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Foreword

The Scientific Committee on Oceanic Research (SCOR) and the International Geosphere-Biosphere Programme (IGBP) stimulated the development of two large-scale international ocean research projects (among others): the Global Ocean Ecosystem Dynamics (GLOBEC) and Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) projects. GLOBEC, which focused on how climate and physical oceanography affect marine ecosystems, has been a highly successful project. The IMBER project was launched when GLOBEC was well under way, and focuses on the interactions between the chemical cycles of the ocean and marine life. The two projects have since worked together on topics of mutual interest.

Although GLOBEC finished at the end of 2009, the project has identified many interesting research questions. With the understanding that IMBER would be best suited to pursue the outstanding questions, IGBP and SCOR commissioned this supplement to the *IMBER Science Plan and Implementation Strategy* to facilitate a successful transition. As this report – compiled by scientists familiar with the two projects – demonstrates, the challenge for IMBER will be to prioritise among the activities identified in this plan in the context of its ongoing work and limited budgets and staffing.

The production of this addendum has greatly benefited from the valuable assistance of Bjørn Sundby (SCOR) and C. T. Arthur Chen (IGBP). We would also like to acknowledge four anonymous reviewers, whose constructive comments helped improve the science plan.

Ed Urban and Wendy Broadgate
SCOR and IGBP Secretariats

Supplement to the IMBER Science Plan and Implementation Strategy

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The team is grateful to Raleigh Hood, who participated in discussions of SIBER.

This Transition Task Team was set up to recommend to the Scientific Committee on Oceanic Research (SCOR) and the International Geosphere-Biosphere Programme (IGBP) how the second phase of the IMBER (Integrated Marine Biogeochemistry and Ecosystem Research) project should proceed to accommodate new developments in marine ecosystem research that need addressing after the completion of the GLOBEC project at the end of 2009.

The team met in Reading, UK from 30 July to 1 August 2008 and in Washington, DC from 15 to 17 December 2008. A draft was circulated to sponsors and to GLOBEC and IMBER Scientific Steering Committee (SSC) members and posted on the websites. Some modifications have been made to this version as a result of these inputs.

The team's terms of reference are summarised as:

To prepare a supplement to the IMBER Science Plan and Implementation Strategy, bearing in mind

1. Key new scientific questions arising from GLOBEC
2. Scientific results of IMBER to date
3. New developments in marine ecosystem science
4. Projects currently within GLOBEC that are planned to continue after 2009 (especially the CLimate Impacts on Oceanic TOp Predators (CLIOTOP) and Ecosystem Studies of Sub-Arctic Seas (ESSAS) projects).

The team was also encouraged to provide IGBP and SCOR with recommendations for mechanisms to facilitate the transition, including representation in programmatic structures.

The team's recommendations, which include a draft Implementation Strategy for a second phase of IMBER (2010-2014), supplement the *IMBER Science Plan and Implementation Strategy* (SPIS) published by IGBP in 2005. The supplement is built upon the IMBER Science Plan, and is intended to advance the existing Implementation Strategy (pp. 47-56) by incorporating the plans described therein plus new insights from the GLOBEC project and the general marine scientific community. It is not a detailed implementation plan; rather such plans have been, or will be, developed by the regional programmes or topical working groups. It is noted that several potential regional programmes of IMBER are only just starting and most are planned as ten-year programmes running well after the present projected life of IMBER. Thus there may be a need for a follow-on ocean research programme after IMBER ends in 2014.

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Background

The IGBP-SCOR Ocean Vision (2004) summarises the role of the ocean in the Earth system and focuses on i) understanding the role of the ocean in Earth system biogeochemistry and ii) predicting the consequences of global change for ocean biogeochemistry and biology, as a means to investigate pathways towards sustainability. In this context, we view the vision of IMBER:

> *"To provide a comprehensive understanding of, and accurate predictive capacity for, ocean responses to accelerating global change and the consequent effects on the Earth system and human society."*

Leading to the IMBER goal:

> *"To investigate the sensitivity of marine biogeochemical cycles and ecosystems to global change, on timescales ranging from years to decades."*

As a starting point, the task team decided to base its work on an integrative definition of an ecosystem as "*a natural unit consisting of all plants, animals, humans and micro-organisms (biotic factors) in an area functioning together with all of the non-living physical (abiotic) factors of the environment*". (adapted from: Christopherson 1996)

The broad nature of ecosystems has led to a spectrum of approaches to studying ecosystems, ranging from a biogeochemical approach emphasising fluxes of carbon and nutrients and the role of micro-organisms on the one hand, to the approach of population dynamics, biological communities and animal behaviour on the other. These approaches are exemplified in the marine environment by the approaches of JGOFS (Joint Global Ocean Flux Study) and GLOBEC, respectively. IMBER aims to bring these approaches together and integrate them in the modern framework of Earth System Science. Hence, it is important to use the term "ecosystem" in its integrative sense, realising that ecosystems (as defined above) are open systems incorporating physical factors, biogeochemical cycles and living populations in interaction with other components of the Earth system such as human societies, atmosphere, land, etc.

Several important issues have emerged since the original IMBER Science Plan was completed, or have remained and grown in importance since that juncture. The issue of ocean acidification was identified in the IMBER Science Plan, but now needs more emphasis in Phase II. Another new area of development is in the assessment and comparison of the ability of coupled biogeochemical - ecosystem models to project ecosystem responses to different global change scenarios. This includes using nested models to scale down from global to regional scales and assimilate data from observing systems into ecosystem models. A third issue concerns new metabolic pathways, biogeochemical processes and the newly recognised roles of viruses, Archaea and other members of microbial communities. With accelerating global change, the urgency of achieving the IMBER vision and goal is even more apparent five years after the IMBER Science Plan was written. Meeting this goal will build on the IMBER activities to date (Box 1).

Box 1. IMBER Activities

Reports:

- IMBER Science Plan and Implementation Strategy (http://www.imber.info/products/IMBER_SPIS_Final.pdf)
- ICED Science Plan and Implementation Strategy (http://www.imber.info/products/ICED_Finaltoprint.pdf)
- Joint SOLAS-IMBER Ocean Carbon Research Implementation Plan (http://www.imber.info/products/Carbon_Plan_final.pdf)
- Capacity Building Implementation Strategy (http://www.imber.info/products/Capacity_Building_final.pdf)
- Communication Plan (2005-2014) (http://www.imber.info/products/IMBER%20Communication%20plan.pdf)
- Joint IMBER-LOICZ Continental Margins: Linking Ecosystems Implementation Plan (in preparation)

Working groups:

- End-to-end Food Webs (http://www.imber.info/e2e_WG.html)
- Joint IMBER/SOLAS Carbon (http://www.imber.info/C_WG.html)
- Capacity Building (http://www.imber.info/CB_WG.html)
- Joint IMBER/LOICZ Continental Margins (http://www.imber.info/CM_WG.html)
- Data Management (http://www.imber.info/DM_home.html)

Regional activities:

- ICED Integrating Climate and Ecosystem Dynamics (http://www.imber.info/ICED.html)
- SIBER Sustained Indian Ocean Biogeochemical and Ecological Research (http://www.imber.info/SIBER.html)

IMBER science conferences:

- 17-21 September 2007
  "Impacts of global, local and human forcings on biogeochemical cycles and ecosystems. IMBER/LOICZ Continental Margin Open Science Conference". Shanghai, China (http://www.imber.info/jobs-announcements/EOS_Cont_Margins_Feb08.pdf)
- 9-13 November 2008
  "First IMBER *Imbizo*: Integrating biogeochemistry and ecosystems in a changing ocean".
  Miami, FL, USA (http://www.imber.info/IMBIZO.html)

Box 2. Selected GLOBEC science highlights

Advances in understanding of marine population variability in response to environmental variability that resulted from GLOBEC science provide the basis for many of the regionally based science programmes that are going forward under IMBER. These advances provide changes in conceptual views of variability of marine food webs and populations, as well as changes in views of approaches to marine research programmes.

Understanding scales of processes

1. An awareness of the scales of natural climate variability has resulted in recognition that ecosystems respond to climate variability over timescales from seasonal to multi-decadal and beyond.

2. The view of marine ecosystems has changed from one that was characterised by variability about a constant state to one of regime shifts that considers a potential transition from one mean state to another.

3. The importance of regional regime shifts for marine resources has led to improved understanding of coupling between coastal, open ocean and atmospheric systems.

4. An emergent issue from GLOBEC science is the importance of thresholds (tipping points) that trigger responses from one marine ecosystem state to another due to climate and human-induced variability.

5. The variability of environmental forcing, and of populations and ecosystems, emerged as an important theme in GLOBEC.

A new view of food webs and population dynamics

1. The recognition of the importance of functional diversity and size in marine food webs has changed our view of food webs to one of a linked system of alternate trophic pathways within food webs that change in importance in response to either top-down or bottom-up forcing.

2. The importance of top predators in influencing marine food-web structure and function has been clearly demonstrated in many GLOBEC science programmes.

3. The changing view of food webs that includes the concept of dual pathways, which are composed of slow and fast response pathways, has provided insights into ecosystem resilience in response to natural and anthropogenic forcings.

4. The elucidation of key processes such as enrichment, concentration and retention linking larval survival to environmental factors, and hence controlling recruitment of marine fishes.

5. GLOBEC has advanced the concept of the importance of humans as predators in marine food webs and the importance of marine ecosystems to humans and human well-being.

New approaches to research

1. GLOBEC fostered an important shift in how research programmes are structured by including integration of coupled physical-biological modelling (along with observations) from the initial phases of research programmes.

2. GLOBEC showed the feasibility and importance of inclusion of climate processes in ecosystem models, from phytoplankton to long-lived top predators.

Box 2. Selected GLOBEC science highlights (continued)

3. GLOBEC science has provided concepts, data and models that have been incorporated to strengthen ecosystem approaches to management of marine living resources, thereby providing a direct transfer of basic science results to applications.

4. The integration of physical and biological processes across a range of scales through the coupled models developed during GLOBEC has made projection of marine ecosystem response to climate change a feasible goal.

Importance of the comparative approach

1. GLOBEC adopted a target species approach to facilitate comparisons of properties of different ecosystems across trophic levels and/or trophic function.

2. Coupled physical-biological models provided the means for effective integration and synthesis across programmes, facilitating comparisons among systems and regions.

3. Comparative studies of responses of human systems to environmental and/or socio-economic forcing showed the important consequences of these for marine food webs.

The Transition Task Team has selected various GLOBEC science highlights (Box 2) to illustrate some of the relevant scientific issues considered by the group in preparing this document. These are taken from the GLOBEC synthesis book (Barange *et al.* 2010)

The selected GLOBEC science highlights (Box 2) and emerging science themes (Box 3) provide IMBER Phase II with the opportunity to integrate ecosystem studies in new and innovative ways. Research programmes and science directions developed around these results and emerging themes are consistent with the programmatic vision and goal originally articulated in the IMBER Science and Implementation Plan. The new ideas and approaches developed in JGOFS and GLOBEC provide IMBER with the potential of developing truly integrated end-to-end views of marine ecosystems. Following from these, the task team identified areas that need new or renewed emphasis so that IMBER Phase II will achieve its scientific vision and goal. These areas are:

- integrating human dimensions into marine global change research
- regional research programmes
- comparative studies within and across regional programmes, including ecosystem models that incorporate the human dimension
- incorporation of emerging scientific themes (Box 3).

Through discussion of GLOBEC and IMBER activities, the task team has identified some emerging scientific issues that are recommended to be addressed in IMBER II. These are illustrative and are not meant to be exclusive.

It is suggested that some of the emerging issues may be important enough for IMBER to arrange workshops to address them across the regional programmes.

Box 3. Some emerging scientific issues

CO_2 enrichment and ocean acidification. High and growing levels of anthropogenic CO_2 in the atmosphere have led to its dissolution in sea water, resulting in declining pH (i.e., acidification) associated with changes in the carbonate buffer system (Feely *et al.* 2004). This chemical process will result in pH decreases of several tenths of a unit within the next few decades (Caldeira and Wickett, 2003), and increasing interference with carbonate precipitation across many groups of marine organisms including corals, crustaceans and molluscs. The effects of the acidification process on non-calcifying microbial and phytoplanktonic communities have not been investigated. The effects of acidification on higher trophic levels are not understood. The effects of these slow processes occurring over decades are not well simulated by conventional experimental designs like mesocosms.

Another consequence of oceanic CO_2 enrichment is possible alleviation of inorganic carbon limitation in diverse phytoplankton groups (Riebesell *et al.* 2007). For example, unicellular diazotrophs appear to be severely limited at ambient DIC concentrations, and may experience enhanced growth and nitrogen fixation in a high-CO_2 ocean, triggering abrupt changes in the marine stoichiometric balance.

New metabolic and biogeochemical pathways. Entirely unexpected new metabolic pathways have been discovered using genomic and other techniques. The Anammox (anaerobic ammonium oxidation) pathway to N_2 (Kuypers *et al.* 2003) contributes a poorly quantified part of denitrification in anoxic sediments and ocean basins such as the Arabian Sea. If this process is important, it would necessitate revision of basin- to global-scale nitrogen budgets. Another discovery concerns the ubiquitous occurrence of proteorhodopsin-containing cells across diverse taxonomic lineages (Beja *et al.* 2002). Light-enhanced oxidation of organic substrates by proteorhodopsin-containing cells may confer a competitive advantage in low-nutrient habitats, but this has not been convincingly demonstrated in natural situations.

Role of viruses. Bacterial phages are the most diverse and numerous biogenic entities in the global biosphere. The importance of viruses as controls on the bulk marine bacterial assemblage has been appreciated for several decades (Suttle 1994). However, genomic tools have enabled much-improved resolution of specific phage-host systems, and led to new understanding of their roles in nutrient cycling and organic matter production. For example, we know that a significant fraction of the refractory dissolved organic matter in the deep ocean is derived from bacterial membranes, but the role of viral attack in its production is only now becoming clear (Suttle 2007; Breitbart *et al.* 2008). We still do not have a quantitative understanding of the relative importance of viral (both lytic and lysogenic phages) vs. bacteriovore sources of bacterial mortality in different regions. Phages active against the marine pelagic Archaea have not yet been documented.

The Archaea have been shown to be one of the most abundant unicellular groups in the ocean, especially in the mesopelagic zone (Massana *et al.* 1997, 2000; Fuhrman and Ouverney, 1998; Karner *et al.* 2001). Molecular biology techniques have revealed that archaea are abundant and distributed in virtually all environments (Chaban *et al.* 2006). In this context, Karner *et al.* (2001) suggest that the global ocean harbours approximately 1.3 X 10^{28} archaeal cells, which is roughly equivalent to 42 percent of the global abundance of bacteria in the ocean. In the last decade several advances have been attained regarding the biogeochemical role of Archaea. For instance, Crenarchaeota have recently been recognised as the main drivers of the oxidation of ammonia to nitrite in the ocean (Schleper *et al.* 2005, Wuchter *et al.* 2006). However, the participation of archaea in the marine global biogeochemical cycles remains largely unknown and this is seen as a potential research area for IMBER II.

Box 3. Some emerging scientific issues (continued)

Thresholds and surprises. It is now well established that changes in the climate system can be abrupt and widespread (IPCC - WGI, 2007). Alley *et al.* (2002) provides the following explanation of abrupt climate change: "Technically, an abrupt climate change occurs when the climate system is forced to cross some threshold, triggering a transition to a new state at a rate determined by the climate system itself and faster than the cause." Biogeochemical cycles, marine ecosystems, and socioeconomic and social-ecological systems are also likely to entail similar non-linearities. Threshold effects arising from system non-linearities are likely to result in "surprises" that will be very important as the world moves through global change. There are likely to be many such thresholds in complex coupled biophysical and social-ecological systems. While it may be possible to identify, characterise and locate some thresholds, others can only be anticipated as sources of risk. The IMBER programme should take these into explicit consideration. In particular, attention should be given to assessing the effects of potential abrupt climate change on marine biogeochemistry and ecosystems.

Coupled biogeochemical-ecosystem model projections. An emerging area of marine modelling is the development of nested models that allow transfer of information from global- to regional-scale models (downscaling) and from regional- to global-scale models (upscaling). Initial implementation of nested models has shown marked improvement in model skill and fidelity of the simulations. Incorporation of two-way scaling approaches, especially for regionally based models, may result in models that can be used for projections of ecosystem response to climate change.

Recent advances in adaptive ecosystem models with emergent properties (Follows *et al.* 2007) provide a new direction for marine ecosystem model development. Models that explicitly include the inherent variability in marine organisms (genetic diversity) provide the possibility of exploring ranges of responses to climate forcing. These models will require the ability to map genotype to phenotype. Thus, this modelling approach will require integration of results from the developing areas of marine genomics.

The characterisation of uncertainty is integral to evaluation of model skill and projections. Development of coupled marine ecosystem models with the capability of providing uncertainty estimates that can be conveyed to user communities is a challenge for the future.

Recommendations

IMBER II will have regional programmes that were not established when the original implementation strategy was written. The research approaches from the IMBER Science Plan and Implementation Strategy (2005), described below, have been adopted in several of the regional programmes and have been slightly rearranged and augmented by the TTT:

1. Innovative approaches
2. Innovative technologies
3. Process studies
4. Sustained observations
5. Palaeo-oceanography
6. Molecular genetics and functional groups
7. Integration of human dimensions in ecosystem models
8. Comparative approach between ecosystems
9. Synthesis and modelling

Regional programmes

A network of complementary regional programmes is essential for effective local implementation of the global IMBER programme. The regional programmes have different approaches and emphases according to the problems being addressed, but should proceed in parallel and assist significantly in achieving the IMBER vision and goal. There should be comparative analyses at regular intervals in order to gain maximum benefit from the understanding gained using various approaches in different ecosystems. The emphasis in all of them should be integration and comparison. In return for these contributions to IMBER research, IMBER should assist in obtaining funding towards supporting the regional programme activities, including their SSC meetings, approved workshops and meetings.

It is recommended that the IMBER SSC forms a task team including instrument and platform developers and modellers to recommend standards and methods to be used across the regional programmes, with a special need to recommend how best to harness new technologies (such as molecular genomics) as input into models. This is needed to show how genomic information should be used to inform models and how genomic sensing might serve to assess and improve model skill.

In order to achieve global coverage, we strongly recommend that the following regional programmes be incorporated into IMBER II, provided that they develop terms of reference in agreement with the IMBER SSC. Each study should include a coupling between biogeochemical and ecosystem research to be accepted as part of IMBER II:

1. *ICED (Southern Ocean)
2. *SIBER (Indian Ocean, tropics)
3. *CLIOTOP (Focus on top predators in open ocean, including tropics)
4. *ESSAS (Sub-Arctic Ecosystems)
5. SPACC (Small Pelagics and Climate Change, upwelling regions)
6. BASIN (Proposed North Atlantic comparative studies)
7. FUTURE (Proposed PICES North Pacific Programme)

* Formally accepted as a regional programme of IMBER

The first five of these are already planned and/or approved by either GLOBEC or IMBER. The sixth and seventh are still at a proposal stage, but are being developed in close collaboration with IMBER. SPACC is a mature component of GLOBEC that has the potential to include biogeochemistry in coastal upwelling regions. Together, they will give IMBER the necessary global coverage to be a representative marine global change research programme. More details on each of these regional programmes are given in the attached draft Implementation Strategy. The normal procedure is for regional programmes to submit their proposed science plans to the parent SSC for endorsement and acceptance as part of the parent programme, after discussion and negotiation.

Data management

Data management will be consistent with the overall recommendations of the IMBER Data Management Committee and their report, *"A Project Guide to Good Data Practices"* (*aka* "The IMBER Data Management Cookbook"). Specific data management policies are outlined in detail in the science plans of the regional programmes. A clear data-sharing policy respecting international standards should be established and acknowledged by the regional programmes to facilitate comparative studies.

Funding issues

IMBER proposes to integrate biogeochemical and ecological research as well as to consider human dimensions issues through its regional programmes and working groups. This difficult task requires the coming together of several different scientific communities that in the past have not worked together closely. To overcome some of these challenges, the Task Team recognises the necessity that IMBER actively promotes cross-disciplinary cooperation and collaboration between these various communities. This activity will require special funding to encourage the necessary direct and ongoing dialogue, especially in the transitional stages of regional programmes in association with IMBER. Therefore we propose that IMBER and its regional programmes find the funds through IGBP, SCOR, IHDP, DIVERSITAS, ICES, PICES and national programmes to help bring this cross-disciplinary integration to fruition. It is believed that once this dialogue is initiated, common scientific issues and interests will develop and funding will come through nationally or internationally funded projects to carry out the research. In addition, with several new regional programmes and working groups under the proposed Phase-II implementation strategy, IMBER will require additional funds to support meetings, steering committee activities, workshops, data management and other activities of the regional programmes, in addition to the IMBER International Project Office. The association with IMBER should assist regional programmes to raise their own funds. There is joint responsibility for active fundraising by both IMBER and its regional programmes.

Implementing mechanisms

It is recommended that the IMBER SSC should comprise a core of members appointed by the sponsors, plus any further *ex-officio* members to represent the regional programmes if they are not already represented on the SSC. It may also be necessary to have special short-term task teams or working groups that should be represented on the SSC. It is recommended that IMBER establish a human dimensions (responses of society) task team as soon as possible because this theme area of IMBER has lagged the other three. It is suggested that this team build on the foundation of the GLOBEC Focus 4 working group. Existing IMBER task teams should be evaluated and disbanded or restructured to meet the needs of IMBER II.

Clearly, there will need to be negotiations between existing regional programmes and the IMBER SSC concerning possible modifications to their science and implementation plans, the composition of their steering committees and funding of meetings and activities. IMBER is to be congratulated on the success of its first *Imbizo* and is encouraged to use this mechanism to facilitate communication and integration across IMBER science programmes.

Other transition issues

There needs to be formal acceptance by IMBER of each proposed regional programme. The formal mechanism will be through submission of completed Science Plans, should the regional programmes wish to do so, for evaluation and review, and subsequent approval by IMBER as adopted programmes. Each research project should specify how much funding it expects to obtain from sources beyond IMBER, along with what it needs annually from IMBER central funds for meetings.

The opportunities provided by, and implications of, the proposed Phase II should be actively communicated to the wider international research community, for example through the GLOBEC, IMBER, SCOR and IGBP newsletters.

Relationship with other programmes

IMBER should continue to engage and co-operate with other research and global change programmes. In particular, IMBER should foster its links with the IPCC, CLIVAR, GOOS and GEO.

Timetable for transition

20 December 2008–21 January 2009: Technical editing of report by sponsors (IGBP & SCOR)

21 January 2009: Immediate response by sponsors, IMBER, GLOBEC and potential regional programmes

1 February 2009: Posting on the IMBER and GLOBEC websites for community comment

1 March 2009: Community comments to TTT

15 March 2009: Revised report to sponsors and principals for review

30 May 2009: Reviews to TTT

24-26 June 2009: Presentation of report to GLOBEC OSM

27 June 2009: Possible one-day final meeting of TTT, only if major edits required by sponsors

September–October 2009: Final report considered by sponsors

January 2010: Commencement of IMBER II.

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IMBER Phase II Implementation Strategy

Research Approaches

IMBER II will have regional programmes that were not established when the original implementation strategy was written. The research approaches described below have been adopted in several of the regional programmes.

Key aspects of IMBER research will be the seamless integration of biogeochemical and ecosystem research in a truly trans-disciplinary approach, and the incorporation of social science research to enable the investigation of options for mitigating or adapting to the impacts of global change. Bringing together these science communities will be a significant challenge, and will need to start with workshops involving all participants. This integration is also important because feedbacks are critical.

Marine biogeochemical and ecosystem responses to global change are complex and diverse, and can only be evaluated through integrated interdisciplinary studies that allow observation and analysis of the target process in the context of the system and its feedbacks. Such studies will include targeted field-based process studies, *in situ* mesocosm studies and laboratory experiments, and comprehensive observation and modelling of biological, chemical and physical processes.

The field research fostered by IMBER will require advances in the networks of sustained observations, using both *in situ* and remotely sensed observations in key domains. This strategy will require close collaboration between IMBER and the Global Ocean Observing System (GOOS) to ensure effective development, coordination and use of GOOS data.

Extrapolation to the global scale will require integration of data from standard transects (e.g. repeat hydrography lines) in close collaboration with CLIVAR and other basin-wide global surveys, such as those planned by GEOTRACES to investigate the global marine biogeochemical cycles of trace elements and their isotopes. IMBER will also foster the development of innovative techniques for interpretation of palaeo-oceanographic records in collaboration with PAGES (including IMAGES) to enable synthesis and development of a predictive capability based on historical observations. Understanding and modelling the complex system of biogeochemical and ecosystem feedbacks will be an important integrating activity across IMBER. This will involve coupling life history models developed by GLOBEC with generic primary production and biogeochemical cycling models developed by JGOFS. This approach requires the development of nested suites of models and expansion of ecosystem models to basin scales. This nested approach will also link regional understanding to the global scale, providing the framework on which to build a predictive capability for the ocean system and its subsystems.

1. Innovative approaches

Past studies have focused on bulk biological processes and measurements rather than on the roles of key species or functional groups. The understanding, in particular, of the distribution and functioning of microbial communities, their dynamics and their role in cycling materials in the ocean is limited. Yet this knowledge is key to predicting ecosystem and biogeochemical responses to global change. Novel techniques must be applied, including biochemical and molecular methods that are targeted directly at the genome of plankton at the level of individuals. These allow direct quantification of specific functional groups of organisms and key species, and to understanding their role under changing environmental conditions. In addition to species discrimination, molecular genomic analysis will provide new proxies for complex biological and physiological processes, including growth, condition and reproduction; senescence and mortality; diapause and overwintering. Another aspect of this is the end-to-end foodweb approach. In the past programmes have tended to concentrate on parts of the plankton community or on fish, neglecting the integration of top predators and the controls and feedbacks they may bring to ecosystem dynamics.

Finally, a new conceptual approach, relevant to both future observational and modelling studies, is the increasing awareness of low-frequency non-linearity in marine systems with the recognition of regime shifts and the different spectral characteristics at differing physical and trophic levels.

2. Innovative technologies

IMBER will take advantage of new and innovative approaches, including the use of stable isotopes for unravelling food web dynamics, biomarkers for identifying functional groups, and new molecular techniques for detecting biological diversity and investigating trophic interactions. *In situ* molecular probes are starting to be used on moorings to identify species of plankton. At present, these *in situ* systems are used in moored applications and are too large for drifters, Autonomous Underwater Vehicles (AUV) or gliders, but this limitation should be overcome through further miniaturisation of the samplers.

Digital imaging systems, both laboratory and *in situ*, have evolved rapidly over the past decade, and there are now many systems available that can be used in the regional field programmes. The parallel development of automatic image analysis methods has allowed these new imaging systems to become operational sampling tools in biological oceanography.

Recent advances in development of autonomous robotic platforms will provide a new generation of ocean sampling platforms allowing high-resolution synoptic multi-scale sampling of ocean physics, chemistry and biology. These platforms include drifters, gliders and AUVs as well as autonomous profiling moorings. New sensors that are critically needed on these platforms include the optical imaging systems and molecular sensors mentioned above, as well as nutrient sensors.

Advances in satellite telemetry, electronic tags and remote sensing methods are also providing new tools that allow the movements and behaviour of individual top predators to be followed. These animal tagging studies are providing insights into the links between predators, prey and the oceanic environment. An exciting, recent development is that electronically tagged animals – such as marine mammals and large fish – can be employed as autonomous ocean profilers to provide environmental observational data, such as temperature profiles, within their habitat.

Hydro-acoustics remains one of the most promising *in situ* sensing methods for zooplankton and higher trophic level organisms. Broadband, multi-frequency acoustics has perhaps the greatest potential and can in principle allow studies of trophic interactions, especially if carried out in conjunction with video and holographic methodologies.

It is important that the SSC gives immediate attention to making the best use of new tools and technologies in the second phase of IMBER.

3. Process studies

We define process studies in a broad sense, including ship-based surveys of state variables and rate measurements; shore-based and open ocean mesocosm experiments; laboratory experiments; and manipulation/addition experiments such as those conducted to examine the role of iron in marine ecosystems.

Process studies are necessary to determine the effects of climatic and anthropogenic forcing of ecosystems and biogeochemical cycles. Process studies in different regions should be conducted to elucidate critical food-web interactions; essential functional groups for biogeochemical cycles; and bottom-up/top-down control of biogeochemical cycles and carbon flux. In addition, experimental process studies conducted in mesocosms or controlled addition experiments will help to understand the effects of ocean acidification, CO_2, micro- and macro-nutrient additions, as well as the role of top predators in structuring marine food webs and controlling biogeochemical cycles. These regional process studies and experiments are essential for model development, validation and the furthering of predictive capacities of key processes important for IMBER. In addition, these regional process studies will provide a framework to compare ecosystem structure and function with respect to biogeochemical cycles. They also will provide a means to ascertain and compare changes in ecosystems due to climate changes and human influences through harvesting and other anthropogenic forcing.

Process studies will be integrated with the sustained observation programmes to ensure that measurements are comparable and that the data can be effectively integrated, leading to more comprehensive understanding. During field studies, research vessels along with AUVs, drifters, gliders and short-term moorings may also be employed, as well as sensors on aircraft and satellites.

Targeted process studies will improve and advance predictive understanding of how climate variability and change influence marine ecosystems. In particular, they will elucidate relations with the seasonal cycle of primary productivity, how nutrient concentrations and ratios change the abundance of individual species and the functioning of marine ecosystems, the effects of low oxygen on ocean biogeochemical cycles and ecosystems, complex action and interaction of pH effects, the composition of key functional groups, both top-down and bottom-up trophic interactions, and the fluxes of carbon to the deep ocean and benthos. Changes in climatic forcing will significantly affect water column stratification and hence the spatial and temporal dynamics of key ecosystem features such as the timing and intensity of the spring bloom, food web structure and energy flow, and vital rates of target species.

Process studies will focus on life-history strategies of target organisms and how they contribute to observed population dynamics, community structure and biogeochemical cycles. The dynamics of populations of organisms with complex life-history strategies are closely coupled to the occurrence and variability in quality of specific habitats or regimes and interaction between behaviour (e.g. vertical migration, diapause) and transport processes that influence the overlap of these key species with their optimal habitats. In the laboratory, realistic and extreme combinations of environmental conditions as derived from the field component will be tested for their impact on developmental rates and survival. Experiments will be carried out on the effects of prey, physical and chemical conditions on individual activity, physiology, metabolic processes, somatic growth, reproduction and survival. The tolerance and preference levels with respect to important environmental variables will be determined and realistic combinations of these parameters used to define habitat limits, habitat utilisation and the role of the animals and plants in biogeochemical cycles.

4. Sustained observations

In situ sustained observations are required to record the unpredictable, extreme and episodic events, such as regime shifts, that have significant impacts on biogeochemistry and ecosystems. Sustained observations will also provide new insight into potential effects of longer-term global change on marine biogeochemical cycles and ecosystems. The JGOFS strategy of sustained observations (i.e. time-series studies) significantly increased understanding of the links between biogeochemistry and ecosystems (Steinberg *et al.* 2000). Similarly IMBER requires long-term observations of physical, chemical and biological variables to monitor and interpret variability in biogeochemical cycles and ecosystems, and to enable development of a predictive capability. Such time-series observations should extend over several decades, augmented by comprehensive data mining and reanalysis.

New, additional sustained observation sites in areas such as the continental margins, high-latitude and polar ocean areas, and within the mesopelagic layer, should be developed with due consideration for relevant time and space scales, nesting of sites and transect designs. Properly designed sustained observations will capture variability on time scales from hours (e.g. sensors on moorings), through events (e.g. salp or diazotroph blooms) and seasons (e.g. monsoons), to interannual and longer (e.g. variability associated with climate modes such as ENSO; El Niño Southern Oscillation and NAO; North Atlantic Oscillation). IMBER will encourage the use of a wide range of measurement platforms, such as floats, autonomous underwater vehicles, moorings, volunteer ships of opportunity, repeat hydrographic lines and new platforms, as these technologies develop. Long-term, cost-effective sustained observations of the ocean, particularly for biogeochemical and biological variables, are in an early stage of development. IMBER must play an active role and take advantage of new developments as they occur. IMBER will form close collaborative links with ongoing sustained observation programmes at international, regional and national levels, including with GOOS, the International Ocean Carbon Coordination Project (IOCCP), existing time-series stations such as Hawaii Ocean Time-series station, Bermuda Atlantic Time-series Study, the Kyodo North Pacific Ocean Time-series station, global plankton surveys such as the Continuous Plankton Recorder and the

Ocean Sustained Interdisciplinary Time-series Environment Observations System (OceanSITES). Such an approach will incorporate and build upon the results of SCOR WG125 on "Global comparisons of zooplankton time series".

Satellite observations are obtained from sensors that measure scattered, reflected or emitted electromagnetic radiation that carries information about the sea surface and upper mixed layer. Once calibrated, some measurements can be transformed into biological or biogeochemical variables. For example, accurate and robust algorithms allow ocean colour to be used as a proxy for surface chlorophyll. Coordinated international activities are being sponsored by organisations such as the IOCCG, IGOS-P GEOSS, and national space agencies. While significant progress has been made, this process needs to continue beyond the present generation of satellites (MODIS, MERIS, OCTS, POLDER) and operational systems to obtain greater ocean coverage (60 percent global, over a three to five day time frame). To achieve this goal IMBER will work collaboratively with IGOS-P in the development of its Coastal Theme and the review of its Ocean Theme. Beyond surface chlorophyll, the development and testing of a new generation of ocean-colour remote sensing algorithms is required to cover other aspects of ecosystem structure. For example, recent developments are able to detect different phytoplankton functional groups (i.e. coccolithophorids, diatoms and cyanobacteria: Iglesias-Rodriguez *et al.* 2002a; Iglesias-Rodriguez *et al.* 2002b; Subramanian 2002), size spectra, dissolved organic matter and suspended matter (Loisel *et al.* 2002; Siegel *et al.* 2002). To ensure the calibration and validation of such tools, IMBER will promote the development of systematic *in situ* measurements for on-going and new satellite ocean-colour analysis. Long time series will be particularly important to quantify and merge ocean colour products from different sensors and platforms.

Although research ships and satellites will undoubtedly remain important observing assets, the development of an ocean observing system encompassing autonomous *in situ* measurements and sampling from the wide range of available platforms is an increasingly important task. Emerging new platforms and sensors and their future potential have been discussed in detail by Dickey (2001). Given the inevitable risk of loss or failure of even the most advanced *in situ* device, real-time (or near real-time) telemetry of the data is an important feature. However, even the next decade's developments in sensors may not meet all measurement needs, hence autonomous *in situ* sampling devices (e.g. trace metal clean samplers) may help to fill the gaps.

A variety of platforms form the backbone of any ocean observation system. A nested approach is required, combining platforms of different types, such as Eulerian platforms (e.g. moorings, buoys, bottom landers and offshore platforms), Lagrangian platforms (e.g. drifters, floats and gliders) and other platforms (e.g. volunteer observing ships and AUVs). However, all these platforms can only assist IMBER research if adequate chemical and biological sensors or autonomous sampling devices are available. Clearly, the use of such platforms is more mature for physical oceanography, with biogeochemical and ecosystem studies limited to date by the availability of chemical and biological sensors of sufficient miniaturisation with sufficiently low power requirements.

Sensors suitable for the above platforms have to be developed under significant constraints in terms of response time, stability, drift, size, power requirements, durability, reliability, susceptibility to biofouling, data storage and telemetry, and cost. Often these challenging requirements cannot be met with current technology, making investment and development in this field crucial. Where simple and rugged detection techniques (e.g. optical – oxygen optode and electrochemical – pH glass electrode) are not yet available, miniaturised systems based on more classical chemical methods have been developed (e.g. nutrients and pCO_2). The application of these systems, however, is restricted because their size, power requirements and costs are often prohibitive (e.g. for use on profiling floats). Bio-optical and bio-acoustic sensors have been widely used in studies of phytoplankton and higher trophic levels. These techniques need further development and adaptation for use on autonomous platforms.

Observation and analysis at ocean-basin scales will be essential for IMBER (see for example the proposed BASIN regional programme in the North Atlantic). Cross-basin transects will allow data collection for integrated analysis of ocean ecosystems and biogeochemical cycles (e.g. hydrography, gases, carbon system parameters, transient tracers, nutrients, primary and secondary production, phytoplankton and zooplankton community composition and trophic interactions). Selected survey lines will focus on specific aspects including micronutrient distributions and turnover and end-to-end food web studies. Extrapolation to the global ocean of observations and results from process studies and sustained observations at specific sites will be achieved, in part, through such surveys. Long transects will be designed for all ocean basins in the coming decade. Coordination with CLIVAR and GEOTRACES may allow ancillary observations for IMBER during planned ocean-basin surveys.

Adequate global observing systems of marine ecosystems will have to be implemented to complement existing physical (e.g. Argo floats, drifters, moorings, etc.) or satellite-derived monitoring systems. Projects aiming at a global description of important components of the ecosystem such as the CLIOTOP-MAAS project that aims at improving our understanding of mid-trophic levels in the pelagic realm are highly relevant and are a key component of the CLIOTOP regional programme. Global-scale monitoring of ecosystem trophic structure can be developed by implementing and coordinating large-scale measurements of isotope concentrations in marine organisms. Fisheries data (fishing effort, species-specific catch and sizes frequencies, tagging data), as well as physical and chemical data from large-scale electronic tagging experiments, should also be gathered in inter-operable databases, in cooperation with the international bodies responsible for them.

5. Palaeo-oceanography

Palaeo-oceanographic approaches will be important for IMBER, as indicated in the theme descriptions. In the past decade the spatial and temporal resolution of studies has increased, highlighting that variations on timescales from seasonal to decadal up to centuries to millennia are characteristic of different key ocean processes. Effective use of palaeo-oceanographic data allows extrapolation of relatively short time series back through time to help distinguish between oscillatory and directional change, and to help distinguish natural from anthropogenic change. Such extrapolations are necessary for the development of models that predict the potential marine effects of global change. This will only be achieved if accurate and understandable proxies of important variables are available. Particularly important for IMBER will be palaeo-proxies that help elucidate how physical and chemical environments impact ocean biogeochemistry and ecosystems. Examples include palaeo-proxies for understanding:

- how physical conditions affect marine species composition
- how oxygen levels affect species abundance and diversity and remineralisation in the mesopelagic layer and in sediments
- how pH affects biogeochemical cycles and ecosystems
- how marine biological diversity affects ecosystem stability
- effects of climate modes on ocean chemistry and biology
- trigger points in transitions from one biogeochemical-ecological regime to another.

Multiple proxies are needed to reveal synchronous biogeochemical and ecosystem variations. Unequivocal interpretation of a proxy record requires an understanding of the processes that control its formation and its preservation in sediments; this understanding of the genesis of a proxy signal is not available for most proxies.

Development of palaeo-proxies will require fieldwork, laboratory experiments and testing of correlations on samples from sediment cores, corals and possibly other sources. Field efforts, for example, should take a synergistic approach with the long-term goal of understanding the variability in the downward pulses of POM and its accumulation and incorporation into sediments. Field efforts should include (i) integrated trapping and environmental monitoring to study vertical fluxes at large temporal and spatial scales; (ii) integrated trapping and sediment studies in order to assess the transformation of the climate signal ("proxies") from the water column to the seafloor and its preservation in sediments; and (iii) assessment of the effect of varying oxygenation on early diagenesis of organic matter and bioturbation rates in different bottom environments.

Biologically important isotopes, trace metals and unusual remnant organic molecules ("biomarkers") should be further explored. For example, records of lattice-bound cadmium in banded corals can help reconstruct patterns of anthropogenic fertiliser flux to the ocean. If possible, new proxies should be related to existing proxies whose behaviour is well understood. Two SCOR/IMAGES working groups, on "Analysing the Links Between Present Oceanic Processes and Palaeo-records," and "Reconstruction of Past Ocean Circulation" (completed, see Lynch-Stieglitz *et al.* 2007) will contribute information needed by IMBER. IMBER will work with these groups and others to advance the use of palaeo-proxies.

6. Molecular genetics and functional groups

The specificity of molecular and genomic techniques provide enormous potential for addressing the complexity of planktonic ecosystems and the resulting links and interactions. At the same time the functional group approach through aggregation of functionally similar groups of organisms provides another approach to complexity, which is useful in biogeochemical models. Both approaches have their value and both will be adopted.

In recent years oceanographers have come to appreciate the value of single-cell-specific (e.g. by flow cytometry) and sub-cellular investigations (including molecular biology and genomics) for identifying, quantifying, understanding and predicting biological patterns and processes at the individual organism, population, community and ecosystem levels. DNA-based characters can define species boundaries, reveal cryptic species, accurately estimate biodiversity for marine organisms from microbes to whales (Hebert *et al.* 2003), detect new metabolic capabilities and pathways, and identify prey species in digestive system contents. DNA can provide a means of documenting trophic relationships in complex food webs, including DNA sequencing of target regions for species identification (e.g. "Barcode of life" and "Fluorescent *In situ* hybridisation"). Molecular genetic analysis can reveal underlying population dynamics (i.e. patterns of recruitment, dispersal and mortality) as well as species' evolutionary histories and responses to climatic variability; for example, recent studies using microsatellite DNA markers for Atlantic cod have linked individual fish to their population of origin (Hansen *et al.* 2001). Mitochondrial DNA (mtDNA) sequence variation can be used to infer historical fluctuations in population sizes for marine organisms (Bucklin and Wiebe, 1998; Grant and Bowen, 1998; Nielsen *et al.* 2001).

Rapid advances in genomics (i.e. study of genomes and their functions) and analysis of gene expression (i.e. creation of proteins from genes) are being used to detect the occurrence of specific metabolic traits and to study recently discovered metabolic pathways in marine organisms. Such techniques allow identification of groups of organisms that perform certain functions within food webs and biogeochemical cycles, for example, nitrogen fixation and calcification. Biological oceanographers can examine environmental effects on gene expression and are developing molecular indicators of complex biological processes, including physiological condition, growth and reproduction, and likelihood of survival. Miniaturisation and automation are becoming standard in molecular laboratories. "Lab-on-a-chip" technologies will increasingly make it possible to conduct molecular assays remotely using equipment on moored or autonomous instrumentation deployed in the ocean. At the ecosystem level, community metagenomics exploiting random "shotgun" sequencing of DNA purified from ocean environments is being used to identify biodiversity hot spots and concentrations of unknown organisms – especially microbes that cannot be cultured. It may soon be possible to assemble and sequence whole genomes of micro-organisms from natural samples, and to discover novel genes and their functions in biogeochemical cycles.

Molecular techniques are opening up new possibilities in addition to their widespread application in systematics and genomics. The trophic complexity of marine pelagic ecosystems remains a significant challenge, particularly in relation to end-to-end food-web studies. We need to be able to identify the prey items of predators from within complex planktonic assemblages and understand the effects of eating different prey, both for the predator and prey populations.

A promising new strategy for assessing feeding interactions is the use of molecular methods to detect prey-specific nucleic acids as biomarkers of trophic interactions (Sheppard and Harwood, 2005). A number of techniques are being developed, the common approach being to isolate DNA from stomach contents followed by detection and possible quantification using PCR-amplification-based methods targeting gene fragments associated with prey organisms. This molecular approach is being increasingly employed to analyse food webs, establish trophic links and to estimate *in situ* feeding rates. Molecular identification enables stomach content analyses to be carried out directly on animals sampled from the field without the potential of bias from conventional incubation-based experiments (Nejstgaard *et al.* 2003; 2007). An additional advantage of the DNA-based molecular approach compared to conventional gut fluorescence and direct microscopic observation methods is the ability to detect non-pigmented and damaged or partially digested prey items.

Biogeochemical and some ecosystem studies can be simplified by the strategy of considering specific plankton functional types (PFTs) (Le Quere *et al.* 2005; Hood *et al.* 2006). Examples within phytoplankton are diatoms, coccolithophores and picoplankton; and within zooplankton, salps, microzooplankton and small copepods, all of which have specific, particularly biogeochemical, characteristics. Similar approaches have also been made with fish guilds. PFTs have been used in a number of current modelling studies, adding extra complexity beyond simple nutrient-phytoplankton-zooplankton-detritus (NPZD) models. However, this approach has been criticised and it has been suggested that future work should build up complexity gradually (Anderson, 2005, 2006; Flynn, 2006; Le Quere, 2006). The PFT approach contrasts with that of Individual Based Models (IBMs) and the focus on individual target species. The definition of functional groups (not only planktonic groups) has to be done carefully to avoid giving rise to modelling artefacts.

7. Integration of human dimensions in ecosystem models

Humans are a part of the global ecosystem, and human activities are becoming ever more important in driving change in the world's oceans. They are also affected by ecosystem changes. Human uses of marine resources are determined by a complex mix of economic, political and social factors. The interaction of these factors with the biophysical characteristics of the marine system can be broadly conceived as constituting the social ecology of these systems.

The doubling of global human population over the past half century has led to growing demands on living marine resources, and impacts on coastal systems. Rapid industrialisation, agricultural expansion and increased use of fossil fuels and fertilizers have had major impacts on coastal systems and the composition of the atmosphere. Anthropogenic emissions of greenhouse gases will be the major driver of future climate change, and will drive ocean acidification and related impacts on oceanic biogeochemical processes. Sediment, nutrient and pollutant flows into rivers, coastal zones and open ocean waters will likely continue to increase, although the rates of change will vary regionally and will depend on the policies that are implemented to control such activities as mining, dam-building, other construction and use of agricultural chemicals in coastal and riparian areas.

Global demand for fish for direct human consumption, as well as for fish meal and oil, has grown rapidly in recent decades. Demand pressure can be expected to continue increasing over the foreseeable future. In addition, fishery markets will likely continue to become increasingly globalised, with substantial international trade in fish and fish products, and a large share of the harvests for some marine species taken by industrial Distant Water Fishing Nation (DWFN) fleets. Increased harvests have been facilitated by a variety of technical improvements, so that the majority of commercially valuable fish species are now considered to be fully exploited or overexploited. Intensive human utilisation of marine species is thus playing a significant role in driving the dynamics of both individual species and whole marine communities.

Human activities are thus affecting the ecology of the ocean from both the top down and the bottom up. It is clear that research focused on understanding forces driving and controlling these human activities is needed in order to fulfil IMBER's vision of providing "*…a comprehensive understanding of, and accurate predictive capacity for, ocean responses to accelerating global change and the consequent effects on the Earth system and human society".* IMBER's work in this area will benefit from close interaction with other international programmes, such as the International Human Dimensions Programme on Global Environmental Change (IHDP), including the joint IHDP-IGBP Land-Ocean Interactions in the Coastal Zone (LOICZ) project.

There are many possible approaches for organising research on societal interactions with the marine environment. One such approach, suggested in the IMBER Science Plan, is that of the DPSIR (Drivers, Pressures, State, Impact and Response) framework. In implementing such a framework, it must be understood that the linkages between these elements are not simply mechanistic. Rather, they depend importantly on differences among nations and communities in initial wealth, infrastructure, composition of economic activities, institutional arrangements, values, expectations, information availability, and beliefs about the functioning of the biophysical systems. Thus, there is considerable heterogeneity in the characteristics of the DPSIR chain across different socioeconomic and political settings. In addition, competition among different social and political groupings for access to the benefits that can be derived from marine resources plays a critical role in driving policy processes and in determining the outcomes of policy choices. Comparative case studies can be used to evaluate the role and significance of various aspects of each social-ecological context in driving the evolution of these DPSIR chains. It is also important to note that multiple stressors often influence ecosystems under stress and that the combined effect of several stressors may be much greater than the sum of individual stresses on a system.

Interconnections between different fisheries and local social-ecological systems are also becoming ever more important as the global economy becomes increasingly integrated. Responses to changes in the abundance and spatial distribution of individual fish stocks include the transfer of fishing effort to other species and locations, with sometimes surprising results. In addition, there are demonstrated non-linearities in the interactions between fishing activities and climate-driven fluctuations in fish stocks. More effort should be given to identifying and analysing these interactions. It is necessary to understand the full dynamics of these processes in order to predict the evolution of coupled human-natural systems and the responses of these systems to natural variability in oceanic ecosystems.

Research in this area will employ economic, political, sociological and anthropological models and assessments to develop an understanding of the nature and functioning of the linkages in the DPSIR chains in particular contexts. This work will build upon the findings of GLOBEC Focus 4 activities, extending that work to encompass a more comprehensive range of interactions between changing biogeochemical processes, ecosystems and human activities. GLOBEC's Focus 4 has already taken steps to facilitate comparison of methods and insights from human dimensions work within the GLOBEC regional activities – for example, through the 2008 workshop on "Coping with Change in Marine Social-Ecological Systems" and follow-up publications. Ongoing integrated socioeconomic-ecological research under the CLIOTOP and ESSAS regional programmes should be further developed within IMBER Phase II, and IMBER Phase II should promote coordination of human dimensions research across the various regional programmes.

There are several advantages to close coordination of human dimensions work across the regional programmes. For example, coordination is necessary to properly account for the real economic and international governance linkages across the various fisheries relevant to each of the regional programmes. As noted previously, markets for the products of marine fisheries are becoming increasingly global in scope, and modern industrial fishing fleets are often highly mobile. As industrial harvesting increasingly competes with long-established artisanal fisheries, the latter will face pressures to adapt. A broad multi-regional perspective is needed to understand the dynamics of the interplay between local artisanal and global industrial fisheries.

Cross-regional coordination also will facilitate the development of common methodologies for assessing the resilience, vulnerability and adaptive capacity of fishery-dependent communities to the impacts of climate change. Comparative case studies can help to shed light on common patterns of the evolution of fisheries, fishery impacts and the effects of changes in fish stocks on fishing communities, as well as interactions between harvesting, fishery managers, indicators for ecosystem approaches to fisheries management, decision support tools and governance design.

A global comparative perspective also will be helpful in assessing the likely evolution of human activities that affect pollutant loading and other impacts on coastal zones. For example, discharges of nutrients into coastal waters are determined, in part, by changes in local human populations and in part by the effects of global markets on the intensification of agriculture in areas adjacent to and upstream of the coastal zone. In addition, rapidly expanding mariculture industries are driven by global demand, but have highly local ecosystem impacts.

Given inevitable uncertainties in observations, models and projections of both the biophysical and human aspects of marine social ecological systems, it is important to understand the significance of these uncertainties for management of fisheries and ecosystems, and for much wider concerns such as geoengineering. In particular, it will be important to evaluate tools for considering uncertainty in decision analyses for fisheries management. It also will be important to assess how scientific information can best be communicated for use in management and policy processes. The PICES FUTURE programme anticipates a focus on uncertainty. A similar focus may be adopted in other regional programmes. Here again, a comparative approach is likely to be informative.

There is an active community emerging in this area (including the GLOBEC Focus 4 working group) that should be further nurtured and developed under IMBER Phase II. In particular, it is recommended that an IMBER Working Group be established on Human Dimensions and Management Strategies. This Working Group would invite representatives from the relevant research projects in each of the regional programmes, and would be expected to organise joint workshops and coordinate comparative assessments.

8. Comparative approach among ecosystems

The comparative approach is a particularly useful method to explore mechanisms linking forcing functions and their ecosystem responses, especially since controlled scientific experiments cannot be carried out on intact natural ecosystems. Comparisons allow a broad perspective and enable generalisations to be made about what are the fundamental general aspects of marine ecosystems as opposed to the unique aspects of specific ecosystems. They provide the opportunity to gather insights within and between ecotypes (e.g. tropical, subtropical, subpolar and polar regions) that could not be achieved within a single ecosystem. IMBER's regional programmes cover each of these ecotypes. Comparative analysis also offers the advantage of potentially increasing the number of degrees of freedom for statistical analyses when exploring relationships between forcing functions and ecosystem responses. It can also reveal patterns of ocean-wide ecosystem structure and processes, which emerge only when considering a wide array of marine ecosystems, as well as insights into the human dimension aspects of ecosystems. The comparative approach has been used successfully to examine various issues, e.g. physiological characteristics of different species (Pörtner *et al.* 2005), the response of similar ecosystem types to climate forcing (e.g. upwelling regions, Alheit and Bakun, 2008), and characteristics of certain species over their distributional range with varying hydrographic conditions (e.g. Atlantic cod growth; Brander, 1994, Pörtner *et al.* 2001; recruitment, Planque and Fredou, 1999; productivity, Dutil and Brander, 2003; condition, Rätz and Lloret, 2003).

Comparison of different ecosystems within a particular ecotype will be carried out within regional programmes. Cross-regional comparisons of ecosystems from different ecotypes will be part of the IMBER synthesis activities and may require the formation of a dedicated Working Group. The approach, in either case, will be principally two-fold. The first, statistical, approach will be to apply the same methodology to similar time series and rate processes data from different ecosystems. The second approach involves modelling. This will include the application of a specific model to different ecosystems as well as the application of different models to a particular ecosystem. It is recognised that no model is perfect for all purposes and therefore a number of different models and modelling approaches will be encouraged. These could include general circulation models (GCM) coupled to hydrodynamic models, nutrient-phytoplankton-zooplankton (NPZ) models, mass-balance food-web models, and dynamic multispecies and aggregate stock production models. In addition, there are socio-economic and management models that can be effectively evaluated within a comparative framework. IMBER has the opportunity to carry out comparisons using an integrative approach building on complete end-to-end system models that include human aspects such as fishing.

In order to do comparative work, standard techniques and standard reference materials have to be adopted and workshops held for inter-comparison and adoption of these.

9. Synthesis and modelling

Models provide a suite of tools to investigate hypotheses, analyse and extrapolate data in space and time, help gather data efficiently through observational system simulation experiments, and identify crucial gaps to be filled by new observations and research to reduce uncertainties. To achieve this a synthesis and modelling framework must be active from the beginning of IMBER to integrate knowledge and to refine the implementation strategy as the programme develops. In the long term, reliable prognostic ocean models that are linked to models of biogeochemical cycles and ecosystems are required to predict the impact of global change on the ocean. The linkages to other Earth system components should be both implicit and explicit; ocean models are needed that provide relevant inputs and parameters for models of atmospheric and terrestrial processes. In the short term, exploratory process-oriented models are needed which improve understanding of mechanisms, controls, feedbacks and interactions. Such models depend critically on the sustained collection of appropriate observational data and targeted process studies.

Continuous synthesis of available information including observational data and model outputs can only be achieved if interconnected databases are constructed, quality controlled, shared in a common format, updated in near real-time and integrated with models. This has to be done jointly for socio-economical, ecological, biological, biogeochemical and physical variables and models. IMBER has the opportunity to contribute to the development of such databases and to integrate them with models to understand, evaluate and project the effects of global changes on the structure and dynamics of pelagic ecosystems. This approach will include a suite of modelling approaches such as mass-balanced, statistical, structured populations, IBMs and mean field models as well as more comprehensive large-scale numerical models extending from physics to biogeochemistry to fish to fishermen to global markets and back.

Building community ecosystem models of intermediate complexity for marine ecosystems is a major goal of IMBER, which will build upon and exploit recent developments in marine ecosystem modelling arising from GLOBEC and other research programmes. These new models will require development of approaches and techniques for two-way coupling [Ocean General Circulation Models (OGCM); Ocean General Biogeochemical Models (OGBM); Ocean General Ecosystem Models (OGEM); and Global Market Economical Models (GMEM)] and new end-to-end food-web models at various trophic levels so that feedbacks can propagate from the bottom up and from the top down. This will allow non-linear dynamics and emergent behaviour to be manifested in the models. Coupling the various component models requires that they operate at compatible spatio-temporal scales and integrate smaller-scale processes through appropriate aggregation techniques of high-resolution sub-models, leading to specific parameterisations. For instance, these might include grid-scale parameterisations of sub-grid scale complex local individual fish-foraging behaviour or zooplankton diel vertical migrations.

Regional comparisons and efficient linking of local ecosystem dynamics in regions of interest for global climate dynamics require development of appropriate nesting strategies and approaches for downscaling and upscaling model results. This will ensure that meso-scale ecosystem dynamics can be linked at regional and global scales. An approach for beginning this process is to build on the tools already developed to implement one- and two-way nesting in OGCMs (i.e., Adaptive Grid Refinement In Fortran, NCAR tools, etc).

Accurate representation of trophic interactions in models is critical because these allow the transfer and the dissipation of energy through food webs, from primary producers to top predators. The proposed Process Studies and Molecular Analyses (see above) will contribute to this. Parameterisation of trophic interactions based on robust invariant principles such as the size-structured nature of predation is necessary to achieve robust representations.

The "rhomboid" approach (de Young *et al.* 2004), which was developed through GLOBEC modelling activities, provides a practical way to obtain a simultaneous and interactive representation of both low resolution functional groups and target species represented with more physiological and behavioural details. It allows the functional complexity to be limited without losing the mass balance of the system. The choice of functional groups (see previous section) and target species to be represented is critical since this has to enable potential alternative trophic pathways (such as the competition between the typical diatom-mesozooplankton-fish and the alternative flagellates-microzooplankton-jellies food chains) to emerge without being specified *a priori* in the model. This approach can provide a natural starting point for ecosystem modelling undertaken as part of IMBER programmes.

Considering trophic interactions requires that the environmentally driven spatio-temporal distribution of the various organisms considered (match-mismatch) be represented properly. For this purpose, the explicit inclusion of individual behaviour (movement, migrations) into ecosystem models is needed. Since physiology acts as a transfer function between environment and behaviour, the inclusion of robust representations of physiology and its linkage to behaviour and fluxes will allow adaptive responses of populations to environmental variability to emerge in the models. Coupling of marine-based models to land-based predator models is needed. For some systems (e.g. Arctic and Antarctic) predator distribution, abundance and productivity is indeed the result of marine and terrestrial forces.

Predation is definitely not the only coupling to be taken into account between lower and higher trophic levels in integrated ecosystem models. To achieve mass conservation, the recycling to nutrients has to be considered through explicit representations of egestion to POM-DOM, excretion to NH_4, respiration of CO_2 and non-predatory mortality fluxes to POM. To achieve a rigorous stoichiometric treatment of energy and material fluxes (needed for many questions), ecosystem models have to include explicit representations of the bioenergetics of organisms, that is, the uptake and use of energy/material for growth, maintenance and reproduction using mechanistic representations of metabolisms such as the DEB (Dynamic Energy Budget) theory (Kooijmann, 2000). The habitat is another important point of linkage in the ecosystem.

Integrating data and models

Data assimilation and inverse modelling techniques provide approaches for quantitative comparisons between ecosystem simulations and the available observations. These approaches provide tools to identify issues of parameterisation or model structure as well as values of the parameters. Addressing these issues identifies observational and data needs. New methods of sensitivity analysis go hand in hand with improved modelling and parameterisations. There is a need to develop appropriate observation models for large-scale data sets to be really useful. For instance, $\delta^{15}N$ and $\delta^{13}C$ should be included in biogeochemical/ecosystem models. This raises the importance of the microbial loop since f-ratios are critical for isotope dynamics, especially in variable systems such as coastal upwelling areas where recycling can be important.

Syntheses and projections

To synthesise and develop future ecosystem scenarios, coordinated retrospective and prospective simulation strategies are needed and could be developed in the framework of the IMBER regional programmes, and other international organisations and targeted workshops. Much ongoing international research in modelling is directed at developing quantitative metrics for assessing the ability of marine ecosystem models and implementing data-assimilative strategies. These could result in forecasting capability for marine ecosystems for specific space and timescales. The IMBER regional programmes all have strong modelling components with goals of obtaining forecasting capability. Through interaction of these programmes, and the comparative approach proposed, IMBER has the potential of helping the community realise the ability to forecast aspects of marine ecosystems. The definition of new indicators to translate the projections into efficient management strategies is critical for these models to be useful for management and policy-makers.

Detailed assessment of the impacts of climate change, especially on the continental shelves, can only be performed based on regional models, as global models are usually too coarse to resolve many of the regional structures. However, future projections at the regional scale require downscaling from the Global Circulation Models (GCMs) to regional hydrodynamic models. Recent studies reveal that the downscaling should be performed using several different GCMs, not just one (e.g. Ådlandsvik 2008). The choice of the models should be based on their ability to hindcast past observations (Overland and Wang, 2007). Within IMBER Phase II emphasis should be placed on the development of future projections using regional models. This requires choosing the GCMs that are most consistent with present observations and performing downscaling from several of these GCMs. The downscaling results from the different models provide one measure of the uncertainty in the regional future projections.

Regional Programmes

A network of complementary regional programmes is essential for local implementation of the global IMBER project. These regional programmes may have different approaches and emphases according to the problems being addressed, but the emphasis in all of them should be integration of the biogeochemistry and food-web approaches, as well as comparative studies. They should proceed in parallel and assist significantly in achieving the IMBER vision and goal. There should be comparative analyses at regular intervals in order to gain maximum benefit from the understanding gained in different ecosystems. In return for these contributions to IMBER, the parent project should assist in obtaining funding to support the regional programme activities including their SSC meetings, approved workshops and meetings. At this stage, we recommend that the following regional programmes described below be incorporated into IMBER II provided they agree with the IMBER SSC on terms of reference and address the IMBER goals: ICED, SIBER, CLIOTOP, ESSAS, BASIN, FUTURE and SPACC.

Table 1 gives some examples of the links between proposed regional programmes of IMBER and the research approaches described in the draft IMBER Implementation Strategy of IMBER II.

All these activities will need integration by the IMBER SSC

- Integration of modelling approaches used in regional programmes, especially in linking of biogeochemical cycles and food webs
- Integration of approaches used to include human dimensions in ecosystem models across regional programmes
- Development of metrics for evaluation of biogeochemical and food-web fluxes in different regions (allows direct comparison of modelling results and will advance understanding and comparisons of effects of climate change in different regions)

Strong regional expressions of global climate change have occurred in Antarctica and the Southern Ocean, the subarctic seas and the Indian Ocean. Understanding the processes that underlie ecosystem responses to climate change is necessary to provide a sound basis for the sustainable management of these regions. An understanding of these processes is also necessary to evaluate and predict the impacts and feedbacks of these regions as part of the Earth system. Many of the priority scientific challenges are at the interfaces between ecosystem, climate, biogeochemistry, fisheries science and the human dimensions of climate change. Existing studies of the impacts of climate variability on biogeochemistry and ecosystem structure, as well as the long-term effects of harvesting, need to be brought together across regions and scientific disciplines.

Table 1: Selected illustrative examples of research approaches that have or may be adopted in the regional programmes. Sustained observations include satellite measurements, such as ocean colour, altimetry, winds, and sea ice extent and concentration. These measurement systems are external to IMBER, but the data sets provided by them are integral to all IMBER science.

	ICED	SIBER	CLIOTOP
New and innovative approaches	Integration at circumpolar scale, linking biogeochemical cycles and food webs	Basin-wide scope with regional and science-based thematic elements	End-to-end modelling
Innovative technologies	Passive acoustic circumpolar monitoring arrays for cetaceans Electronic tagging of predators Biogeochemically equipped Argo floats	Electronic tagging of predators Biogeochemically equipped Argo floats	Electronic tagging of predators Mid-trophic Automatic Acoustic Sampling (MAAS) Stable isotope measurements in essential/non-essential amino acids
Sustained observations	*CEMP, CPR, SOOS, land-based research stations, automatic weather stations Circumpolar monitoring arrays and measurement programmes	IndOOS, IO-GOOS and regional GOOS programmes	Fisheries catch, size and fishing efforts Market price data for tuna Growth rates, population survival for major fish, seabird and mammal populations
Process studies	End-to-end food-web comparisons for decreasing/increasing sea-ice environments Biogeochemical and ecosystem comparisons in polynya/non-polynya regions Top-down and bottom-up controls in regions affected by harvesting Bentho-pelagic coupling	Arabian Sea grazing vs. Fe limitation Oxygen Minimum Zones	Movements/migrations Feeding/spawning behaviour Energetics Larval survival
Synthesis and modelling	Circumpolar biogeochemical food-web circulation models Regional comparisons	Basin-wide eddy-resolving models Regional nested grids/models	Two-way coupled numerical models from physics to fish to markets Indicator panels for management
Molecular, biochemical & genomic techniques	Identification of krill stocks from genetics Food-web connections Organism condition Stable isotopes	Stable isotopes Fatty acids DNA analysis of larvae stomach contents	Stable isotopes Fatty acids DNA analysis of larvae stomach contents
Integration of human dimensions in ecosystem models	Effect of harvesting of top predators on food-web structure	Coupled population-fisheries economic models. Marine resources governance	Coupled population-fisheries economic models. Marine resources governance

*CEMP (CCAMLR Ecosystem Monitoring Programme); CPR (Continuous Plankton Recorder); SOOS (Southern Ocean Observing System)

ESSAS	BASIN	FUTURE	SPACC
Comparative studies of subarctic seas	Basin-wide scope with regional and science-based thematic elements	Modelling of bottom-up and top-down effects including fisheries	Spawning habitat dynamics and the daily egg production method (DEPM) Use of environmental indices in the management of pelagic fish populations
AUVs, biological moorings, new satellite technologies	Optical imaging systems, AUVs		CUFES (Continuous Underway Fish Egg Sampler)
Contributions to monitoring hydrography, currents and fluorescence	Continuous Plankton Recorder Survey	New monitoring strategy to assess ecosystem changes, provide necessary data for model boundary conditions and evaluation	CUFES (Continuous Underway Fish Egg Sampler)
Role of temperature, sea ice, and advection on ecology; trophodynamics	Key processes determining how climate forcing impacts population dynamics of target species Key aspects of ecosystem-biogeochemical dynamics	Process studies on ecological responses to climate forcing to improve understanding and model parameterisation	Daily somatic growth of young fishes, plankton production and physical forcing
ECOPATH, production models, biophysical models, end-to-end models	Rhomboid approach, Obervation System Simulation Experiments (OSSEs)	Biophysical modelling, downscaling of global-climate-model projections to regional models from global to regional-scale models	Transport and early life history models
	Determining species composition of plankton		
Coupled population-fisheries-economic models Marine resources governance		Uncertainty and risk in management decisions	Integrated models of the worldwide system of small pelagic fisheries

ICED

The ICED (Integrating Climate and Ecosystem Dynamics) programme is designed to address major ecological challenges arising as a result of climate and human-driven change in the Southern Ocean. The programme is envisaged as a decade-long international, multidisciplinary study with a focus on circumpolar processes in the Antarctic. ICED is a natural extension of the Southern Ocean GLOBEC and JGOFS programmes, which showed the importance of going beyond regional-scale studies to understand the controls that structure Southern Ocean food webs and regulate biogeochemical cycles. The recognition of the importance of interactions and feedbacks between food web and biogeochemical cycles provide the basis for inclusion of ICED as a regional programme under IMBER. The *ICED Science Plan and Implementation Strategy* has been published jointly by GLOBEC and IMBER (IMBER Report No. 2). The programme was developed in conjunction with the Scientific Committee on Oceanic Research (SCOR) and the International Geosphere-Biosphere Programme (IGBP), through support from both IMBER and GLOBEC. The British Antarctic Survey has provided funding for an ICED Programme Officer to facilitate communications, workshops and other activities.

The long-term goal of ICED is to determine the major controls on the dynamics of Southern Ocean ecosystems and the potential for feedbacks as part of the Earth system. Emphasis will be given to developing the basis for forecasting the impacts of climate and harvest-driven change on Southern Ocean ecosystems. Thus, the major focus is on integrated regional and circumpolar analyses of whole ecosystem operation, particularly at the interfaces of climate, biogeochemistry and fisheries science.

To address its long-term goal, ICED has three major scientific objectives:

1. To understand the structure and dynamics of ecosystems in the Southern Ocean and how they are affected by, and feed back on, climate processes.

2. To understand how ecosystem structure and dynamics affect, and are affected by, biogeochemical cycles in the Southern Ocean.

3. To determine how ecosystem structure and dynamics should be incorporated into management approaches to sustainable exploitation of living resources in the Southern Ocean.

ICED consists of three major areas of science activity: modelling, historical data synthesis and analysis, and fieldwork. Activities in these areas will be guided by close collaboration and multidisciplinary integration of knowledge from research groups operating throughout the Southern Ocean. A major focus of ICED is improvement of the reliability of projections of future ecosystem dynamics, including ecosystem responses to climate change and harvesting. ICED will focus on development of a suite of models of oceanographic circulation, biogeochemical cycles, and end-to-end operation of food webs, within a hierarchical framework of models of different spatial, temporal and trophic resolution. The ICED programme attaches a high priority to integrating existing data sets to enable investigation of long-term, large-scale marine ecosystem functioning, variability and change across the Southern Ocean. The ICED fieldwork will address gaps in knowledge that have been identified though modelling activities and historical data analyses, and plan the process to maximise international efforts to fill them. Details of each of the major study areas are given in the *ICED Science Plan and Implementation Strategy* (http://www.imber.info/products/ICED_Finaltoprint.pdf).

As the research components of ICED develop, linkages will be made with numerous relevant Southern Ocean programmes, such as the Commission for Conservation of Antarctic Marine Living Resources (CCAMLR) and the Scientific Committee for Antarctic Research (SCAR).

SIBER

SIBER (Sustained Indian Ocean Biogeochemical and Ecological Research) is an approved regional programme of IMBER. Planning workshops (www.imber.info) have provided consensus on the prominent research questions that need to be addressed to better understand climate change and anthropogenic forcing on biogeochemical cycles and ecosystems in the Indian Ocean.

Significant infrastructure supporting SIBER will be deployed in other programmes. To obtain a better understanding of the atmospheric and oceanic variability in the Indian Ocean, the Climate Variability and Predictability programme (CLIVAR) and the Global Ocean Observing System (GOOS) are currently deploying a basin-wide observing system in the Indian Ocean [*International CLIVAR Project Office*, 2006].

Although there are significant challenges, deployment of an array of more than 30 buoys is planned in the open ocean between 20°N and 20°S spanning the entire basin. These buoys will be accompanied by a variety of physical oceanographic survey and mooring support cruises. In addition, several nations in the Indian Ocean (most notably India, Oman and Australia) are deploying coastal observing systems. These systems, in combination with newly available research capabilities and technologies, such as Argo float measurements and an Indian satellite ocean colour sensor, provide a unique opportunity for staging international, interdisciplinary research in the Indian Ocean, which can address many of the IMBER research questions noted earlier.

SIBER planning workshops have identified six major research themes:

1. Boundary current dynamics, interactions and impacts.
2. Dynamical variability of the equatorial zone, southern tropics and Indonesian through-flow and their impacts on ecological processes and biogeochemical cycling.
3. Controls and fates of phytoplankton and benthic production in the Indian Ocean.
4. Physical, biogeochemical and ecological contrasts between the Arabian Sea and the Bay of Bengal.
5. Climate and anthropogenic impacts on the Indian Ocean and its marginal seas.
6. The role of higher trophic levels in ecological processes and biogeochemical cycles.

The *SIBER Science Plan* (www.imber.info) provides the background, core questions and implementation strategy to address these major research themes.

CLIOTOP

CLIOTOP (CLimate Impacts on Oceanic TOp Predators) is a ten-year (2005-2014) research programme initially developed within GLOBEC. The implementation of CLIOTOP has been designed as a two-phase strategy (see *CLimate Impacts on Oceanic TOp Predators (CLIOTOP) Science Plan and Implementation Strategy*, GLOBEC Report, No. 18, 2005; http://www.globec.org/). The completion of the first phase of the programme (2005-2009) occurs synchronously with GLOBEC and IMBER merging, so that the second phase (2010-2014) will be carried out under IMBER.

The general objective of CLIOTOP is a large-scale worldwide comparative effort aimed at identifying the impact of both climate variability (at various scales) and fishing on the structure and function of open ocean pelagic ecosystems and their top predator species by elucidating the key processes in open ocean ecosystem functioning. The ultimate objective is the development of a reliable predictive capacity for the dynamics of top predator populations and oceanic ecosystems that combines both fishing and climate (i.e. environmental) effects.

These objectives require an approach involving research teams currently working in process-oriented projects which address the mechanisms linking physical forcing; zooplankton production; prey abundance and distribution; top predator physiological, behavioural and population ecology; and human exploitation. Those process studies are accompanied by interdisciplinary studies by modellers involved in climate, physical and biogeochemical oceanography, and individual, population and ecosystem dynamics.

To conduct standardised worldwide comparative analysis, homogeneous comprehensive records of climate variability, ocean and atmospheric circulation changes and related regional and local environmental changes are used and compiled. CLIOTOP serves to improve the availability of these data sets to the ocean and fisheries sciences communities, and to encourage incorporation of historical archived data.

Integrative process-oriented studies (including retrospective analysis, field experiments, survey and monitoring) in a comparative framework are a key objective. In this respect, a strong modelling component is also fundamental for CLIOTOP. This includes a range of models of different complexity from simple box models, through more detailed energy budget and behavioural models to spatially explicit ecosystem-biogeochemistry models driven by OGCMs. The validation of ongoing ocean modelling and the development of more realistic models is a prime objective to advance predictive capabilities in the short, medium and long term.

While CLIOTOP is aimed at improving understanding of ocean top predators within the ecosystem, its successful implementation might have a significant impact on the management of the very important fisheries that exploit tunas and tuna-like species. It is believed that the CLIOTOP comparative approach for the Pacific, Atlantic and Indian oceans will bring a major additional value to the research developed in each ocean separately.

The scientific questions addressed by CLIOTOP can be classified according to three general foci: processes, responses and management issues. To answer these questions, two main integrated programme elements are envisioned:

1. to evaluate the impact of both fishing and climate variations on marine ecosystems inhabited by open ocean top predators by analysing and comparing long-term data series, ocean/atmosphere and biogeochemical reanalyses, field observations, *in situ* and laboratory experiments and measurements;

2. to use modelling and extensive simulations from physics to biogeochemistry to top predators to fisheries in a comparative framework to deduce and understand the dynamics of the ecosystem and its dependent resource populations, leading toward development of next-generation models which embody a high degree of realism and predictive skill. Models will help in identifying the main processes of the system (those indispensable for realistic predictions) and how they interact. Comparing various species, regions and ecosystems by searching for regularities and differences is of fundamental importance because universal patterns would reveal common principles underlying the organisation of ecosystems and their response to climate forcing.

CLIOTOP is organised around five working groups focused on key processes and scales (early life history of top predators; physiology, behaviour and distribution of top predators; trophic pathways in the open ocean pelagic ecosystem; synthesis and modelling – prediction and management indicators; socio-economic aspects and management strategies) and the CLIOTOP-MAAS group focusing on the development and implementation of a global monitoring system for pelagic mid-trophic organisms which are preyed on by top predators.

More details about CLIOTOP science and implementation can be found in the *CLIOTOP Science Plan* (Maury and Lehodey, 2005).

ESSAS

The goal of the ESSAS (Ecosystem Studies of Sub-Arctic Seas) programme is "*to compare, quantify and predict the impact of climate variability and global change on the productivity and sustainability of subarctic marine ecosystems.*" Geographically, it includes all of the subarctic seas in the North Atlantic and North Pacific oceans, where seasonal sea ice is present or where Arctic waters impose a significant influence. ESSAS began as a regional programme of GLOBEC with publication of its science plan (Hunt and Drinkwater, 2005a). Its interests include climate, hydrography, biogeochemical processes and food-web structure and dynamics from bacteria to marine mammals and seabirds, with a special focus on the role of physical forcing in controlling variability in marine ecosystems. Stronger links between biogeochemistry and food webs are a focus for ESSAS science programmes, which will allow this programme to fit within the vision and aims of IMBER.

The ESSAS programme includes four nationally funded projects (Japan, the United States, Iceland and Norway), and comparative studies between Norway and Canada as well as between Norway and the United States. It led an International Polar Year (IPY) Consortium; has four internal Working Groups (Climate Change, Biophysical Coupling, Modelling and Gadoid-Invertebrate Interactions); holds annual meetings including topical workshops organised by the Working Groups; and a Project Office in Bergen, Norway.

The ESSAS implementation plan consists of five main activities. The first has been completed and is the assembly of information on each of the major subarctic seas to facilitate comparisons among the regions. Major reviews of four subarctic regions were published (Oyashio, Bering Sea, Icelandic waters and the Barents and Norwegian Seas) as part of the *ESSAS Symposium Volume* (Hunt *et al.* 2007), and reviews for several other seas appeared in the ESSAS publication by Hunt and Drinkwater (2005b).

The second main activity is the conduct of regional ESSAS studies with emphasis on determining the external forcing functions linking climate processes to the physical and chemical oceanography of the subarctic seas and the response of ecosystems to the variability in climate. These are being achieved through a combination of integrated field studies, retrospective analyses (including time-series analysis) and modelling, and match several of the approaches suggested by IMBER. Although the role of climate on the ecosystem is the primary focus, it is recognised that major impacts to the ecosystem are also imposed directly by humans through harvesting, and hence, an important aspect of the work will be to determine the interactions between climate, fisheries and internal ecosystem dynamics.

The third aspect of the ESSAS implementation plan is to actively undertake comparative analyses of the subarctic seas through a combination of statistical analyses and modelling studies. Such comparisons between subarctic seas provide the opportunity to gather insights that could not be achieved within the regional studies. Two major comparative studies are under way, including one between Norway and Canada (NORCAN), focusing on the Barents/Norwegian Seas and the Labrador Sea and adjacent Canadian Shelves, and another between Norway and the United States (MENU) comparing the Barents/Norwegian Seas, Georges Bank/Gulf of Maine, the eastern Bering Sea and the Gulf of Alaska. Further comparative studies are planned involving other subarctic seas. As part of these comparative studies, as well as part of activities by the ESSAS Modelling Working Group, intercomparison of models used in different subarctic seas are being carried out including applying models developed for one region to investigate other subarctic seas.

The fourth major goal of ESSAS and one of the major goals of IMBER is the development of ecosystem scenarios of responses to both short-term climate variability and long-term climate change. The results from regional and comparative studies will be combined with information or models of future climate variability and climate change to develop scenarios of the effects of future climate on the ecosystems of the regional subarctic seas. While these scenarios will be an ultimate product from the programme, this activity is ongoing at the same time as the regional and comparative studies. The results from the scenario modelling will feed back to the regional and comparative studies.

The final aspect of the ESSAS implementation plan is programme synthesis. One part of this synthesis will be the regional projections of changes to the ecosystem under climate change. In addition, the results of the comparative studies will be used to determine what, if any, generalisations can be made regarding the structure and function of marine ecosystems in subarctic seas and the response to climate variability and change. One aspect that will be emphasised in the synthesis is the linkages between the biogeochemistry and food webs.

SPACC

SPACC and IMBER have not had formal discussions about SPACC becoming a potential regional programme of IMBER. It is likely that SPACC would need to augment its science plan – see GLOBEC website for documentation – and expand its activities to include biogeochemical aspects. The inclusion of SPACC in IMBER would expand IMBER's global coverage to include coastal upwelling regions.

The goal of the GLOBEC Small Pelagic Fish and Climate Change (SPACC) programme is to understand and predict climate-induced changes in the fish production of marine ecosystems. In addition to having broad economic and ecologic importance, this goal is especially pertinent today because of the expected changes in the Earth climate over the next hundred years and their impact on the ocean and marine life.

Small pelagic fishes are an ideal subject for the study of the effects of climate change on marine ecosystems because they are globally distributed and constitute more than one-third of the global marine fish catch. Moreover, by having a short lifespan and by feeding on the plankton-based food chains, they respond rapidly to changes in ocean forcing. Ocean-wide decadal swings in abundance have been identified and are thought to be environmentally driven. Lastly, time series of catches and abundance offer a rich data resource for retrospective data analyses.

The SPACC programme is a major component of the GLOBEC field research programme. An aim is to identify the physical forces that control the dynamics of small pelagic fish populations. Modelling is also a key issue for SPACC. By using a combination of retrospective data analyses, process studies and modelling experiments, the long-range goal of SPACC is to provide scenarios of changes in the abundance and distribution of small pelagic fish populations caused by human- and naturally induced climate changes.

The approach of SPACC is to compare the characteristics and variability of the physical environment, zooplankton population dynamics and fish population dynamics among ecosystems. SPACC involves:

- Retrospective studies, in which ecosystem histories are reconstructed by means of time series, paleo-ecological data and genetic data.

- Process studies, in which cause-and-effect linkages between fish population dynamics and ocean climate are investigated and compared between ecosystems.

The SPACC science and implementation plans were developed in the late 1990s (see GLOBEC Reports 8 and 11). They were revised in 2000 to increase focus and ensure maximum use of resources. SPACC is organised along four major scientific themes:

Theme 1: Long-term changes in ecosystems: retrospective analyses

The focus of Theme 1 is to explore how fish populations respond to ocean climate over time spans of hundreds to thousands of years. Long time series of data and modelling are used to determine how variation in the coupled ocean-atmosphere climate system affects the ecosystems in which small pelagic fish are important. It has a global and atmospheric perspective because climatic teleconnections are believed to be involved. The palaeo-ecological component is driven by the fundamental discovery that anoxic sediments in regions with small, pelagic fish contain scales that can be used to reconstruct time series of abundance of those fish over thousands of years.

Theme 2: Comparative population dynamics

Fish biomass per unit of stock is used to compute and compare quantitative estimates of small pelagic fish production and, most important, production of biomass or recruits per unit area of spawning and feeding habitats. This work provides a quantitative basis for comparing fish production between and within all systems in standard production units.

Theme 3: Reproductive habitat dynamics

The focus of Theme 3 is comparisons between systems to identify how small pelagic fishes adapt their reproductive strategies to the various kinds of physical forcing and mesoscale features of their habitat, and how such systems constrain fish productivity. A central hypothesis is that changes in productivity are caused by changes in the temporal and spatial dimensions of the spawning habitat, as well as its location and quality. A major component of Theme 3 is based on the use of CUFES (Continuous Underway Fish Egg Sampler) for mapping egg distributions and to achieve a quantitative description of the spatio-temporal dynamics of spawning. The use of hydrodynamic models coupled with NPZD and IBM models is also a central focus in order to investigate the links between environmental variability, spawning and recruitment success. Ecosystems are compared to separate physical forcing from stock-dependent effects on spawning and recruitment selection and to examine the extent to which productivity is limited by space and time variation in spawning habitat. The role of predators in defining habitat use by adults may be important and needs study.

Theme 4: Economic implications of climate change

Issues considered are (a) effects of low- and high-frequency climatic events on fish productivity; (b) impacts of climate change on harvesting and processing capacity and fisheries investments; (c) economic benefits of cooperative management of transboundary stocks; (d) impacts of the international trade of small pelagic fish and their substitutes; and (e) the value of improved long-range climate prediction.

The major focus of SPACC research is in the Eastern Boundary Current upwelling systems globally. *These regions, as well as sustaining the major small pelagic fisheries, also have special biogeochemical characteristics. These have not as yet been addressed by SPACC.*

BASIN

A growing issue in marine ecosystem research is the recognition of the need to carry out studies at the basin scale when considering ecosystem-climate linkages. The link to climate demands consideration of both broad spatial scales as well as recognition of longer temporal scales. Linkages between the open ocean and the surrounding shelves are also critical. An example of such an approach is that proposed by BASIN (Basin-scale Analysis, Synthesis and Integration).

BASIN is a proposed ten-year multidisciplinary programme to improve the integrated understanding of the dynamics of the marine ecosystems of the North Atlantic Ocean and to produce tools to meet the future increasing demands for an ecological strategy to marine management based on the precautionary approach. In developing a programme with the geographic scale of BASIN, the primary focus will be the subpolar gyre system and associated shelf systems of the North Atlantic, but important connections to the subtropical gyre will not be neglected.

BASIN is a joint EU/North American research programme initiative to elucidate the mechanisms underlying observed changes in physics and biology in the North Atlantic Ocean and to quantify and predict consequences of climate and environmental variability and change. The ultimate goals are:

(i) the development of an understanding of the links between climate and the marine ecosystems of the North Atlantic Basin and the services these ecosystems provide including exploited marine resources;

(ii) to use this understanding to develop ecosystem-based management strategies that will anticipate the effects of climate change on the living resources of the region.

Thus the overarching aim of the BASIN initiative is *"to understand and predict the impact of climate change on key species of plankton and fish, and associated ecosystem and biogeochemical dynamics in the North Atlantic Basin and surrounding shelves, in order to improve ocean management and conservation".*

With its focus on ecosystem dynamics, biogeochemistry and modelling, BASIN has all the characteristics of a programme that integrates biogeochemical and ecosystem research and is therefore highly relevant to IMBER. Developed under GLOBEC, the basin-scale approach of BASIN together with the proposed ten-year duration of the programme fit well with the second phase of IMBER. BASIN would benefit from the international connection through IGBP and SCOR.

BASIN can be viewed as geographically complementary to ESSAS (Arctic and Nordic Seas) and CLIOTOP (subtropical and tropical Atlantic). By linking the three programmes through comparative observational, process and modelling studies a coherent approach will be achieved to a wide latitudinal range of ecosystems in the Atlantic Ocean. BASIN will also link with regional organisations such as ICES and concurrent ongoing programmes such as CAMEO and CLIVAR.

Three main thematic questions have been identified:

Theme 1. How will climate variability and change – for example changes in temperature, stratification, transport, acidification – influence the seasonal cycle of primary productivity, trophic interactions and fluxes of carbon to the benthos and the deep ocean?

- How will the ecosystem's response to these changes differ across the basin and among the shelf seas?
- How are the populations of phytoplankton, zooplankton and higher trophic levels influenced by large-scale ocean circulation and what is the influence of changes in atmospheric and oceanic climate on their population dynamics?
- What are the feedbacks of changes in ecosystem structure and dynamics on climate signals?

Theme 2. How do life-history strategies of target organisms, including vertical and horizontal migration, contribute to observed population dynamics, community structure and biogeography?

- How are life-history strategies affected by climate variability?
- How will life history influence the response of key species and populations to anthropogenic climate change?

Theme 3. How does the removal of exploited species influence marine ecosystems and sequestration of carbon?

- Under what conditions can harvesting result in substantial restructuring of shelf or basin ecosystems, that is, alternate stable states?
- Do such changes extend to primary productivity and nutrient cycling?
- How is resilience of the ecosystem affected?
- What is the potential impact on the sequestration of carbon?

These will be addressed through an integrated multidisciplinary programme with the following outline structure:

- Modelling and Observing System Simulation Experiments (OSSES).
- Retrospective/reanalysis.
- BASIN observations: sampling technologies, observing platforms, broad-scale sampling programme and process studies.
- Management applications of BASIN.

Useful and relevant results for management are essential to the success of the BASIN programme. BASIN has the potential to offer data, analysis and models that could be included in ecosystem management activities around the whole of the Atlantic basin in a fully integrated way. Explicit plans to coordinate the integration of basic science into management will be developed. One approach is for BASIN to form, from its inception, partnerships with the management agencies in North America and Europe (NOAA/NMFS, NAFO, DFO, ICES and DG FISH) to ensure that the science developed is relevant to needs of management.

A draft of the BASIN Science and Implementation Plan has been completed, based on the ideas developed at a number of workshops, and is currently available, together with workshop reports, at:

http://web.pml.ac.uk/globec/structure/multinational/basin/basin.html

FUTURE

There has not been a formal approach by FUTURE to IMBER for association as a regional programme. Most of the text below comes from the draft science plan of FUTURE, January 2008. There have been initial discussions between PICES and IMBER concerning FUTURE. See: http://www.pices.int/members/scientific_programs/FUTURE/FUTURE_final_2008.pdf

FUTURE (Forecasting and Understanding Trends, Uncertainty and Responses of North Pacific Marine Ecosystems) is a new integrative science programme being undertaken by the member nations and affiliates of PICES, the North Pacific Marine Science Organization. FUTURE's main goal is to understand and forecast responses of North Pacific marine ecosystems to climate change and human activities at basin and regional scales, and to broadly communicate this scientific information to members, governments, resource managers, stakeholders and the public. To achieve this FUTURE will:

- investigate the mechanisms underlying ecosystem response to natural and anthropogenic forcing;
- improve forecasting capabilities and provide estimates of the uncertainty associated with these forecasts; and
- develop more effective ways to convey knowledge and predictions.

FUTURE builds upon the results from the Climate Change and Carrying Capacity (CCCC) programme that PICES initiated as a regional programme within GLOBEC.

The effects of climate and climate change on physical, geochemical and biological processes at geographical scales ranging from the North Pacific Basin and its marginal seas to the coastal regions are of interest to PICES member countries. Thus the scientific priorities of FUTURE include:

- marine ecosystem responses on seasonal to decadal timescales and the consequences of these responses to ecosystem goods and services (e.g. provisioning of foods, regulation of carbon and nutrient cycles, cultural and recreational benefits);
- ecological interactions and connections between estuarine, coastal and offshore waters, the western and eastern Pacific, and the northern and equatorial Pacific;
- direct and indirect effects of human activities, such as fishing, aquaculture, introduced species, habitat alteration, pollution and greenhouse gas emissions and their consequences for member countries;
- cumulative effects of multiple ecosystem stresses on biological diversity and ecosystem resilience and productivity with a better understanding of thresholds, buffers and amplifiers of change;
- risk-based ecological assessments within a policy/management framework to communicate future states of nature, their implications and uncertainties to decision-makers and the public.

An overarching question for FUTURE is "What is the future of the North Pacific given current and expected pressures?" In an attempt to answer this question FUTURE is organised around three research themes characterised by the following key questions:

- What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?
- How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?

- How do human activities affect coastal ecosystems and how are societies affected by changes in these ecosystems?

To determine the response of the continental shelf regions to human-forced future climate change will require downscaling of global climate model projections to regional models as well as linkage of these regional ocean models to hydrological models of watersheds to capture the dynamics of coastal ecosystems influenced by large rivers.

FUTURE's scientific strategy includes data compilation and retrospective studies, monitoring, mathematical modelling and process studies, all done with the perspectives of understanding, forecasting and communicating. Data compilation and retrospective studies will be used to identify the key physical, chemical and biological processes that are at highest risk from climate change and other anthropogenic stresses. Recommendations will be developed on future monitoring of the North Pacific so that ecosystem change of societal importance can be detected and understood. Monitoring will also provide the data needed for mathematical model development that will range from fine-scale models for coastal areas to whole ecosystem models of multiple trophic levels, including humans and top predators.

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