With deep ocean residence times at centennial to millennial scales, the global ocean system is only slowly ventilated and circulated.

Biogeochemical signals in the deep ocean are integrative of processes occurring over very long time periods. Biological processes in the deepest ocean layers are closely tied to particle dynamics and transformations and microbial food webs that are only poorly characterised (Aristegui et al., 2009). The challenge is to evaluate the current and future role of the deep realm considering observed and predicted changes in global ocean functioning, especially in the upper ocean circulation and its potential influence on deep ocean water masses. These processes are key to the evolution of the global ocean sink for carbon and nutrient distributions and their responses to climate variability and global change (Jiao et al., 2010; 2014). These potential effects on current and future physical-biogeochemical-food web interactions remain to be explored and are integral to addressing the research questions posed under this Grand Challenge.

The open ocean is linked to the continental margins, where the effects of terrestrial linkages (e.g., runoff, atmospheric deposition) and direct human influence are concentrated. More than 40% of the carbon sequestration in the ocean is believed to occur in continental margins, where relatively large amounts of carbon are stored in the sea floor (e.g., Muller-Karger et al., 2005; Chen and Borges, 2009). Besides this burial, some carbon and other constituents are also transferred to the deep ocean (Thomas et al., 2004). Although shelf-open ocean exchanges are critical for the biogeochemical balance of continental margins, there is limited understanding of the physical and biogeochemical processes that control and mediate these exchanges. There are also significant uncertainties regarding the biogeochemical balance of continental shelves, the input of carbon from land, and the variation in response times to anthropogenic input (Borges, 2005). These uncertainties severely limit our ability to accurately integrate the continental margins in global assessments (e.g., Bauer et al., 2013).

The effects and challenges of change and multiple stressors are particularly acute in the continental margins, where more than 70% of the global fish catches are harvested, all marine aquaculture is found, and presently 40% of the total human population lives within 100 km of the coastline (Brander, 2007; Cheung et al., 2010). These systems are experiencing many challenges resulting from eutrophication, pollution, changing freshwater input, exploitation of renewable and non-renewable resources, sea level rise and changing wind patterns, for example, the effects of which may have disproportionately large impacts.

Continental margin processes are complex because of regional, seasonal and local heterogeneity, and may either amplify or dampen impacts on primary production, acidification, hypoxia, and fisheries production (e.g., Levin et al., 2015). Eastern boundary current upwelling regions along continental margins support up to 25% of the global marine fish catches while occupying only 5% of the ocean area (Jennings et al., 2001). These regions are experiencing warming and modifications due to changes in large-scale atmospheric forcings, the physical, biogeochemical, food web and social consequences of which are poorly understood (Glavovic et al., 2015; Levin et al., 2015).

2.2 Grand Challenge II – improving scenarios, predictions and projections of future ocean-human systems at multiple scales

The Challenge: *To incorporate understanding of the drivers and consequences of global change on marine ecosystems and human societies at multiple scales into models to project and predict future states*

Rationale: Marine biogeochemical cycles and food webs are, in the broadest sense, a continuum characterised by the complexity in which their components are both potential drivers of, and potential solutions to, global change issues. Marine biogeochemical cycles are sensitive to climate change, and these changes have the potential to significantly impact the structure and functioning of marine ecosystems (see Grand Challenge I). Distinguishing and attributing causes and effects of biogeochemical changes to anthropogenic processes is challenging, but such efforts are necessary to inform projections (estimated

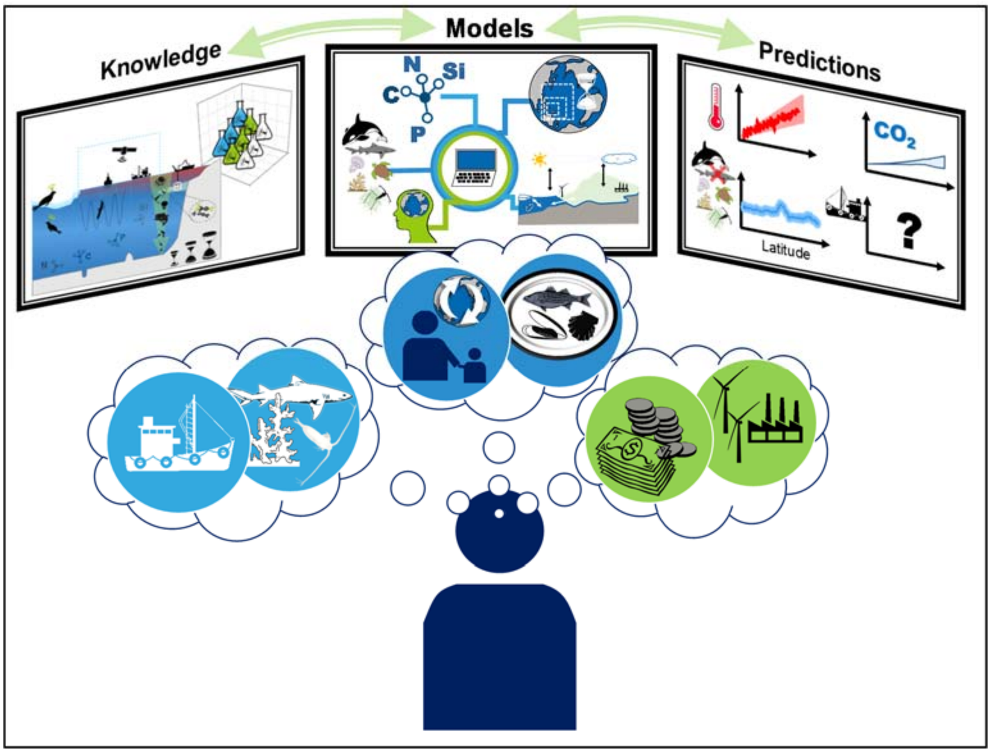


Figure 4. Infographic illustrating Grand Challenge II. Knowledge gained in Grand Challenge I is used to (i) develop models incorporating biogeochemistry, biodiversity, fishing, economics, human development, behaviour and well-being, and feedbacks between these, and to (ii) predict and project changes to biodiversity and ecosystem functioning including provision of ecosystem services at a range of time and space scales.

outcomes based on specific conditions) and predictions (dependent on initial conditions) of future ecosystem conditions, including scenarios and estimates of potential human interference (Gruber and Galloway, 2008; Doney et al., 2012: Ciais et al., 2014). In this respect, there is still much to be studied, understood and consequently explained, projected and predicted for the benefit of end-users, decision makers and society at large. The priority research areas for this Grand Challenge are to advance the understanding gained from Grand Challenge I to develop scenarios and projections of future states of marine ecosystems (**Text Box 3**) and representative marine species (**Text Box 4**), and to assess the impact of those changes for human well-being and livelihoods (**Fig. 4**).

Text Box 3

Grand Challenge II Priority Research Area
Scaling up for projection and prediction

Overarching Research Question

What interdisciplinary understanding is needed to improve ecosystem models developed for multiple scales and systems to allow projection and prediction of future states and evaluation through scenario development?

Related Questions

What levels of biogeochemical, ecological, and social complexity are appropriate for providing realistic scenarios and projections of future states, including human well-being and livelihoods?

How can this complexity be included in end-to-end ecosystem models to improve projections over multiple scales?

How might governance processes and infrastructure be included?

What are the limits to realistic ecosystem predictability?

Knowledge Gaps: Food web and biogeochemical processes are fundamental elements in the structure and functioning of marine ecosystems, yet large knowledge gaps remain. IMBeR has made significant progress in identifying and filling some of these knowledge gaps, but questions remain about the interactions between biogeochemical cycles and food webs in a changing environment. Identification of critical linkages between food webs (from microbes to megafauna), biogeochemical cycles, and human well-being and livelihoods is needed to make detection and attribution of changes feasible and to project potential consequences for future states, and this need is reflected in the specific research questions posed under this Grand Challenge (**Text Box 3**).

Growing evidence shows that projections and predictions of different future states obtained from climate models can be improved through explicit inclusion of the feedbacks to the climate system, resulting in changes in biology and geochemistry (e.g., Lengeigne et al., 2009; Zhang et al., 2009; Jochum et al., 2010). Understanding these processes and linkages is critical for the next generation of climate models and integral to the development of governance strategies (mitigation and adaptation options) to minimise the impacts of climate change on the marine environment and human societies (e.g., Miller et al., 2010).

The knowledge gaps and uncertainties inherent in studies of change make the use of scenarios from global and regional climate models a promising approach to explore drivers, attribution, and the consequences of and potential responses to change (e.g., Moss et al., 2010; Bopp et al., 2013). Regional-scale projections provide a powerful approach to evaluate the effects of climate change on biogeochemical cycles, food web interactions, and human well-being and livelihoods (Cheung et al., 2009; Chust et al., 2014). However, the level of confidence that can be associated with projections and predictions at the regional scale is often low (Wang et al., 2009). Approaches for combining global and regional models and for combining large-scale projections with specific regional information remain to be developed and implemented. Also, global change scenarios (e.g., climate, ocean acidification, fisheries, pollution) need to be evaluated to determine which aspects of ocean systems are missing (e.g., Cheung et al., 2009) and revised to maximize their benefit for future projections.

Similarly, major knowledge gaps remain regarding the potential loss of species diversity and species extinction risk in the sea, the rates of which may be comparable to those for terrestrial systems (e.g., Carpenter et al., 2008). Assessments have been undertaken for marine megafauna and reef-building corals, but less than half the marine fishes and even fewer invertebrates have been assessed. The results of such assessments have important implications for conservation, sustainability of fisheries and other activities, and the well-being of dependent human societies (Worm et al., 2006; Lewison et al., 2014). Understanding and quantifying the processes, drivers, and stressors that underlie the loss of species requires coupling of observational and experimental studies focused at the level of individual species, as well as the overall food web (Text Box 4), and collection of information at space and time scales that allows species loss to be detected.

Text Box 4

Grand Challenge II Priority Research Area
Extinction Risk in the Sea

Overarching Research Question

What are the states and trends of a representative sample of marine species?

Related Questions

How and why does extinction risk to marine species vary among taxonomic groups?

How and why does extinction risk to marine species vary over space?

How and why is extinction risk for marine species changing over time?

Which marine sites contribute significantly to the global persistence of biodiversity?

What are the implications of marine extinction risk for human well-being?

The linkage of modelling structures that can accommodate and simulate ecosystem states resulting from species loss with scenarios of future states provides a powerful approach for assessing the effects of biodiversity changes (e.g., Pereira et al., 2010) that are integral to addressing research questions posed under this Grand Challenge. The addition of impacts of social systems is key to development of policy and governance approaches for mitigating and adapting to changing marine ecosystems. The resultant linked modelling framework will allow issues of the ecological value of marine biodiversity to be addressed and understanding of how species migrations in response to global change will affect marine ecosystems and human society.

2.3 Grand Challenge III –Improving and Achieving Sustainable Ocean Governance

The Challenge: *To improve communication and understanding between IMBeR science, policy and society to achieve improved governance, adaptation to and mitigation of global change, and transitions towards ocean sustainability.*

Rationale: Global change issues are typically viewed as environmental issues, but in reality they are social and human issues within linked social and ecological systems (Perry et al., 2012). Issues of marine governance, including the acquisition, mobilization and provision of evidence-based advice to marine managers, policy-makers, and other research end-users, contribute to transitions towards marine sustainability and are integral components for understanding global change (Bundy et al., 2012; Chuenpagdee and Song, 2012). Because humans are both the main driver and the ultimate recipient of environmental change, it is essential to engage humans, as individuals, communities and governance bodies, in approaches that lead towards sustainable ocean development (Glaser et al., 2012, and references cited within). To do so requires mechanisms that (i) enable interdisciplinary research and cooperation between natural and social scientists and researchers in humanities, and (ii) effective communication and public engagement at local and regional scales.

The priority research areas for Grand Challenge III integrate the science from Grand Challenges I and II to develop new interdisciplinary research approaches and linkages across systems and scales (**Text Box 5**) and strengthen and broaden the science-policy-society interactions and dialogue to provide a more holistic approach which provides the basis for improved understanding and implementation at the science-policy-society interface (**Text Box 6**).

Approaches through interdisciplinary research across the natural and social sciences, humanities and society, are needed to support the decisions that society is facing in terms of

Text Box 5

Grand Challenge III Priority Research Area
Developing new interdisciplinary research linkages and interactions between marine and human systems

Overarching Research Question

How can integrating research across the natural and social sciences and humanities improve our understanding and response to the impacts of global marine change in relation to the livelihood and well-being of coastal and maritime communities?

Related Research Questions

What are the trade-offs amongst the multiple demands on ocean resources and services?

How can IMBeR science best contribute to the provision and implementation of trade-off options for adaptation and mitigation?

How can IMBeR science contribute to the adaptation/adaptive capacity of communities to the cultural, social and ecological consequences of marine global change?

How can natural science, social science and humanities research be integrated into global change science so that it is useful to policy makers and the broader society?

sustainable use, management and conservation of marine resources and services (**Fig. 5**). Addressing Grand Challenge III requires innovative approaches on several levels and in several sectors. Also important are issues of scale, in particular cross-scale linkages in both the spatial and temporal domains.

Knowledge Gaps: Observing past and current human responses to major transitions in harvestable resources in a range of marine environments is only one aspect of research into linkages between ocean and human systems (Visbeck et al., 2014). Identifying the spatial and temporal scales of human responses to local, regional and global marine change, exploring the effects of alternative/adaptive management responses and governance systems on human-related risk exposure and impacts, and quantifying the differences in the local versus distant fisheries on human societies and sustainability are important areas where research is needed (Bundy et al., 2014; Bundy et al., 2016).

Figure 5. Infographic illustrating Grand Challenge III, which incorporates results from Grand Challenges I and II to develop the trade-offs, negotiations, communication and engagement mechanisms and decisions within aspects of natural science, social science and humanities research required for ocean sustainability under global change.

A major challenge to improving the science-policy-society interface is presentation of results from projections in ways that are understandable and useable for managers and policy makers (e.g., Link et al., 2010; Shin et al., 2012; Coll et al., 2016). Information needs to be provided on space and time scales that are relevant for management or policy settings. Current frameworks used by managers and policy makers also need to be adapted to allow for the incorporation of future states/scenarios and responses so that options and management strategies can be developed (see Bundy et al., 2015). Also, marine science results are of interest to managers and policy makers who work outside of marine issues, such as mitigation and adaptation to climate change, the food-energy nexus, decarbonization, human health and pollution. Developing an understanding of what information is needed versus what is possible represents a knowledge gap that needs to be addressed so that advances in this area can be made.

Potential risks and vulnerabilities may arise from new frontiers of economic exploitation of marine resources, such as expansion of energy extraction, mining and maritime transport activities, including fragile areas like the thawing Arctic and many continental margins. There is need for better assessment of potential risks (exposure and impacts) and for identification of vulnerable ecosystems before such activities are carried out. However, not all risks can be reduced to measurable uncertainties, especially when understanding the linkages and interactions between biogeochemical processes, ecosystem functioning, and impact on, and responses of society, is still developing. In addition, there may be unanticipated synergistic impacts between drivers and stressors related to new uses of marine environments and climate change, for example, more and increasingly powerful storms, enhanced warming, sea level rise, and the related migration of communities in response to change.

Text Box 6

Grand Challenge III Priority Research Area Improving the science-policy-society interface

Overarching Research Question

How can IMBeR science inform policy in a changing world, and what is required to improve the science-policy-society interface?

Related Questions

How can the results and predictions from Grand Challenges I and II be translated into acceptable, desirable, feasible strategies to adapt, manage, and govern marine-human systems (more) sustainably?

How can science be designed, generated, communicated and used in policy fora and the public domain?

How can IMBeR science be made more accessible, engaging and understandable?

What mechanisms (including engagement, co-design and co-production) provide the most effective communication and delivery, and how can these be expanded?

Who are the main end-users of marine research, which of their needs can and should IMBeR address, and how can IMBeR ensure their engagement in project activities for mutual benefit?

What scientific evidence-based knowledge do policy makers and other stakeholders and end-users of marine science want, consider important, and need?

How can the scenario approach from Challenge II be extended to connect science to society and policy, and enhance understanding of the linkages between them and likely outcomes?

3. Innovation Challenges

Four Innovation Challenges highlight research topics that are integral to the Grand Challenges and are areas where IMBeR can make progress in the next three to five years. These Challenges focus on metabolic diversity and evolutionary processes, contributions to observing systems, observations and modelling, ecological feedbacks in Earth System models, and integration of social science into ocean research. Priority research questions are provided for each Innovation Challenge.

3.1 Innovation Challenge 1: to enhance understanding of the role of metabolic diversity and evolution in marine biogeochemical cycling and ocean ecosystem processes

Rationale: Marine organisms possess varied and diverse metabolic capabilities that are acted upon by evolutionary processes. Increased understanding of how evolution and metabolic diversity influence species' stability, flexibility and adaptability is key to understanding ecosystem resistance and resilience to change. Metabolic diversity and evolution need to be included in models to better predict ecosystem response to environmental change (**Text Box 7**). This Innovation Challenge is integral to understanding ecosystem responses to natural and anthropogenic changes and interactions across a range of space and time scales (Grand Challenge I) and developing scenarios for projection and prediction of future states (Grand Challenge II).

Knowledge Gaps: Marine species are sensitive to global environmental change, in terms of both total biomass and community composition. Predicting how marine communities, taxa and individual species will acclimate and adapt to environmental change requires an understanding of both the metabolic diversity present in these communities and the influence of evolutionary processes on them (Follows and Dutkiewicz 2011; Doney et al., 2012). The metabolic diversity and evolutionary responses of individual marine species is largely unknown.

Text Box 7

Innovation Challenge 1

Priority Research Questions

How do metabolic diversity and evolutionary processes affect:

a) the role of marine organisms in ocean biogeochemical cycles and food webs?

b) the resilience of marine organisms and their capacity to adapt to change?

What approaches are needed to include metabolism and evolution in marine ecosystem models at multiple scales?

Consequently, how these individual species' responses will influence whole-community responses and ecosystem functioning is based on speculation at best. The application of 'omics techniques (e.g., metabolomics, (meta-)proteomics and transcriptomics) shows promise in terms of providing insights into the in situ metabolic functioning of both individual species and highly diverse communities. The application of population genetics and experimental approaches to evolution will provide insights into the important traits and population characteristics (mutation, dispersal) that play a role in the evolutionary response of organisms to environmental change. In combination with classical approaches, such as morphological taxonomy, the application of 'omics techniques and evolutionary approaches holds promise for revolutionizing our understanding of the range of changes that marine ecosystems may undergo in the future.

3.2 Innovation Challenge 2: to contribute to the development of a global ocean ecosystem observational and modelling network that provides ecosystem Essential Ocean Variables (eEOVs) and to improve marine data and information management

Rationale: The collection of high-quality data in the world's oceans is critical to understanding the drivers of global change on marine ecosystems and human societies and to project their evolution in response to these changes (Grimes 2007; Constable et al., 2016). The IMBeR regional programmes and endorsed projects collect vast amounts of physical, biological and biogeochemical data throughout the world's oceans, which are distributed among many global, regional and national repositories. The ability to evaluate, validate and improve model projections, and to detect long-term trends in ocean and human systems depend on the nature and quality of observations (Doney et al., 2009). Thus, observations will be essential to validate and improve overall model performance (**Text Box 8**). This Innovation Challenge contributes to aspects of all three Grand Challenges, but is particularly relevant to development of scenarios, predictions and projections under Grand Challenge II.

Text Box 8

Innovation Challenge 2

Priority Research Questions

Which new biogeochemical and ecological sensors are needed to support IMBeR science and contribute to the development of existing and planned observational networks and infrastructure?

Which remotely sensed and *in-situ* observation systems are desirable and can feasibly be developed and implemented as part of IMBeR science initiatives?

How can IMBeR contribute to the synthesis and integration of global datasets and link these to ecosystem modelling?

Knowledge Gaps: Understanding and detecting long-term changes in marine ecosystems and feedbacks to global and regional climate requires collection of long-term high-quality data at temporal and spatial scales that resolve the mechanisms controlling the physical, chemical and biological responses to climate changes and their feedbacks (Constable et al., 2016). Equally important is coordination with data and information management systems that allow access and use of large datasets (e.g., remotely sensed data, ‘omics related data) and non-traditional data (case studies, non-geo-referenced) from multiple sources. Coupling between observations and models is critical to the development, testing and routine use of new data collection systems, analysis techniques, and models (Brasseur et al., 2009). The assimilation of marine biological and biogeochemical information from observing systems into coupled physical-biogeochemical-ecosystem models is key to developing predictive capability (Brasseur et al., 2009; Gregg et al., 2009). This requires development of novel techniques for analyses of these data and for assimilation into models.

3.3 Innovation Challenge 3: to advance understanding of ecological feedbacks in the Earth System

Rationale: Ecological processes participate in the storage and flux of carbon dioxide and other greenhouse gases, thereby affecting future climate. For instance, the oceanic uptake of carbon through the solubility and biological pumps is influenced by ecological processes that transform carbon and by physical processes that modify stratification. These biological and physical processes are linked, thereby providing the potential for feedbacks. Understanding these dynamics and feedbacks at seasonal, interannual and decadal scales is critical to interpreting and predicting, or projecting, marine ecological responses to global and local changes (**Text Box 9**). This Innovation Challenge provides important inputs for Grand Challenge II that is focused on improving scenarios, predictions and projections of future states.

Text Box 9

Innovation Challenge 3

Priority Research Questions

How do ocean ecosystem interactions with other components of the Earth System significantly affect climate processes and how are these interactions affected by change?

What level of complexity is needed to represent these interactions and feedbacks?

What approaches are needed for these interactions and feedbacks to be modelled and projected?

How are ocean-human system interactions incorporated into Earth System models?

Knowledge Gaps: Ecological interactions in global and regional models can significantly alter the results of physical and biogeochemical projections and predictions, and hence subsequent biological and biogeographical responses (e.g., Follows and Dutkiewicz, 2011).

Knowledge of feedback processes, their amplitude, and potential evolution is needed to appropriately parameterize coupled physical-biogeochemical-ecological models of the ocean (e.g., Le Quéré et al., 2005). Mechanistic understanding of the feedbacks and the scales over which these operate to control marine ecosystems is integral to the analysis of carbon and other major element cycles and food webs, and in understanding the role of the ocean in the Earth's climate system.

3.4 Innovation Challenge 4: To advance and improve the use of social science data for ocean management, decision making and policy development

Rationale: Data and information (including narratives) are collected on human societies, their past and current coastal and maritime practices, and their beliefs, behaviours and responses to changing marine, social and economic conditions and resource availability. However, much of this information is unevenly distributed in time and space, in contrast to some oceanographic data, that can be collected globally by satellites to provide synoptic, continuous views and can be analysed over a range of spatial and temporal geo-referenced scales. The effective use of social science data and information underlies the research questions within Grand Challenge III, but is also relevant to the coupling of ocean and human systems in Grand Challenges I and II.

Knowledge Gaps: Social science data are generally collected in local or time-bound studies over varying periods of time, sometimes taking years to collect. These data are often collected using a variety of protocols with different objectives and stored in individual databases (that are not readily accessible). In addition, social science data are not always geo-referenced and there may be access restrictions due to privacy protection issues. These differences create challenges for the integration of social and natural science data (**Text Box 10**).

Text Box 10

Innovation Challenge 4

Priority Research Questions

How can coastal community data and information collection and transfer be increased and improved for the end users of marine science?

What are the obstacles to developing a global database of coastal community data collected through a diverse range of research projects, with varying intellectual property protocols? How can they be overcome?

How can data and information collected at different spatial and temporal scales from the social and natural sciences be integrated, analysed and synthesized?

What is needed to improve the capacity for management and use of social science data?

How can linkages between marine ecosystem models and observations be improved to make better use of social science data?

4. Implementation Strategy

IMBeR research is carried out via regional and global programmes, working groups, task teams, endorsed and contributing projects, and biennial IMBIZO conferences and ClimEco summer schools. This current structure (**Fig. 2**) is evolving to phase out working groups and task teams that have achieved their objectives. Task teams with term limits (e.g., 3 years) that are focused on specific aspects of the Grand Challenges and Innovation Challenges are being established. The transition to task teams will optimize scientific focus and provide flexibility in the use of resources.

IMBeR also promotes and forges strong links to relevant projects and programmes, and broadens its network through the supply of information, capacity building, and connections to relevant researchers and stakeholders (see **Appendix 1**). The implementation of these activities is dependent on the magnitude and source of funding. The funding base for IMBeR's basic and applied cross-disciplinary research challenges needs to be expanded to include national and international, private, business and industrial sources. Accessing these disparate funding sources requires alignment of the Grand and Innovation Challenges with mission statements, priority research areas, topical research interests, and national research programmes.

The focus for IMBeR will continue to be on research into sustainable fisheries, healthy oceans, human well-being, biodiversity conservation, fundamental oceanography, biogeochemistry and ecosystems, and making the science relevant to society. Also essential is ensuring that IMBeR science is used to influence decision making to safeguard marine ecosystems and their dependent human societies, that is, to develop a "social contract". Achieving this requires the involvement of a diverse science community drawn from different disciplines, including quantitative global change social science, international relations, and ocean geopolitics.

4.1 Grand Challenges

4.1.1 Grand Challenge I – Understanding and Quantifying the State and Variability of Marine Ecosystems

The IMBeR regional programmes, individually and collectively, provide the scientific expertise to address the overarching and specific research questions posed under this Grand Challenge. The regional programmes effectively bring inter- and multi-disciplinary groups together to develop understanding of how marine ecosystems respond to climate variability and change, and the consequences of this for ecosystem productivity and dependent human communities. The current regional programmes (**Fig. 2**) encompass the global ocean and provide targeted activities in specific regions and ocean basins. Addressing the questions associated with this Grand Challenge requires that the regional programmes continue and expand their efforts to have explicit linkages to human systems.

The IMBeR high-latitude regional programmes, the Ecosystem Studies of Subarctic and Arctic Seas (ESSAS) and the Integrating Climate and Ecosystem Dynamics (ICED) in the Southern Ocean, undertake and are planning studies that address changes in these systems and therefore, the research questions posed under this Grand Challenge. For example, ESSAS is examining water mass exchanges between the Arctic and Subarctic and the fate of material and organisms that are transported with the water, including what will happen under climate change, while ICED is examining the effect of environmental changes on Southern Ocean food webs at a circumpolar scale.

The impact of climate variability and fishing on the structure and function of open ocean pelagic ecosystems and their top-predator species are identified and quantified in the CLimate Impacts on Oceanic Top Predators (CLIOTOP) programme to enhance predictive capability at individual or species levels. The Sustained Indian Ocean Biogeochemistry and Ecosystem Research (SIBER) programme is undertaking studies to address interactions between biogeochemical cycles and marine ecosystem dynamics at basin scales.

The IMBeR working groups also provide structures that bring together experts to address specific aspects of Grand Challenge I. The Continental Margins Working Group, in collaboration with the Future Earth Coasts project, 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 global change scenarios (Glavovic et al., 2015). The IMBeR-Future Earth Coasts joint working group is undertaking scoping studies with the goal of identifying emerging science and social issues in selected contrasting continental shelf systems.

Acidification of the surface ocean and consequent changes in the marine carbonate system have led to changes in biogeochemical cycles, ecosystems and their interactions. IMBeR, in collaboration with the Surface Ocean-

Lower Atmosphere Study (SOLAS) project, supports ocean acidification (OA) science through the development of an OA research community and dissemination of OA research results to stakeholders and policy makers. The joint IMBeR-SOLAS-CLIVAR (Climate and Ocean – Variability, Predictability and Change) Upwelling Systems Working Group focuses on eastern boundary upwelling regions, including oxygen minimum zones, to address aspects of the research questions posed for Grand Challenge I.

The need for 'whole system' understanding requires a thorough examination of interactions between human communities and marine ecosystems. As with natural marine systems, human communities are affected by spatial and temporal variability that impact their livelihood activities and influence their behaviour and decisions. Research on how the social and governing systems operate and interact at different levels and scales is ongoing in the IMBeR Human Dimensions Working Group, focusing mostly on how human communities respond to change (e.g., climate change and over-fishing). IMBeR will undertake research efforts to properly integrate these responses as part of whole-system modelling.

4.1.2 Grand Challenge II – Improving Scenarios, Predictions and Projections of Future Ocean-Human Systems at Multiple Scales

Predicting change in complex ocean and human systems requires exploration of a range of approaches that can be combined to resolve the relative importance of process interactions at different scales. These include comparative studies across many systems, using multi–scale models coupled with high-resolution observations to understand the global functioning of marine ecosystems (see Salihoğlu et al., 2013).

The IMBeR regional programmes are undertaking and planning activities that address the research questions posed under this Grand Challenge. The comparative studies undertaken by ESSAS (Mueter et al., 2009; Drinkwater and Pepin 2013; Hunt et al., 2014), and those in collaboration with ICED (McBride et al. 2014; Hunt et al., 2016) provide a foundation for studies that explicitly consider feedbacks and linkages to human systems across a range of scales. Comparative studies of Southern Ocean ecosystems (Murphy et al. 2013; Murphy et al., 2016) and approaches for evaluating the effects of climate variability on these ecosystems (Murphy et al., 2012, Murphy and Hofmann, 2013) developed by ICED, provide a foundation for developing projections, predictions and future state scenarios that are needed to address the priority research areas of Grand Challenge II. The aim is to develop a series of community-agreed scenarios within the regional programmes for multiple stressors that will be used to develop projections of change for key species, food webs and biogeochemical cycles. This will involve the development of appropriate alternative model structures, drawing on current and planned modelling activities in collaboration with international initiatives in this area, such as the MARine Ecosystem Model Intercomparison Project (MAREMIP) and the Fish Model Intercomparison Project (FishMIP).

The role of changing biodiversity is an important part of scenario development, and information needed for its inclusion will be provided by the comparative studies undertaken by the regional programmes. Collaboration with the International Union for Conservation of Nature (IUCN) provides the opportunity to incorporate these data into a global context and offers additional expertise to assess scenarios and models. Quantification of uncertainties provides a focus for generating and communicating projections that are useful in the development of policy and identifying appropriate management and mitigation procedures.

Collaboration with international observational-based projects, such as the Group on Earth Observations (GEO) and its Global Earth Observation System of Systems (GEOSS) provide access to data networks that are critical for formulating, evaluating and constraining models. In particular, datasets from the SCOR-sponsored GEOTRACES programme are of relevance to the implementation of this Grand Challenge. Results from GEOTRACES provide understanding and data that can be used for the refinement of biogeochemical processes, quantification of fluxes, and assessment of sensitivity to changing environmental conditions. Projections of change and responses of marine ecosystems will be undertaken through integrated research and collaboration between IMBeR and other climate-focused research projects (e.g., CLIVAR, the North Pacific Marine Science Organization (PICES) Forecasting and Understanding Trends, Uncertainty and Responses of North Pacific Marine Ecosystems (FUTURE) programme, the International Council for the Exploration of the Sea (ICES)/PICES Strategic Initiative on Climate Change Impacts on Marine Ecosystems (SICCME)) and other global environmental change projects (e.g., SOLAS, Future Earth Coasts, Past Global Changes (PAGES), Earth System Governance (ESG), bioDISCOVERY, bioGENESIS, International Global Atmospheric Chemistry (IGAC), and Analysis, Integration and Modelling of the Earth System, AIMES).

Scenario development and analysis provides an approach for predicting how human communities respond to change, if information related to social complexity, including how and why people make certain decisions, is available. Decision theory and behavioural economics research are crucial to enhancing this understanding. Decisions are also conditioned by the governing system, thus requiring analysis of formal and informal institutions. Coupling understanding of responses of human communities to change and its linkages to marine ecosystems is a new research area. Incorporating marine social science data into integrated physical-ecological-human modelling frameworks will require new approaches. These integrative approaches, including two-way ecosystem-human coupling, are an opportunity for IMBeR to develop and deploy innovative and new observational technologies, modelling methods, analyses and infrastructure that will produce integrated views of ocean-human ecosystem responses. Through activities such as the IMBIZO, IMBeR can promote dialogue between natural and social scientists in the formulation of methods and enabling mechanisms for interdisciplinary development and analysis of future scenarios. IMBeR will undertake the development of potential scenarios that will challenge cross- and trans-disciplinary research and modelling to produce realistic projections.

4.1.3 Grand Challenge III – Improving and Achieving Sustainable Ocean Governance

The priority research questions posed under this Grand Challenge require interdisciplinary (i.e., different disciplines within the natural and social sciences) and transdisciplinary (i.e., interdisciplinary and include stakeholders, managers, non-governmental organisations) teams. IMBeR is well-placed to contribute from an integrated research perspective and a whole-ecosystem approach, and to attract and lead the development of new partnerships. However, effective communication between natural and social sciences requires development of common concepts, conceptual models, and quantitative models. The research questions posed by IMBeR provide frameworks for the development of effective tools for communication between natural and social scientists, and with decision makers and other stakeholders.

An ocean-human research agenda will facilitate a dedicated effort on critical, emerging issues, such as resilience of marine ecosystems, fisheries and the vulnerability of associated communities. Continued development of conceptual and applied frameworks, such as I-ADApT (IMBeR-Assessment based on Description responses and Appraisal for a Typology; Bundy et al., 2015), provide a foundation for integrated assessment and learning platforms for marine global change responses. Development of integrated indicators/metrics of coupled natural and social conditions, particularly as early warning systems of potentially significant changes in either sub-system (natural or societal), allows assessment and monitoring of the effects on the performance, viability and sustainability of the entire coupled system.

The IMBeR Human Dimensions Working Group is working with the Too Big To Ignore research network, a partner of IMBeR, to apply and fine-tune I-ADApT to develop it into a ‘community tool’ for small-scale fishing communities around the world. There is also a unique opportunity for the IMBeR community to play an important role in the implementation of the Food and Agricultural Organisation Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries, by contributing better understanding of marine ecosystems for the ecosystem-based management principle that the guidelines embrace.

4.2 Innovation Challenges

The Innovation Challenges focus on research areas that are intended to advance the Grand Challenges in a three- to five-year time frame. The Challenges will be reviewed, progress assessed, and new Challenges developed through IMBeR activities, such as the biennial IMBIZO. The Innovation Challenges provide flexibility to modify IMBeR's science focus, respond to emerging science issues, and incorporate new research results.

4.2.1 Innovation Challenge 1 – To enhance understanding of the role of metabolic diversity and evolution in marine biogeochemical cycling and ocean ecosystem processes

Understanding the evolution and adaptive capacity of marine ecosystems is fundamental to the development of scenarios, and projections and predictions of future states. This innovation challenge will provide the mechanistic basis needed to ascribe cause and effect to species' responses to drivers, stressors and change. As such, this Innovation Challenge is relevant to all aspects of IMBeR. The IMBeR regional programmes, and national and endorsed programmes, provide venues for implementing experimental and observational studies related to this Challenge. Results from this Innovation Challenge provide critical information for the modelling activities undertaken as part of Grand Challenges I and II.

Effective implementation of this Challenge requires expertise in population genetics and experimental evolution approaches and the ability to blend this with traditional approaches (e.g., taxonomy). Rapid methods for understanding the response of organisms to environmental changes are needed. A key aspect of successful implementation of this Innovation Challenge is interaction with modellers who can explore the use of such new information in describing ecosystem functioning and responses to stressors and drivers, and in the development of scenarios and projections. The IMBeR regional programmes, and endorsed projects provide the means to develop the research community that can provide and use the information generated under this Innovation Challenge. Targeting researchers with the required expertise for inclusion in activities, such as science meetings and working groups, provides one approach for implementation. It is particularly important to focus on early-career researchers who are adopting techniques from other fields (e.g., 'omics from human biology) and applying them to the marine environment. Also, through collaboration with Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES)-related initiatives, IMBeR is well positioned to adopt and apply these new technologies and conceptual frameworks, and to help understand the limitations of their usage.

Proactive development of scientific and technical strategies to deal with the large and complex datasets that will emerge from 'omics research are needed, and these can build upon recent and existing data systems (e.g., Ocean Biogeographic Information System (OBIS), International Census of Marine Microbes (ICoMM), Global Biodiversity Information Facility (GBIF), IPBES, bioGEOTRACES). Activities undertaken through Innovation Challenge 2 will contribute to the use of these data systems.

4.2.2 Innovation Challenge 2 – to contribute to the development of a global ocean ecosystem observational and modelling network that provides ecosystem Essential Ocean Variables (eEOVs) and to improve marine data and information management

IMBeR is dedicated to the collection of recommended ecosystem Essential Ocean Variables (eEOVs), such as surface and subsurface physical (e.g., temperature, salinity, currents), chemical (e.g., nutrients, oxygen, carbon, ocean tracers) and biological (e.g., plankton, fish) variables (Constable et al., 2016). These eEOVs, collected through IMBeR programmes and projects, use the Framework for Ocean Observing best-practice guidelines, for setting requirements, coordinating observation networks, and delivering information products for sustained global ocean observing to address scientific and societal issues. Also, the EOVs proposed by the International Ocean Carbon Coordination Project (IOCCP), are relevant to this Innovation Challenge because these provide an analysis of the accuracy, observation strategy, sensor and infrastructure readiness. These international activities provide a basis around which IMBeR can coordinate and contribute to the collection of eEOVs.

Satellite and other remote-sensing and autonomous measurements are integrated into all aspects of IMBeR science (**Fig. 3**). New satellite missions planned for launch in the next 5-10 years (e.g., NASA Pre-Aerosol, Cloud, and ocean Ecosystem (PACE) and the European Space Agency (ESA) Sentinel missions of the Copernicus programme) will enhance understanding of climate-physical-ecological processes and linkages. The data streams from these missions will provide information that is needed to predict responses to climate and environmental change. Regional programme activities under this Innovation Challenge will provide the analysis of these data that will inform the questions posed under Grand Challenges I and II.

Continued deployment of biological sensors on physical observational platforms such as moorings, gliders and (BGC-) Argo floats (e.g., Claustre et al., 2010) and emerging new technologies (e.g., in-water microbial sensors, genetic fingerprinting) will be promoted along with strategies for the collection, quality control and dissemination of the data. Explicit goals and timelines for these efforts will be defined to maximize connection with existing initiatives, such as the Integrated Ocean Observing System (IOOS), the International Ocean Colour Coordinating Group (IOCCG), and the Global Ocean Data Assimilation Experiment (GODAE). Continuation and expansion of ocean data systems and platforms (e.g., Continuous Plankton Recorder, Atlantic Meridional Transect) and analyses of these data are important for Grand Challenge I. Similarly, maintenance of existing long term (e.g., decades) time-series sites is critical, as is expansion of these sites to accommodate new sampling technologies and new sensor deployments. These data systems will be used and supported through ongoing regional programme activities as part of SIBER and ICED, for example. Global coordination and/or synthesis of higher trophic level acoustic surveys and animal-carried instrument and tagging deployments are integral to CLIOTOP activities. Large multi-decadal datasets from research vessels and ships of opportunity from individual ecosystems, nations, and institutes that are not well integrated or easily accessible for the international research community will also be sourced.

Improved data and information management systems that allow access and use of large datasets (e.g., remotely sensed data, 'omics related data) and non-traditional data (case studies, non-geo-referenced) from multiple sources are needed. A challenge for data management is to identify and tag data derived from IMBeR-related and endorsed activities. Currently, data from IMBeR activities are dispersed in a variety of databases, with varying levels of accessibility and quality control. The development of an IMBeR metadata catalogue that links to these databases provides one possible solution that can be implemented in collaboration with existing data management systems (e.g., Global Change Master Directory), but maintenance of such a system requires dedicated resources.

Partnerships with organisations such as the Research Data Alliance (RDA) the Belmont Forum e-Infrastructures and Data Management Collaborative Research Action, and the European Marine Observation and Data Network (EMODNet) provide an approach for implementing IMBeR-wide efforts to enhance knowledge transfer within and between IMBeR activities, with its partners, and with science end users at national, regional and global levels. The Ocean Acidification International Reference User Group (OA-iRUG), in which IMBeR participated, is an example of successful knowledge transfer across disciplines and users.

Combining observations with numerical ecosystem models enhances the information value of observations and improves model results. Model-data fusion provides important realistic information, especially of combined spatial and temporal ecosystem variability, that is not possible from measurements alone. The use of tools such as Observing System Simulation Experiments (OSSE) provides an approach for implementing optimized integrated observing-modelling systems for regional programmes and contributing projects.

4.2.3 Innovation Challenge 3 – to advance understanding of ecological feedbacks in the Earth System

Biotic interactions are important components of the climate system. Plankton dynamics can affect the thermal stratification of the upper ocean (e.g., Murtugudde et al., 2002; Wu et al., 2007; Zhang et al., 2009), alter upper ocean seawater viscosity (Stachowitsch et al., 1990; Seuront et al., 2010), increase cloud cover and hence albedo by dimethyl sulfide production (Malin and Steinke 2004), and influence diapycnal mixing (Kunze et al., 2007; Dabiri 2010). These interactive processes may in turn influence the persistence of phytoplankton blooms and hence biogeochemical dynamics (Jolliff and Smith, 2014). The efficiency of the biological pump varies depending on the planktonic species, which in turn affects carbon dioxide build-up in the atmosphere (Manno et al., 2015, Turner, 2015). Potential changes in plankton species abundance and distribution will alter carbon export and sequestration in the ocean (Ainsworth et al., 2011). These species occur as part of oceanic food webs and their responses to change are determined in part by trophic interactions and associated feedbacks that affect the resilience properties of the ecosystems in which they occur (Mukherjee et al., 2015; Saint-Beat et al., 2015). How such biological interactions influence climate processes and the impacts of change within ecosystems is poorly understood. The extent to which such interactions generate feedbacks that may act to amplify or dampen climate changes or moderate the biogeochemical and ecological consequences of change is also largely unknown. Capturing the biological complexity of these effects to underpin approaches and methods for inclusion in climate and Earth System models remains to be done.

The ocean ecosystem model intercomparison exercises (MAREMIP and FISH-MIP) provide a strong basis for addressing the research questions posed under this Innovation Challenge, and can be linked to developing analyses within the regional programmes. The high-resolution coupled circulation-ecosystem models developed through the programmes provide specific frameworks for determining the importance of biological feedbacks in a range of systems and for developing approaches to represent these in climate and Earth System models. Expanding these regional results to larger scale climate and Earth System models can be done thorough partnerships with the World Climate Research Programme (WCRP).

The IMBeR-SOLAS carbon working groups have made considerable progress in understanding the biological pump and carbon export, and in developing databases that can be used to constrain and validate carbon transport estimates. The IOCCP/IMBeR/SOLAS Surface Ocean CO_2 Atlas (SOCAT) is a valuable ongoing activity that provides a synthesis of surface ocean marine carbonate chemistry measurements that can be used to quantify trends in the ocean carbon sink and ocean acidification (Bakker et al., 2016). Continuing activities that include collaborations with the regional programmes, with a strong focus on quantifying the importance of changes in food web structures, will ensure incorporation of these results into regional and large-scale climate models.

4.2.4 Innovation Challenge 4 – to advance and improve the use of social science data for ocean management, decision making and policy development

Data collected in the natural and social sciences differ in availability, accessibility, storage, management, analysis and synthesis. There is an urgent need to develop the infrastructure to provide wide-spread access to marine social science data to enhance understanding of social–ecological systems and enable end users to address pressing resource-related challenges. There is a need for capacity building in data management and analysis, and quantitative (e.g., statistical and computational) and qualitative skills to access and fully utilise the data, and to integrate data across disciplines, platforms and activity sectors. Existing marine social science data also need to be archived in readily accessible formats.

The I-ADApT framework is an approach for compiling social science data within a format that can be used to address approaches for responding to climate change. This Innovation Challenge will be implemented through expansion of I-ADApT to help decision makers and other end users prioritize and improve their actions, make decisions efficiently, and evaluate how and where to most effectively allocate resources to reduce vulnerability and enhance resilience of coastal people to global change.

4.3 Capacity Development and Outreach

The three IMBeR Grand Challenges and four Innovation Challenges require the development and optimization of human and research capacity in the international science community. As an integrated, global environmental change research project, IMBeR fosters research within and across disciplinary boundaries. The key to success is to develop capacity to conduct the necessary integrated research and synthesise the approaches and results provided by both natural and social sciences, that is, to develop an interdisciplinary approach.

Fostering interactions across disciplines and programmes to identify synergies and common problems and approaches is critical to address the Grand Challenges and Innovation Challenges. The 2014 IMBeR Open Science Conference (OSC) provided opportunities for this type of interaction, as well as a mechanism for capacity development, learning and training at all career levels. The success of the OSC in bringing together an interdisciplinary science community was such that IMBeR will convene OSCs at five-year intervals to engage the community and assess progress in addressing the Grand Challenges and Innovation Challenges. Future OSCs will include more training activities for early-career scientists, such as best practices for science communication, engagement with the public, and publication. Activities to ensure longer-term impacts, such as e-lectures and publications, will also be incorporated into OSC planning.

The science symposia convened by CLIOTOP, ESSAS, ICED and SIBER activities provide more focused community engagement across disciplines and projects. These activities have been successful in engaging and fostering the development of a research community focused on the objectives of these regional programmes. These meetings and interactions will be continued and expanded.

Training activities and summer schools are effective for developing disciplinary, inter- and transdisciplinary scientific and technical capacity. The biennial IMBeR IMBIZOs and ClimEco summer schools are successful examples of an integrated approach for capacity development. However, by design, these activities have limited participation and networking of participants must be sustained over longer time periods to have measureable impacts. The challenge is to develop more robust and extensive approaches through the existing and new regional programmes and working groups (see **Fig. 2**) to engage the larger international community at all career levels. Assessment of the long-term effectiveness of the IMBIZOs and summer schools is also needed. Some impact occurs via social media (e.g., Facebook, Twitter and WhatsApp) that maintains contact among participants. The post-event networking will be expanded to develop quantitative measures of effectiveness (i.e., retention in field, development of collaborative projects) and creation of an Early-Career Scientists Network.

The Capacity Building Task Team suggested approaches (see Morrison et al., 2013) to enhance human capacity through existing activities and networks (e.g,. travel grants, mentoring, social networking). In addition to these approaches, IMBeR's new research agenda requires larger scale capacity building efforts to align its scientific goals with the scientific needs and priorities of the researchers and countries/institutions involved (Morrison et al., 2013). Capacity building is already underway as part of the regional programmes, working groups, and other organisations and initiatives (e.g., PICES, Association of Polar Early Career Scientists) that include contributions from IMBeR researchers. However, these activities require expansion and additional resources to have long-term impacts. The connectivity afforded by social media and Internet access provides opportunities to engage a global audience that crosses disciplines in developed and developing countries. Online tutorials, webinars, and other engagement activities related to IMBeR science, and hosted by IMBeR scientists, provide one approach for engaging a larger community.
The development of massive open-access online courses based on IMBeR summer school lectures, presentations from IMBIZO workshops and working group activities, will ensure that information is preserved, archived and made accessible to a larger audience. Hosting such products by a single entity (IMBeR) with connections to other organisations and groups will make access easier and more direct.

IMBeR will build upon its success by continuing to offer opportunities for a variety of researchers at different career stages to engage in research and capacity-building activities (e.g., summer schools, IMBIZOs, conferences). The focus will be on integration of capacity building in all IMBeR regional programmes, working groups, and task teams.

4.4 IMBeR Scientific Steering Committee and Project Offices

IMBeR science is directed and coordinated by a Scientific Steering Committee (SSC) composed of volunteers from the international science community. The SSC members are appointed based on nominations received in response to an open call that is widely disseminated within the marine community, advertisement via other relevant societies and organisations, recommendations by SSC members, and approval by the project's sponsors. The rotation of SSC members and the corresponding expertise in the SSC reflect the changing emphasis in IMBeR science. The composition of the SSC will continue to be modified, in consultation with its sponsors, to best serve IMBeR's science goals and mission. Representatives from the regional programmes and working groups who serve either as full members of the SSC or invited ex-officio participants, are an important liaison between their respective research communities and the IMBeR SSC.

The IMBeR International Project Office (IPO) and Regional Project Office (RPO) are vital components of IMBeR. The IPO, presently located at the Institute of Marine Research (IMR), Bergen, Norway, provides coordination and management at local, national, regional and international levels. The IPO assists with fund-raising activities to support working groups, workshops, conferences and summer schools that further IMBeR science. It also assists with dissemination of IMBeR science results via its website, social media, newsletters and publications. The IPO will be hosted at IMR until 2020, after which it will be relocated.

The RPO, based at East China Normal University (ECNU), State Key Laboratory of Estuarine and Coastal Research (SKLEC), Shanghai, People's Republic of China, facilitates IMBeR-related projects in the Asia-Pacific region and supports international initiatives. Such regional nodes are critical for the dissemination of IMBeR science and the establishment of additional regional nodes will provide greater impact. This RPO will be maintained at ECNU, at least until 2020.

4.5 Funding

IMBeR has ongoing efforts to provide financial support for the activities of regional programmes, working groups, project-wide activities and events, and educational and training initiatives. IMBeR is fortunate to have had strong institutional sponsors in the International Geosphere-Biosphere Programme (IGBP) and SCOR; both worked with the project to secure funding for activities. With the transition to Future Earth, IMBeR is expanding its remit to include applied research and delivery of results to key end users such as marine resource managers and policy advisors (Grand Challenge III), while maintaining a strong research basis and strengthening its community (Grand Challenges I and II). This broadening of scope means that IMBeR's funding base must increase. IMBeR will continue to work with SCOR to develop and submit proposals for funding of activities. A funding strategy developed through Future Earth is needed to support IMBeR's expanding activities in the integration of social sciences and policy with natural science.

Regional programme and working group activities will continue to be supported at some level through IMBeR core funding, although with the inclusion of new initiatives anticipated as part of Future Earth, these funds will be more thinly spread. A proactive approach by the IPO and RPO, in collaboration with the Future Earth Secretariat, to identify and secure additional funding for these activities is required. Continued support from SCOR, realistic matching support from Future Earth as an IMBeR co-sponsor, and secured, ad-hoc national and international funding sources and private foundations are critical to the success of the project.

Funding opportunities to support IMBeR summer schools, conferences and meetings will be identified and applied for, in addition to funding proposals submitted with SCOR. Funding requests targeted to specific agencies or organisations, such as the Asia-Pacific Network that supported activities of the Capacity Building Task Team and a ClimEco summer school, are critical for continuation of many IMBeR activities.

An important contribution to IMBeR is the support provided for the IMBeR IPO and RPO by their respective national funding agencies and host institutions. The support from the host institutions (respectively, the Institute of Marine Research, and the State Key Laboratory of Estuarine and Coastal Research/East China Normal University (SKLEC/ECNU)) and national funding agencies (Research Council of Norway) is gratefully acknowledged. Continuation of this support is critical for the ongoing success of IMBeR.

4.6 Alignment with International Research Programmes and Collaboration with Relevant Research Projects and Initiatives

IMBeR's marine focus provides an important and critical component of Earth System research. Through its activities, IMBeR has increased the knowledge of key interactions in marine ecosystems, their role in the Earth System, responses to global change, and responses of society to these changes. Understanding and quantifying marine ecosystem processes continues as a focus for IMBeR (Grand Challenge I) and will be expanded to consider projection, prediction and scenario evaluation (Grand Challenge II).

Implementation of Grand Challenges I and II is aligned with SCOR's overall goal of fostering ocean research to improve conceptual understanding and advance methodological approaches for marine research. The Innovation Challenges, especially Innovation Challenge 2, address topics that are relevant to ongoing and planned SCOR activities.

IMBeR's research agenda aligns well with the research themes of Future Earth. The innovation challenges address aspects of all three Future Earth themes. The *Dynamic Planet* and *Global Sustainability and Development* research themes are captured in IMBeR's Grand Challenges I and II and the related priority research areas provide direction as to how IMBeR will contribute to these two themes. Future Earth's *Transformations Towards Sustainability* theme is encompassed in IMBeR Grand Challenge III. IMBeR brings to Future Earth an integrated and interdisciplinary global environmental change project that is implementing activities to connect natural and social sciences at different spatial and temporal scales, with a local, regional and global focus. The Future Earth Ocean Knowledge Action Network (KAN) provides an opportunity to implement activities related to the IMBeR Grand Challenges and to expand these into additional research areas, building on established and new collaborations between the SCOR and Future Earth core projects. The Ocean KAN provides a forum for strengthening natural-social science activities and for engaging in research that goes beyond the Grand Challenges, such as marine pollution and geoengineering. The IMBeR community is well poised to be a major contributor to Future Earth marine initiatives including an Ocean KAN.

IMBeR's emphasis on projection, prediction and scenario evaluation for coupled ecosystem modelling studies (Grand Challenge II, Innovation Challenge 3) and observations (Innovation Challenge 2) provides a natural link with the WCRP grand challenges that focus on understanding climate changes and sensitivities to these changes. Collaboration with the WCRP core project CLIVAR allows advances in combining physical climate and ecosystem processes to improve climate and Earth System models.

All the Grand Challenges and Innovation Challenges have requirements for ocean observations. Observational activities to meet these needs will be implemented through the regional programmes and endorsed projects. A partnership with the Global Ocean Observing System (GOOS) will provide observation and data management strategies, governance structures, and capacity to facilitate implementation. GOOS also provides connection to an international community that is developing operational observing and forecasting systems. The resources afforded by a partnership with GOOS will strengthen the observational and data management aspects of IMBeR science, and IMBeR can contribute to the operational systems with ecosystem data and models. Also, the recent development of the GOOS Biology and Ecosystems Panel and Biogeochemistry Panel provides a natural link for IMBeR working groups, regional programmes, and researchers to provide inputs and be participants in GOOS activities.

5. 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 organisations. Such comparisons and sharing of knowledge are essential when addressing complex, multi-scale issues across natural and human systems. 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, which is an advantage because it allows development of research activities 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 interactions. 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. Reaching and engaging this wider community of researchers depends on linkages to ongoing and planned research initiatives, partnerships with national and international organisations, and recruitment of experts from the social sciences and humanities.

The integrated research agenda for the next decade outlined in this SPIS supports IMBeR's new vision and goal, maintains a strong commitment to basic, curiosity-driven marine science and expands 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.

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Appendix 1. Partner Organisations

AIMES	Analysis, Integration and Modelling of the Earth System http://www.aimes.ucar.edu
APECS	Association of Polar Early Career Scientists http://www.apecs.is
BFe-Inf	Belmont Forum e-Infrastructures and Data Management Collaborative Research Action www.bfe-inf.org
BioDISCOVERY	http://www.biodiscovery.com
bioGENESIS	http://www.futureearth.org/projects/biogenesis
CLIOTOP	CLimate Impacts on Oceanic Top Predators http://www.imber.info/en/projects/imber/science/regional-programmes/cliotop
CLIVAR	Climate and Ocean – Variability, Predictability, and Change project http://www.clivar.org
ECNU	East China Normal University, Shanghai, China http://english.ecnu.edu.cn
EMODnet	European Marine Observation and Data Network http://www.emodnet.eu
ESG	Earth System Governance http://www.earthsystemgovernance.org
ESSAS	Ecosystem Studies of Subarctic and Arctic Seas http://www.imr.no/essas
FishMIP	Fish Model Intercomparison Project https://www.isimip.org
Future Earth	http://www.futureearth.org
Future Earth Coasts	https://www.futureearthcoasts.org
GCMD	Global Change Master Directory http://gcmd.nasa.gov
GEO	Group on Earth Observations http://www.earthobservations.org
GEOSS	Global Earth Observation System of Systems http://www.earthobservations.org/geoss
GEOTRACES	An International Study of the Marine Biogeochemical Cycles of Trace Elements and Their Isotopes http://www.geotraces.org
GODAE	Global Ocean Data Assimilation Experiment https://www.godae-oceanview.org
ICED	Integrating Climate and Ecosystem Dynamics in the Southern Ocean http://www.iced.ac.uk
ICES	International Council for the Exploration of the Sea http://www.ices.dk

IOCCG	International Ocean Colour Coordinating Group http://ioccg.org
ICoMM	International Census of Marine Microbes http://icomm.mbl.edu
IGAC	International Global Atmospheric Chemistry http://www.igacproject.org
IMR	Institute of Marine Research, Bergen, Norway http://www.imr.no/en
IOC	Intergovernmental Oceanographic Commission of UNESCO http://www.ioc-unesco.org
IOCCP	International Ocean Carbon Coordination Project http://www.ioccp.org
IOCCG	International Ocean Colour Coordinating Group www.ioccg.org
IOGOOS	Global Ocean Observing System in the Indian Ocean http://www.incois.gov.in/portal/iogoos/home.jsp
IOOS	Integrated Ocean Observing System https://ioos.noaa.gov
IUCN	International Union for Conservation of Nature https://www.iucn.org
IPBES	Intergovernmental Platform on Biodiversity & Ecosystem Services http://www.ipbes.net
LOICZ	Land-Ocean Interactions in the Coastal Zone project
MAREMIP	MARine Ecosystem Modelling Intercomparison Project http://www.aimes.org.uk/activities/maremip
OA-iRUG	The Ocean Acidification International Reference User Group www.iaea.org/ocean-acidification/page.php?page=2198
OSSE	Observing System Simulation Experiments http://cimss.ssec.wisc.edu/model/osse/osse.html
PAGES	Past Global Changes http://www.pages-igbp.org
PICES	North Pacific Marine Science Organization https://www.pices.int
RDA	Research Data Alliance https://rd-alliance.org
SCOR	Scientific Committee on Oceanic Research http://www.scor-int.org

SIBER	Sustained Indian Ocean Biogeochemical and Ecosystem Research http://www.incois.gov.in/Incois/siber/siber.jsp
SKLEC	State Key Laboratory of Estuarine and Coastal Research http://english.sklec.ecnu.edu.cn
SOCAT	Surface Ocean CO_2 Atlas http://www.socat.info
SOLAS	Surface Ocean - Lower Atmosphere Study http://www.solas-int.org
SOOS	Southern Ocean Observing System http://www.soos.aq
TBTI	Too Big To Ignore http://toobigtoignore.net
US-OCB	U.S. Ocean Carbon Biogeochemistry http://www.us-ocb.org
WCRP	World Climate Research Programme http://wcrp-climate.org