IMBER

Integrated Marine Biogeochemistry and Ecosystem Research

Draft IMBER Science Plan and Implementation Strategy

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IMBER

Science Plan and Implementation Strategy

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on behalf of the IMBER Transition Team.
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Executive Summary

The last decade of internationally coordinated marine research has greatly increased our ability to describe and model the ocean's many biological, chemical and physical processes. We have quantified the global fluxes of the major elements, such as carbon, and we continue to identify the organisms and processes central to the functioning of marine ecosystems. A newly emerging challenge, one dictated by society's needs to understand and prepare for the impacts of global change on the Earth System, is to bridge and merge the knowledge bases of the marine biogeochemical and ecosystem disciplines. In response to this need, the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project is being formed as an activity jointly sponsored by International Geosphere-Biosphere Programme (IGBP) and the Scientific Committee on Oceanic Research (SCOR). The IMBER project goal is:

> *To understand how interactions between marine biogeochemical cycles and ecosystems respond to and force global change.*

To achieve this goal it will be important to understand the mechanisms by which marine biogeochemical cycles control marine life and, in turn, how marine life controls biogeochemical cycles. In this light, IMBER research aims to identify key feedbacks from marine biogeochemical cycles and ecosystems to other components of the Earth System. IMBER will focus on processes within, and interactions between, the euphotic and mesopelagic layers of the ocean, the continental margins, and high-latitude and polar ocean areas. An interdisciplinary approach to this research, bringing together the biological and biogeochemical communities, as well as utilising long-term sustained observations, will be important. Embedding process studies within long-term observatories and surveys is required for assessing the changing ocean. An even greater challenge will be drawing together the natural and social science communities to study some of the key impacts and feedbacks between the marine and human systems.

The challenge to the scientific community is to understand interrelationships between biogeochemical cycles and food web dynamics, quantify and predict responses of the marine system to natural and anthropogenic perturbations, (e.g., changes in temperature, stratification, pH and nutrient loading), and estimate feedbacks from the ocean to the Earth System. Critical to our progress will be consideration of the marine system as a continuum from the inshore continental margins to the open ocean and of food webs from microorganisms to top predators. This approach will require an effort much larger than any single nation can mobilise to answer the broad interdisciplinary questions, which require multiple investigators from a range of disciplines and intercomparisons of data from a wide range of systems. IMBER will collaborate with and build on other projects that provide the physical, chemical, and biological context that will support the focus of IMBER research.

To address the IMBER goal, four scientific themes, each including several issues, have been identified for the IMBER project. The themes of IMBER are broad; however, their context is narrowed by the issues and priority questions identified. The eventual content of IMBER will be focused further as detailed implementation plans are developed for each theme and individual nations fund specific research.

Theme 1. Key Processes: What are the key marine biogeochemical cycles, ecosystem processes, and their interactions, that will be impacted by global change?

Issues

- Sources and sinks in marine biogeochemical cycles and how these impact macro- and micronutrient stoichiometry;
- Relationships between biodiversity, structure, function, and stability of marine food webs; and

- Interactions between biogeochemical cycles and the structure, function and dynamics of marine food webs.

Theme 2. Sensitivity to Global Change: How will key marine biogeochemical cycles, ecosystems and their interactions, respond to global change?

Issues

- Impact of climate-induced changes in circulation, ventilation and stratification on marine biogeochemical cycles and ecosystems;
- Response of marine biogeochemical cycles, ecosystems and their interactions, to increasing anthropogenic CO_2 and changing pH; and
- Response of marine biogeochemical cycles, ecosystems, and their interactions, to changes in inputs of macro- and micronutrients.

Theme 3. Interactions with the Earth System: What is the role of the ocean biogeochemistry and ecosystems in regulating climate?

Issues

- Oceanic storage of anthropogenic CO_2;
- The role of hypoxia/anoxia in the oceanic nitrogen cycle; and
- Direct ecosystem feedbacks on ocean physics and climate.

Theme 4. Responses of Society: What are the relationships between marine biogeochemical cycles, ecosystems, and the human system?

Issues

- Human lifestyle effects on the state of the ocean; and
- Mitigative and adaptive policies that could reduce the impact of global change on society.

IMBER will encourage investigations in four key domains of the ocean: the euphotic zone, the mesopelagic layer, the continental margins and high-latitude and polar ocean areas.

IMBER will take advantage of new and innovative approaches to conducting marine research, ranging from new molecular techniques to sustained in situ and remotely sensed observations. The development of sustained observation sites will be an important part of the implementation strategy for IMBER, which will be complemented by targeted field-based process studies, in situ mesocosm studies, and both field and laboratory experiments. A suite of hierarchical models will be developed to investigate hypotheses, analyse and extrapolate data in space and time, and identify crucial gaps to be filled by new observations to reduce uncertainties in our knowledge. Extrapolation to the global scale will require integration of data from basin-wide global surveys. To support the modelling and synthesis efforts, interconnected databases of biological, geochemical and physical variables will be constructed, extended and updated in near real time.

The following outcomes are anticipated over the ten-year life of this project.

- An understanding of key marine biogeochemical and ecosystem processes and their sensitivity to global change;
- An increased understanding of the role of biodiversity and food web structure on the cycling and storage of carbon in the ocean;
- Establishment of new high-technology systems for sustained measurements;
- A hierarchy of integrated models that link the mechanisms of biogeochemical cycles with ecosystem processes and provide predictions of the impacts of global change on the ocean system;

- Internationally shared, publicly available data sets and assimilated data products of ocean biogeochemical and ecosystem state variables;
- Identification of potential adaptive and mitigative policies to address the impacts of global change on the ocean system;
- A new generation of marine scientists from developed and developing countries trained in interdisciplinary research and using a systems approach; and
- Sound scientific knowledge to assist policy makers in making informed decisions.

IMBER will encourage the development of collaborative activities that will draw on the expertise of other projects and programmes to avoid unnecessary duplication and ensure that IMBER takes an interdisciplinary scientific approach. These collaborative associations will involve other IGBP/SCOR marine projects and IGBP integrative projects and programmes such as the World Climate Research Programme (WCRP), the International Human Dimensions Programme (IHDP), global observing programmes such as the Global Ocean Observing System (GOOS). A close collaborative relationship with GLOBEC (Global Ocean Ecosystem Dynamics) will be particularly important to ensure that fully integrated biogeochemistry and ecosystems research is undertaken across the entire food web. After 2009 the IGBP II structure will contain a single marine project.

Introduction

The Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) project is jointly sponsored by IGBP and SCOR. The project goal is:

> *To understand how interactions between marine biogeochemical cycles and ecosystems respond to and force global change.*

Important knowledge gaps must be filled over the next decade of research in order to meet society's need to address the challenges of global change. IMBER research will seek to identify the mechanisms by which marine life influences marine biogeochemical cycles, and how these biogeochemical cycles, in turn, influence marine ecosystems (Figure 1). We must develop a predictive understanding of how marine biogeochemical cycles and ecosystems respond to complex forcing factors, such as large-scale climatic variations, changing physical dynamics, changes in carbon system chemistry, and changing nutrient inputs. Changes in marine biogeochemical cycles and ecosystems also have consequences for the broader Earth System. Advancing our knowledge and quantification of these interactions and feedbacks will be the central feature of the IMBER project.

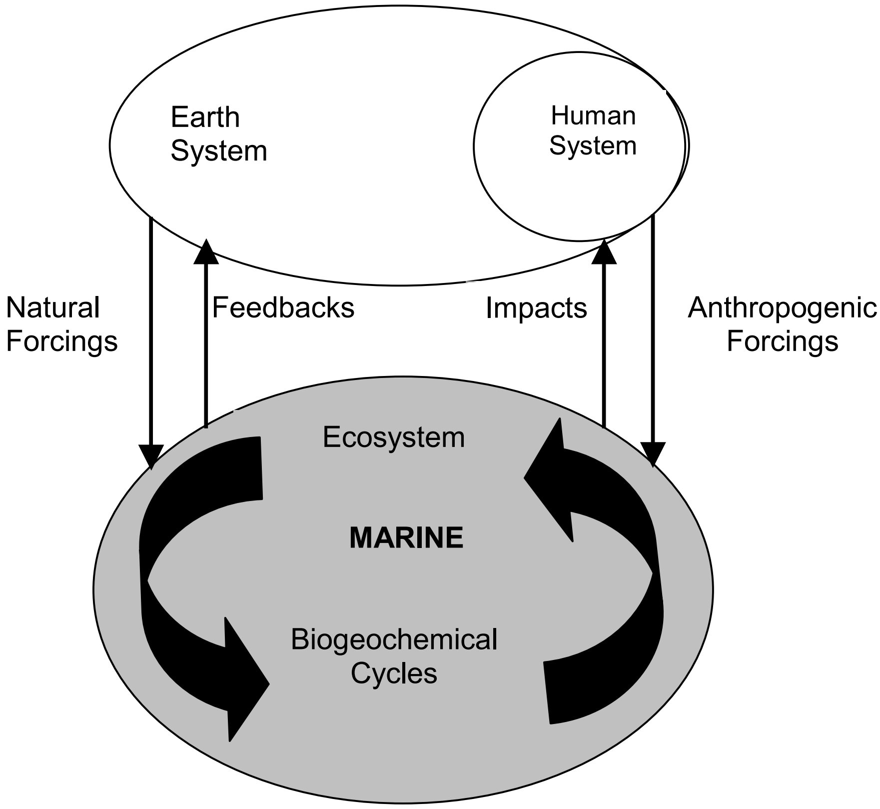

Figure 1. Schematic depiction of the essential features of the IMBER project. These include impacts of natural climatic and anthropogenic influences on marine biogeochemical cycles and ecosystems, their interactions, and feedbacks to the Human and Earth Systems.

The IMBER Science Plan and Implementation Strategy is largely based on input from the OCEANS Open Science Conference held in Paris in January 2003, which involved more than 370 participants from 36 countries, and the IGBP/SCOR *Framework for Future Research on Biological and Chemical Aspects of Global Change in the Ocean* (IGBP/SCOR, 2002).

Scientific Background

The ocean has a vast capacity for storage and exchange of heat and gases and thus exerts a major control on global climate. It is the most extensive and yet most poorly understood part of the Earth System. Significant advances in the understanding of the ocean have been achieved using coupled models, but we still cannot answer key biogeochemical and ecosystem questions or identify material sources and sinks.

In addition, the ocean system is experiencing unprecedented stresses due to human activities such as increased discharge of macro- and micronutrients caused by changes in land use, changes in marine biodiversity and marine ecosystem structure resulting from fishing and other human activities, and increased release of CO_2 and other gases (Figure 2). These changes have direct impacts on the ocean's physics, chemistry and biology.

Increased release of CO_2 is driving large-scale climate change affecting both terrestrial and marine ecosystems. These changes will not only affect atmospheric chemistry and temperature, but also ocean chemistry and temperature, and potentially, ocean physics (e.g., circulation and stratification). How such change will cascade into key biogeochemical cycles and marine food webs is a critical issue in understanding the impacts of global change on the marine system. Evidence from GLOBEC studies and Joint Global Ocean Flux Study (JGOFS) time-series observations suggest that low-frequency variability in the physical system (e.g., changes in stratification, circulation, ventilation, wind transport, and mixing) can have major impacts on the lower trophic levels of marine food webs and associated biogeochemical cycles. In particular, introduction of macro- and micronutrients to the euphotic zone is strongly controlled by physical processes, the mechanisms and strength of which are altered directly by variations and changes in the climate system.

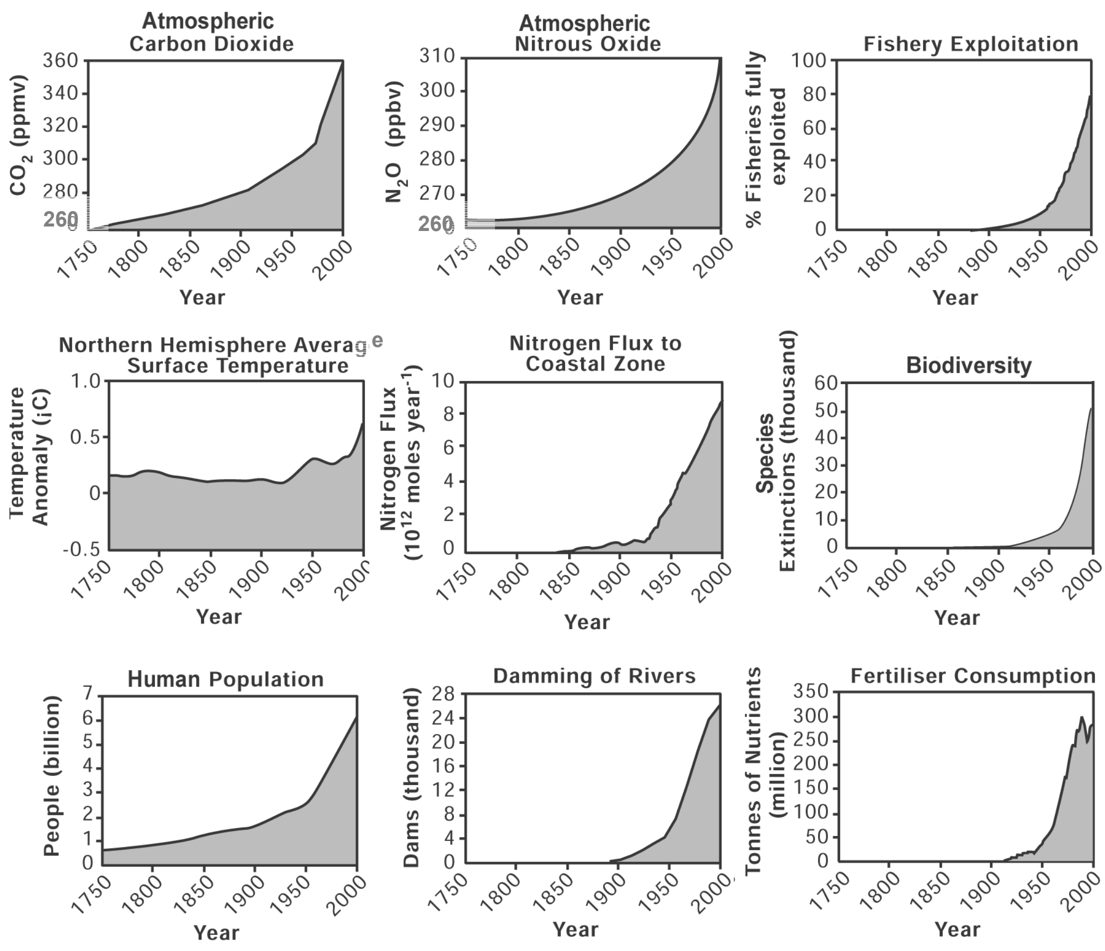

Figure 2. Examples of global change since 1750 (adapted from Steffen et al., 2004).

In addition, nutrients from terrestrial and coastal sources enter the ocean via the atmosphere and exchange with the continental shelf. These stimulate food web productivity and can affect species composition and complexity of marine ecosystems, impacting flux patterns of the major elements. Over the past century significant amounts of fertiliser have been released into rivers, impacting freshwater systems, estuaries, and enclosed and semi-enclosed seas. How far these impacts penetrate into the marginal seas, coastal ocean and the open ocean is unresolved in terms of biogeochemical cycles and marine food webs.

Previous studies of marine ecosystems have demonstrated the effects of both climate and human activity on marine food webs. Palaeoceanographic records, for example, indicate that the abundance of anchovies off California has fluctuated by a factor of 20 over the past two millennia, well before commercial fishing began. At shorter time scales, it has been suggested that catch trends of several pelagic and demersal fish species varied in or out of phase with global atmospheric indices over the past 50 to 70 years (Klyashtorin, 1998; Schwartzlose et al., 1999).

Changes in the decadal pattern of climate variability, as reflected in the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO) indices, has been related to major ecosystem disruptions and population changes, ranging from phytoplankton to top predators such as fish and sea birds (Thompson and Ollason, 2001; Beaugrand et al., 2002; Chavez et al., 2003). The mechanisms through which climate influences marine food webs, however, are poorly understood, because climatic influences act directly at each trophic level, by effects of physical changes on organisms as well as indirectly via transfers through biogeochemical cycles, from nutrients up through food webs.

Selective exploitation of marine organisms can change the size and age structure of populations, with subsequent impacts on population dynamics and, hence, ecosystems via food web interactions (Marshall, 1999; Köster et al., 2001). For example, excessive removal of large fish (Myers and Worms, 2003) changes the trophic structure of food webs (Pauly et al., 1998), interfering with the flow of matter within the pelagic domain and between the pelagic and benthic domains, with potential impacts on marine biogeochemical cycles.

Large-scale ocean research projects of the past decades have largely divided marine food webs into lower and higher trophic levels. JGOFS focused on phytoplankton, microbial food webs, and their relations to biogeochemical cycles, whereas GLOBEC has focused on physical environmental forcing on zooplankton and fish. These major projects have not studied the entire ecosystem, from microorganisms to top predators. IMBER will work collaboratively with GLOBEC to achieve a more complete understanding of the entire food web structure and function.

We have only a cursory understanding of the interaction of biogeochemical cycles and marine food webs. Broadly, three classes of food web/biogeochemistry interactions may now dominate the ocean:

- *vertical exporters*, such as found in diatom-dominated systems;
- *regenerators*, such as represented by the oligotrophic subtropical gyres; and
- *allochthonous exporters*, such as food webs impacted by N_2 fixers.

These categories are generalisations and the factors structuring these classes are only partially known. Identifying the exceptions to these fundamental paradigms of system function will expand our understanding. The physical and other factors forcing transitions from one class to another, with subsequent impact on higher trophic levels, require analysis. The controls and feedbacks for any of these classes of food webs are poorly understood.

Understanding and modelling the complex system of biogeochemical and ecosystem feedbacks is an important integrating activity across the IMBER project. IMBER research will also address interactions of the marine system with other components of the Earth System.

Developing, validating, and testing the predictions of Earth System models is impossible without a solid understanding of the interactions between ecosystems and biogeochemical cycles. IMBER will investigate the regional manifestations of global change on marine biogeochemical cycles and ecosystems, and the resulting feedbacks to the Earth System. The project also will include feedbacks associated with the human component of the Earth System and human decisions that influence the feedbacks to this system.

Themes and Issues

The themes of the IMBER project are closely linked (Figure 3). Theme 1 focuses on identifying and developing an understanding of key biogeochemical and ecosystem processes and their interactions, that are likely to be impacted by global change. Theme 2 considers the prediction and quantification of the response of these key processes and interactions to global change. Theme 3 investigates the role of the ocean biogeochemistry and ecosystems in regulating climate. Finally, Theme 4 focuses on drawing information from the previous three themes and investigating key interactions with the human system and the policies that can be developed to mitigate or adapt to the impacts of global change on marine biogeochemical cycles and ecosystems.

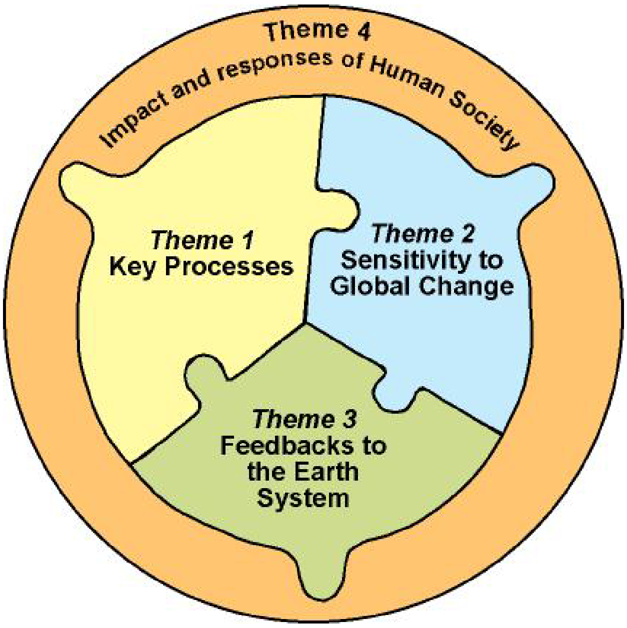

Figure 3. Linkages and relationships of the IMBER themes

Domains of Study

IMBER will build on previous and ongoing open ocean *euphotic zone* studies, taking advantage of existing and planned capabilities (such as time-series stations) in the euphotic zone. Because the long-term goal is to address the end-to-end food web, IMBER will pay particular attention to the euphotic zone. In addition, three domains within the ocean have been identified as not sufficiently understood, given their importance in the context of integrated understanding of biogeochemical cycles and ecosystems. These domains are the mesopelagic layer, continental margins, and high-latitude and polar ocean areas. IMBER research will focus on these domains to gain sufficient understanding of the marine system as a whole, to make predictions of the impacts of global change on marine biogeochemical cycles and ecosystems.

The mesopelagic layer (defined here as the layer between the bottom of the euphotic zone and 1000 m) has been identified as an important ocean region for decomposition of organic matter and the recycling of nutrients (Fasham et al., 2001). Processes occurring in the mesopelagic layer (also known as the "twilight zone") control the remineralisation of organic matter produced in the overlying euphotic zone, making macro- and micronutrients available for phytoplankton production upon return to the euphotic zone. Organic material that escapes remineralisation falls to the seafloor, where it is decomposed, consumed or buried. However, many of the biogeochemical processes occurring in the mesopelagic layer are poorly understood. Mesopelagic ecosystems are structured vertically and horizontally by the changing biogeochemistry of particles and dissolved organic matter, and by the diurnal movements and migrations of organisms seeking to optimise feeding and reduce predation. In such, migration of mesozooplankton provides a key link between the euphotic zone and the mesopelagic layer (Steinberg et al., 2000). Knowledge of the structure and functioning of mesopelagic ecosystems is needed to provide an understanding of the processes responsible for exchanges among the euphotic zone, the seafloor, and the ocean margins. Such knowledge is also needed to enable prediction of responses of these exchanges to such diverse perturbations as climate change, iron fertilisation, CO_2 injection, and increased exploitation of mesopelagic fish stocks. Understanding the biological and chemical processes in the mesopelagic layer, as well as their temporal and spatial variability, will broaden our understanding of tightly coupled biogeochemical cycles in the ocean and how they will change in the future.

Continental margins are regions of high productivity, especially in coastal upwelling areas where a large proportion of the global fish production and capture occurs. These regions are also significantly impacted by human activities via the input of nutrients, sediments, and pollutants; oil, gas and mineral extraction; and fishing. The IMBER project has adopted a functional definition of continental margins as the region between the land and the open ocean that is dominated by processes resulting from land-ocean boundary interactions. The exact dimensions of the margin depend on the issue of interest, but the definition is focused on the unique aspects attributable to the boundary system and generally consists of the continental shelf, slope, and rise and will include marginal seas. Recent global change research in the continental margins has focused on the budgets and cycling of carbon, nitrogen and phosphorus (e.g., by Land-Ocean Interactions in the Coastal Zone (LOICZ) and the LOICZ/JGOFS Continental Margins Task Team), and has demonstrated that these regions can be responsible for significant draw down and release of atmospheric CO_2 and cross-shelf export of carbon (Fasham et al., 2001). However, there has been less consideration of the exchange of CO_2, nutrients and marine organisms across the continental margin-open ocean interface. Continental margins are characterised by a close coupling between the water column and the sediment, with surface water mixing down to the shallow sediment surface in some areas, thus strongly influencing nutrient cycling. Down-slope transport of particles to the deep ocean in the benthic boundary layer and increased cross-isopycnal mixing due to friction with slope sediments may significantly contribute to the flux of organic carbon and heat to the deep ocean. Thus, the sediment-water interface is critical to ocean biogeochemical cycles and their coupling to marine ecosystems. At the land-ocean margin boundary, IMBER will seek to establish collaborative research with LOICZ, which has interests in nutrient and freshwater inputs to continental margins and biogeochemical cycles in this region.

High-latitude and polar ocean areas. Sedimentary palaeo-records have demonstrated that high-latitude ocean areas are important for biogeochemical cycling and are likely to be particularly sensitive to global change. Models based on palaeoceanographic data predict that increased biological productivity and draw down of excess nutrients in surface waters within these areas may lead to increased CO_2 utilisation and lowered atmospheric CO_2 during glacial periods. In addition, palaeoceanographic studies suggest that the driving mechanisms of deep-water formation and thermohaline circulation have periodically changed as a result of ice cover and freshwater inputs into the North Atlantic Ocean and the Southern Ocean (Rahmstorf, 2002). Similar ventilation changes are predicted for the Southern Ocean in the future, with large impacts on intermediate water oxygen concentrations throughout major ocean basins, with the potential for impacts on global marine biogeochemical cycles and ecosystems. These oscillations occur at millennial to centennial time scales, and appear to impact low-to-high latitude heat exchange, intermediate water ventilation, monsoon systems, and moisture transport on a global scale, all with potential marine biogeochemical feedbacks. Our understanding of the global climate's sensitivity to sea-ice cover, and intermediate and deepwater circulation, is therefore a key issue both for marine resources and future atmospheric CO_2 projections. The largest high-nutrient low-chlorophyll (HNLC) region in the global ocean is located in the high-latitude Southern Ocean, hence the response of this ocean area to global change may have a particularly strong feedback to the Earth System. Recent observations and climate scenarios show a large change in high-latitude and polar ocean areas, affecting sea-ice thickness (notably in the Arctic), mixed layer dynamics, circulation and river plumes. Accurate representation of these areas within marine biogeochemical and ecosystem models represents a major focus for future IMBER/Climate Variability and Prediction (CLIVAR) collaboration. A synthesis of pCO_2 flux data for the global ocean has shown that the Southern Ocean is a CO_2 sink as a result of both the biological and physical pumps, with a significant proportion of the draw down related to frontal systems. The predicted changes in the chemical and physical climate of the Southern Ocean are likely to have a significant impact on the food web structure there, with the prediction of a shift to more diatoms in the region (Boyd and Doney, 2003).

The time domain of IMBER is essentially determined by its main objective of understanding the interactions between global change and marine biogeochemistry and ecosystem processes. Global change is mainly discernable on decadal and longer time scales, but its manifestations contain intra-seasonal to inter-annual variability. Thus, modelling and observational activities under IMBER will specifically emphasise longer than annual time scale. Consequently, IMBER will have to deal with space domains affected by processes corresponding to these time scales, for example, the mesopelagic layer, shallow benthos and basin-scale gyres.

IMBER Approach to Research

The field research fostered by IMBER will focus on encouraging the development of a network of sustained observations, using both in situ and remotely sensed observations in the 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 data from sustained GOOS observations. The sustained observations will be complemented by targeted field-based process studies, in situ mesocosm studies, and laboratory experiments. Extrapolation to the global scale will require integration of data from the Repeat Hydrography Lines in close collaboration with CLIVAR and other basin-wide global surveys such as those planned by a collaborative multi-national programme to investigate the global marine biogeochemical cycles of trace elements and their isotopes (GEOTRACES). IMBER will also foster the development of innovative modelling techniques, and interpretation of palaeoceanographic records (in collaborations with International Marine Past Global Changes Study ((IMAGES) and Past Global Changes (PAGES)) to enable synthesis and development of a predictive capability based on past observations. This nested approach will link regional understanding to the global scale, providing the framework on which to build a predictive capability for the ocean system and its subsystems.

The IMBER project must also take advantage of new and innovative approaches to conducting marine research, including the use of stable isotopes for unraveling food web dynamics, biomarkers for identifying functional groups, new molecular techniques for detecting biological diversity. Past studies have focused on bulk biological processes and measurements rather than on the roles of key species or functional groups. Our understanding of the distribution and functioning of microbial communities, their dynamics, and their role in cycling materials in the ocean remain at a rudimentary level. Yet this knowledge is key to predicting ecosystem and biogeochemical responses to global change. We must apply novel techniques, including enzymological and molecular methods, that are targeted directly at the genome of plankton at the level of individuals, to allow direct quantification of specific functional groups of organisms and key species.

The most important aspect of IMBER research will be the seamless integration of biogeochemical and ecosystem research in a truly interdisciplinary approach and the integration of social science to enable the investigation of policies that could be developed to mitigate or adapt to the impacts of global change. Bringing together these science communities will be a significant challenge for the project and will need to start with the development of common terminologies that can be understood by all participants.

Education and Capacity Building

IMBER will encourage the full participation of undergraduate and graduate students, who will gain experience with interdisciplinary studies and system approaches to ocean science. IMBER will place a priority on professional training for the next generation of college and university faculty, in both developed and developing countries, who will transfer this new understanding to their students and colleagues. The knowledge developed in the IMBER project can be used to strengthen curricula related to the sensitivity of the ocean to global change from primary school to university level.

Anticipated Outcomes of the IMBER Project

Over the ten-year life of this project, IMBER research will develop a significantly increased understanding of how the interactions between marine biogeochemical cycles and ecosystems respond to and force global change. This increased understanding will provide policy makers with sound scientific knowledge to make informed decisions on the management of global change and its impacts on the marine system, and will include the identification of potential adaptive and mitigative policies to address the impacts of global change. The increased understanding will be based on internationally shared, publicly available data sets from a wide range of experiments, current and new high technology time-series stations, sustained ocean observations and results from a hierarchy of integrated models. The models will link the mechanisms of biogeochemical cycles with ecosystem processes and provide a predictive understanding of the impacts of global change on the ocean system.

Collaboration with Other Projects and Programmes

The IMBER project will build on the approaches taken and the knowledge gained in previous projects and will establish collaborative links with related projects to eliminate the important gaps in research activities. In particular, IMBER will foster a close partnership with GLOBEC to enable studies on interactions of biogeochemistry with food webs at all trophic levels.

Collaborative research will also be developed with the following:

IGBP/SCOR Interface Projects

- LOICZ - in studies on the continental margins; and
- SOLAS – (Surface Ocean – Lower Atmosphere Study) on the impact of atmospheric inputs on marine biogeochemistry and ecosystems and on the cycling of carbon and nitrogen in the ocean.

IGBP Integration Projects

- PAGES and IMAGES - in understanding physical and biogeochemical processes operating in the ocean on time scales longer than the period of instrumental records; and
- GAIM – (Global Analysis, Integration and Modelling) in the development of Earth System models that incorporate ocean processes.

Earth System Science Partnership Programmes

- WCRP/CLIVAR – In particular CLIVAR, on the role of physical processes, particularly climate variability and change on marine biogeochemical cycles, ecosystems and their direct feedbacks on physics;
- DIVERSITAS – (International programme of biodiversity science) on the impacts of biodiversity changes on marine biogeochemical cycles and ecosystems;
- IHDP – on integrating social science; and
- GCP – (Global Carbon Project) in the study of global carbon cycling;

SCOR Activities

- GEOHAB – (Global Ecology and Oceanography of Harmful Algal Blooms) on the effects of physical, chemical and biological conditions on phytoplankton population dynamics with Intergovernmental Oceanographic Commission (IOC);
- GEOTRACES – in the global study of trace elements; and
- IOCCP – (International Ocean Carbon Coordination Project) in the observations of carbon cycling and storage in the ocean (with IOC and GCP).

Ocean Observation Programmes

- GOOS - to ensure effective collection and use of sustained observations.

Details of how these collaborations will be implemented are outlined in the *Linkages With Other Projects and Programmes* section of this document. Linkages to national and regional activities will be established as these activities develop.

Structure of the IMBER Science Plan and Implementation Strategy

The IMBER Science Plan and Implementation Strategy is based on four themes, and within each theme, issues are identified with priority questions in each issue. The first section of the document introduces the science themes and issues with a review of the present state of understanding. The introduction is followed by the priority questions within each issue, which indicate priority areas for research. Implementation approaches are outlined in the Promising Scientific Approaches and Collaborations for each issue and theme. A number of crosscutting issues, including modelling, sustained observations and data management, which are important to each of the themes, are outlined later in this document. The final section of the document describes the organisation and management of IMBER, including the linkages to other projects and programmes. Publication of this Science Plan and Implementation Strategy will be followed by the development of specific and more detailed implementation plans for specific sections of the science plan by groups of interested scientists working together with the IMBER Scientific Steering Committee.

Science Themes

Theme 1: Key Processes: What are the key marine biogeochemical cycles, ecosystem processes and their interactions that will be impacted by global change?

Introduction

Marine ecosystems are structured by complex interactions between physical factors (such as light, temperature, mixing, turbulence and currents), chemical factors such as concentration, distribution, and bioavailability of macronutrients and micronutrients/trace elements that are required for life, and biological processes such as primary production, grazing and predation that alter the form and distribution of chemical elements in the ocean system. When viewed statically, individual factors may seem to exert considerable control or limit specific biological processes. However, the ocean system is dynamic and it is the interactions among physical, chemical, and biological processes that determine the state of marine ecosystems. Understanding how biogeochemical cycles and fluxes integrate with food web dynamics provides a major intellectual challenge of marine science and the IMBER project. We have identified three key issues within this theme. The first issue investigates the sources, sinks and stoichiometry of macro- and micronutrients; the second focuses on food web structure and dynamics, and the third bring biogeochemical cycles and food web structure and dynamics together to investigate the interactions between them.

The inputs, losses, dynamics, and chemical forms of micro- and macronutrients influence the autotrophic and heterotrophic organisms found in the ocean (Bruland et al., 2001; Mann et al., 2001; Svensen et al., 2002; Granger and Ward, 2003) with subsequent non-linear impacts on metabolic rates and processes, population and community dynamics, and food web and community structure. The bioavailability of macro- and micronutrients required for the functioning of specific enzymes and metabolic pathways may exert considerable control on the species composition of communities of marine organisms and functional metabolic pathways. The ocean's ability to support life, and the role of life in controlling the chemical composition of the ocean, are affected by macro- and micronutrient cycles on a wide range of space and time scales. Changes in microbial and phytoplankton activity due to changes in the concentrations, types and ratios of macro- and micronutrients can alter the composition, production, and subsequent degradation of organic matter. Differential remineralisation may lead to decoupling of nutrient cycles within the water column (Karl, 1999; Karl et al., 2001b).

Through uptake, metabolic transformations, active and passive transport, extracellular complexation and recycling, biological communities exert considerable control on the oceanic abundance and distribution of macro- and micronutrients and other particle-reactive elements. Such transformations may themselves be influenced by factors internal to marine food webs, such as species composition, as well as external factors that may vary in time and space. Understanding marine biogeochemical cycles and ecosystems will require a significant increase in our understanding of the interactions between biological and geochemical processes.

It is important to recognize that the magnitude and impact of individual transport, metabolic and biogeochemical processes vary spatially and temporally in response to numerous forcing factors. Interactions between biogeochemical cycles and food webs are expected to differ between environments such as continental margins associated with coastal upwelling, high-latitude and polar regions, and tropical and subtropical oligotrophic gyres. Comparison of these different systems will provide new insights for identifying and understanding fundamental interactions between marine biogeochemistry and ecology.

Issue 1. Sources and sinks in marine biogeochemical cycles and how these impact macro- and micronutrient stoichiometry

Introduction

Evaluation of the interactions and feedbacks between marine biogeochemistry and ecosystems requires knowledge of the distribution and residence times of biologically important elements. Reactions and transfer of macro- and micronutrients, particle-reactive elements, and isotopes occurring at ocean interfaces (air-sea, land-sea, and sediment/water) represent the fundamental means whereby changes in source and sink strengths propagate into the marine environment and alter the oceanic biogeochemical state. In the reverse sense, transfer across these interfaces also represents the means by which the ocean influences other parts of the Earth System. IMBER seeks to advance our understanding of how the transfer of materials and energy across these interfaces influence and are influenced by marine biogeochemical and ecosystems interactions. The rate and magnitude of potential interface-dependant reactions are strongly controlled by specific sets of chemical and ecological interactions. New insight into the processes that control the input, internal cycling, and ultimate fate of biologically important elements in the ocean system will provide the means to describe and evaluate the potential for significant non-linear responses of the ocean to even modest changes in forcing related to global change.

Palaeoceanographic records over the past four glacial cycles indicate clearly that during the maximum glacial conditions (e.g., around 20 to 30 thousand years ago) sea level was 120 to 140 m below present (Labeyrie, 2002). During past warm periods (interglacials), such as 125 to 130 thousand years ago, sea level was higher (by 5 to 10 m) because global continental ice cover was less extensive than today. During glacial sea-level lows, the enlargement of exposed continental areas probably led to changes in the input of terrestrial material and runoff. All of these processes can provide potential links to ocean systems, but the magnitude and the time scales of modulation in response to human and climate perturbations remain poorly quantified. In addition, we must advance our understanding of the physical, biological, and chemical controls of sediment-water exchange.

In the deep ocean, as well as on continental margins, the deposition of particulate material on the seafloor represents only the first step in the potential removal of material from the ocean. The final deposition and preservation of material and biologically important elements depends on the biogeochemical and physical characteristics of the sediment/water interface, including seawater chemistry, water flow characteristics, including (tidal effects), rates of deposition, sediment physics, interstitial water chemistry, microbial community activity, and benthic community status. Changes in sediment fluxes also alter the quantity, quality, and distribution of biogenic habitat and communities that have major influences on chemical and energy fluxes between benthic and pelagic systems. The eventual burial of biogenic elements is variable and is controlled by complex factors. The importance of early diagenesis (i.e., remineralisation, carbonate dissolution/precipitation, silica dissolution and iron recycling, reverse weathering) and sediment resuspension in controlling feedbacks to climate change are largely unknown. Differential regeneration and release of biologically important elements to deepwater can alter stoichiometric distributions from those required for balanced biological growth.

Another source and sink process that has been known for several decades is the direct input of micronutrients, many biologically relevant, to the ocean via high temperature seawater plumes exiting the seafloor. There is also significant exchange of material that occurs more subtly via “low temperature” circulation of water through the extensive flanks of mid-ocean ridges. In such zones, large quantities of deep ocean water are processed (at temperatures lower than those found in vent systems) through the sediment and aging crust, providing a mechanism for altering the stoichiometry of chemical elements in the emerging water and for supporting microbial life (Cowen et al., 2003). This hydrothermal circulation exerts considerable control on the chemical composition of the entire ocean over the long term, and may affect local chemistry in ridge crest areas and ridge flanks on shorter time scales.

In addition to direct transfer of biologically important elements to or from the ocean, inputs and removal of certain elements can control important chemical transformations within the ocean. Recent work has suggested that the availability of iron relative to nitrate may control the fixation of biologically utilisable forms of nitrogen from gaseous N_2, and may exert considerable influence on marine ecosystems (Karl et al., 2002; Karl, 2002). Progress toward a new understanding of the complex systems that control oceanic distributions will be advanced by identification and quantitative description of the sources, sinks, and internal transport processes and rates that control the distribution of the elements that link ecosystems and biogeochemical cycles.

It has long been known that the biological availability and accumulation of potentially toxic micronutrients in the ocean (i.e., Cu, Hg), are strongly influenced by their chemical speciation, which may be controlled by biologically produced chelators (Moffett, 1995; Moffett and Brand, 1996). Recent studies have found potential control on biological systems stemming from synergistic effects of macro- and micronutrient distributions. Among the factors identified as being important for the bioavailability of biologically important elements are the oxidation state of the central element, its degree of organic or inorganic complexation, the specific ligand dominating speciation, and whether the ligand is present in dissolved, colloidal, or particulate form (Morel and Price, 2003). One of the best examples for which we know a portion of its potential complex interactions with ecosystem function is iron. The bioavailability of iron depends directly on its oxidation state, complexation by siderophores or other unknown organic ligands, and partitioning of iron among particulate, colloidal, and dissolved forms. In the past decade, our understanding of the chemical speciation of iron and its interaction with biological systems has changed considerably (Turner and Hunter, 2001). Thought to be completely complexed by inorganic hydroxides as recently as 10 to 15 years ago, iron is now believed to be almost completely complexed by organic ligands. This new picture of iron chemistry in seawater greatly changes our conceptual ideas of the interactions between iron and ecosystems. The chemistry of other biologically important micronutrients may well be equally misrepresented and consequent relations to biological function and ligand production may also require new examination.

The chemical properties of most micronutrients, including their isotopes, are complicated, with variable oxidation states, solubility, hydrolysis, formation of complexes, and exchange with colloidal and particulate phases. This situation makes it essential to develop an understanding of their sources and sinks in the ocean and their transformations between different physical and chemical forms. Of particular importance is the formation and dissolution of the primary biogenic mineral phases. For example, calcium carbonate ($CaCO_3$) and opal can serve as ballasting materials, enhancing vertical fluxes of particle reactive elements. Production and dissolution of $CaCO_3$ can also modulate seawater pCO_2 levels. In addition, these transformations may control the availability of micronutrients to organisms and the reactivity of these elements in abiotic processes. These factors may change in the future and, hence, are of particular importance to understand in terms of the processes involved.

Priority Questions

- What is the role of continental margins in controlling biogeochemical cycles and macro- and micronutrient abundances?
- How and to what degree are large-scale marine biogeochemical cycles impacted by interfacial transfers of macro- and micronutrients?
- What role does remineralisation within the mesopelagic layer play in controlling distributions of macro- and micronutrients in surface waters and export to the deep ocean?

- What controls the chemical form of "bioreactive" elements (dissolved vs. particulate, organic vs. inorganic) in space and time?

Numerous studies have reported net transport of the macronutrients between the oceanic water column and atmospheric, terrestrial, sedimentary, and hydrothermal systems. Nevertheless, an accurate and complete assessment of these exchanges has not been achieved, especially as to how they propagate into larger-scale ecosystem dynamics and biogeochemical cycles important to the global ocean. One factor that has confounded these studies is anthropogenic activities which alter exchange rates on time scales that are short relative to mean oceanic residence times of important elements. Inputs, outputs, and ocean inventories are not in balance for some elements (e.g., fixed nitrogen: (Middelburg et al., 1996; Codispoti et al., 2001).

Estimates of the mean oceanic residence times and average vertical profiles for most elements in the periodic table have been published (Nozaki, 1997). These profiles generally indicate whether an element displays a nutrient-like profile or more chemically conservative behaviour. However, our knowledge of these characteristics is generally not adequate for examining the interactions between biogeochemical cycles and food webs. Important unresolved issues include determining whether all of the important sources and sinks have been identified and quantified for specific elements, whether all or only a few specific forms of the element are available for uptake and utilisation by the biological community, and how efficiently each element is transported vertically via the biological pump.

One of the important domains identified for the IMBER project is the continental margins, which include continental shelf, slope, and rise areas, and inland and marginal seas. Many transport processes are unique to, or intensified at the boundaries and contribute to the high spatial and temporal variability of these systems (Figure 4). Examples include wind-driven upwelling and associated high biological productivity, accelerated cross-isopycnal mixing and input of materials from terrestrial sources, submarine groundwater discharges and related chemical inputs, and input from cold vents related to gas hydrates and hydrocarbon seepage. Furthermore, the transport of macro- and micronutrients on and off the shelf has been purported to impact the dynamics of both shelf and offshore ecosystems (e.g., Gallego et al., 1999). It has been suggested that ocean margin systems are globally significant in the oceanic uptake of anthropogenic carbon dioxide (Tsunogai, 1999; Yool and Fasham, 2001), in the deep vertical flux of organic matter (Jahnke, 1996; Van Weering et al., 2001; Wollast and Chou, 2001a, b), in the removal of fixed nitrogen from the ocean via denitrification (Middelburg et al., 1996, Codispoti et al., 2001), and in the burial of opaline silica (DeMaster, 2002). Furthermore, the flux of dissolved iron from coastal anoxic sediments and the extraction of iron from resuspended sediment particles have been suggested as sources of bioavailable iron (Berelson et al., 2003). More than 90% of the organic carbon burial in sediments occurs in these boundary regions (Hedges and Keil, 1995). Physical, chemical, and biological processes on the continental shelf and slope transport and transform material entering the open ocean.

For example, as anthropogenic CO_2 invades the ocean, the pH of surface waters is expected to decrease. Increases in water column stratification from warming could lead to increased hypoxia in deepwaters. There is a need to understand the sensitivity of micronutrients speciation to reduction-oxidation (redox) conditions, and the how this speciation is useful in predicting changes in bioavailability, toxicity, solubility, and other critical properties as ocean surface conditions (e.g., pH, temperature and oxygen content) are altered.

The linkages between benthic and pelagic systems are clearly identified as critical components in the study of continental margin and deep-water biogeochemistry. Benthic exchange of nutrients can alter nutrient ratios in coastal upwelling waters, impacting surface food webs and consequent export. The spatial extent of the deep seafloor and known exchange processes suggest that this interface must also be understood to fully constrain the large-scale cycling of biologically important elements in the ocean. Implicit in research on

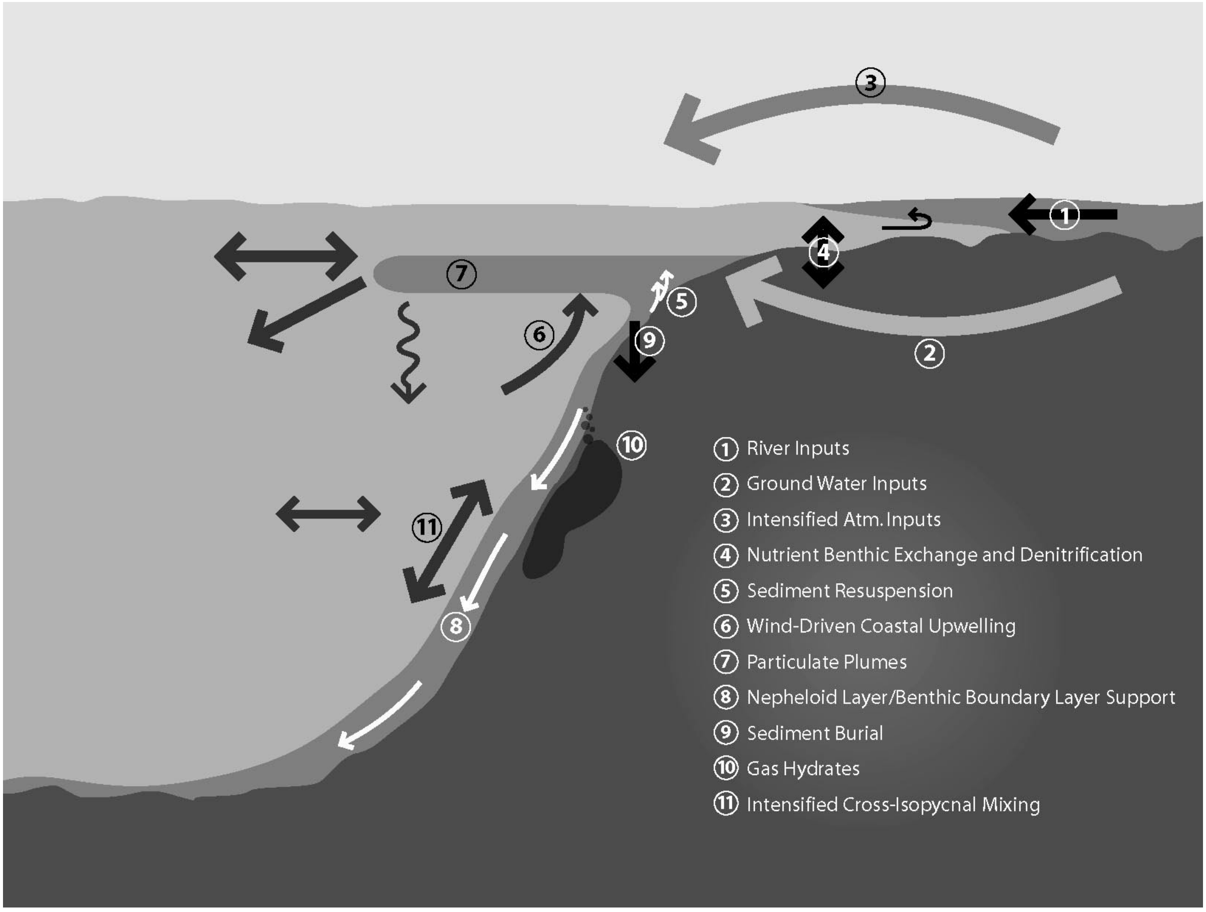

Figure 4. Schematic depiction of processes that are unique to or intensified at ocean-continental boundaries Many of the processes depicted are sensitive to global change, with both local- and global-scale consequences for biogeochemical cycles and foods webs.

the sediment-water interface is the need to further characterise the diagenetic processes that control the intricate balance between deposition rates, recycling and burial that ultimately control the present and future biogeochemical state of the ocean. These studies would also strengthen the accuracy with which the sedimentary record can be related to oceanic conditions and processes, a requirement for determining the temporal variability of oceanic biogeochemical and ecological systems and climate.

The mesopelagic layer, located between the photosynthetic surface ocean and 1000m, is critical to the connection between the two main interfaces for exogenous sources and sinks of biologically important elements in the ocean. Processes occurring in the mesopelagic layer control the remineralisation of organic material produced by organisms in the overlying euphotic zone to release macro- and micronutrients, affecting the consequent quantity and stoichiometry of material delivered to the deep waters and seafloor. The mesopelagic layer is also critical for the reflux of biologically important elements back into the sunlit surface ocean and hence plays a critical role in controlling primary production on global change time scales. Most of these processes are carried out by mesopelagic ecosystems, the vertical and horizontal structures of which are controlled by the changing biochemistry of particles and dissolved organic matter (DOM), by the movements and migrations of organisms, and by currents and mixing processes that follow isopycnals.

Knowledge of the structure and functioning of mesopelagic ecosystems is needed to provide understanding of exchanges between the photic zone, the benthic zone, and the ocean margins. There needs to be a better quantification of the magnitude of fluxes and the chemical transformations controlling the stoichiometry of material passing through the mesopelagic layer. The dominant processes involved in the transformations must be identified and evaluated as to their role in oceanic response to global change, including anthropogenic change. Because transfer across the mesopelagic layer varies regionally, we need to determine basin-wide distributions of chemical components that result from vertical exchanges, input and removal at boundaries, and advective transports.

Remineralisation processes are difficult to observe and quantify, particularly in the mesopelagic layer, and consequently remain poorly characterised throughout the entire water column. This situation requires immediate attention since biogeochemical models seeking to develop a predictive representation of the fluxes and material transformations in the mesopelagic layer need to include information about the depth dependence of nutrient remineralisation and the factors that control it. Better characterisation of these processes should lead to better estimation of the responses of these fluxes to such diverse perturbations as climate change, iron fertilisation, CO_2 injection, and harvesting of mesopelagic fish stocks. Linkage to the euphotic zone, particularly inclusion of ecological structure and the microbial system, must play an important role in the character of exported material, and hence in determining the depth range over which material is degraded. Association of organic matter with mineral grains may impact the rate and depth of remineralisation by protecting organic molecules from enzymatic attack and by acting as particle ballast to increase sinking velocities. Differential remineralisation of biologically important elements and upwelling may lead to the decoupling of nutrient cycles within the water column. This, in turn, could lead to changes in which nutrients limit plant growth and result in subsequent ecosystem shifts. We need a better understanding of the relationships among remineralisation depth, vertical scales of stratification, circulation, and isopycnal ventilation that determine the time scales of nutrient sequestration and reflux.

Predictive biogeochemical models must be developed, that accurately represent remineralisation processes and respond realistically to changes in forcing on time scales relevant to global change. However, substantial uncertainties remain in our understanding and quantification of the processes involved, and many basic questions must be answered before accurate parameterisations can be developed.

Promising Scientific Approaches

Examining the sources and sinks of nutrients and their internal cycling within the marine system will require a combination of approaches. Sustained observations at locations where important input and loss processes can be characterised will be critical to advancing our understanding of the temporal dynamics of boundary exchanges. Equally important is the need to quantify oceanic distributions of the biologically important elements in conjunction with the determination of physical transport. This will require a combination of shipboard sampling surveys (such as those planned by the GEOTRACES project), sediment traps, and emerging observatory technologies such as fixed mooring arrays, free drifting and ”gliding” undulating sensor platforms, and autonomous water samplers (Bell et al., 2002). Advances in numerical simulation and visualisation will permit biogeochemical and ecological observations to be placed in a physical oceanographic context to an extent not previously possible. Advances in analytical techniques lead to major new research opportunities in examining the distributions and dynamics of micronutrients and ligands. Measurement of isotope abundances of micronutrients may provide unprecedented insight into the dynamic linkages between ecological and biogeochemical systems.

Study of the intricate interactions between biological community composition and function, and the abundance and biological availability of macro- and micronutrients, requires detailed process studies. An important aspect of the IMBER research strategy, therefore, is to co-locate process studies and sustained observations and link these sites with basin-wide surveys and numerical models. These study locations should, at a minimum, represent the IMBER focus regions (continental margins, high-latitudes and polar regions and the mesopelagic layer) to facilitate comparative studies. Furthermore, collaboration and coordination with SOLAS and LOICZ studies that are directed at advancing our understanding of the spatial and temporal dynamics of boundary exchanges will be critical for parameterising feedbacks and interaction between ecosystems and biogeochemical cycles and climate change.

Issue 2. Relationships between biodiversity, structure, function and stability of marine food webs

Introduction

Species richness of Archaea, bacteria and eukaryotes in the ocean may number at least in the millions, and most of those species have not yet been identified or scientifically described. The potential number of interactions between them is almost infinite; however, the ecological structure of marine ecosystems does not appear to be chaotic or unpredictable. Whether this is due to external forcing or to biological interactions, or both, a strong selective pressure seems to exist that not only shapes individual adaptations but, through them, the characteristics of marine food webs. To understand marine biodiversity and food webs, one has to understand how natural selection operates in the highly variable marine environment and how physical forcing and species interactions contribute to stability. As interactions vary from viral infections of cyanobacteria (Bratbak et al., 1994) to orcas feeding on whales, very different spatial and temporal scales are involved.

Unravelling the relationships between biodiversity and the structure and function of marine ecosystems requires simplification that reduces biodiversity to a manageable set of entities. This can be done in many ways. In marine ecology the “structure” of ecosystems is most often condensed to a food web in which species are aggregated in size, functional or trophic groups. However, these functional groups are not consistently applied and generally have no direct link with biodiversity. A more biodiversity-oriented approach is to focus on species that are expected to explain major characteristics of food webs and ecosystem functioning, either because they have high, abundance and biomass, a major impact on a biogeochemical process (key species), because they structure the physical and chemical environment (engineering species in the benthos) or because they are top predators and may be of commercial value. A third approach is to use (parts of) the genome of one or even all of the species collected, or to measure the expression of selected genes in situ and relate this to abundance of key ecosystem processes such as nitrogen fixation.

The advantage of using the food web approach is that food webs can be described by a limited number of state variables (size, functional or trophic groups) of which the internal dynamics can be understood in terms of genetic, biochemical and physiological processes The trophic groups are, in turn, linked through trophic interactions (nutrient uptake, competition, predation) that can be quantified and are considered to represent the “function” of the ecosystem. The link between structure and function is then relatively straightforward. The “functional group” approach most closely links the structure of a food web with its biogeochemical activity, the flows of energy and materials through the system.

The structure and composition of marine food webs are controlled by a variety of forcing factors, that include changing physical and chemical regimes, and the indirect and direct impacts of human activity (Figure 5). Examples include the types and concentrations of nutrients and contaminants, fishing and other exploitation of living resources.

Knowledge of biological control within and across the trophic levels will be essential for understanding the longer-term persistence of systems. Biodiversity prepares functional redundancy of the marine ecosystem and the redundancy play an important role of the systems ability to withstand natural and anthropogenic disturbance. The impact of changes in

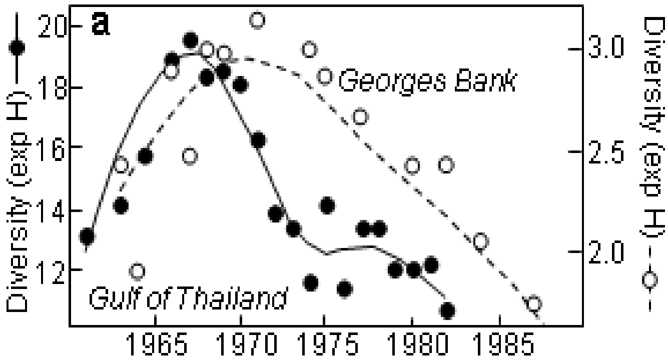

Figure 5. Changes in biological diversity of fish catches in the Gulf of Thailand and the Georges Bank, 1960-1985. The graphs show increases in fish diversity associated with the development of the fishery, followed by a progressive decline thereafter as a consequence of over fishing. Gulf of Thailand (data from Pauly (1987) and Georges Bank from Solow (1994).

biodiversity on food web structure and function and stability of the ecosystem may prove to be key in determining the impact of global change.

Although the food web is essentially a continuum, research on marine food webs has been fragmented. One obvious dichotomy is between pelagic and benthic food webs. In the past, research on pelagic food webs has tended to focus on both the phytoplankton and microbial food web, or on zooplankton, fish, and top predators. This is, to some extent, due to the perception that food webs are either regulated bottom-up (through nutrient and light availability) or top-down (through predation and competition). The production of fish depends on the structure of food webs (GLOBEC, 1999) with important implications for human society in terms of food security, biodiversity, and the management of marine resources (IHDP, 1999; Loreau and Oliveri, 1999; DIVERSITAS, 2002; Perry and Ommer, 2003). Recent evidence shows that heavy fishing has removed larger commercially valuable fish worldwide, leaving primarily smaller, less commercially valuable fish (Pauly et al., 1998; GLOBEC, 1999). Observational and theoretical evidence suggests that such large changes at the top of marine food webs can induce switches in equilibrium states at lower trophic levels (Spencer and Collie, 1997). How far downward into lower trophic levels this effect propagates is not known.

It is clear that future research must approach marine food webs as entire entities from viruses to top predators and consider the interactions between benthic and pelagic systems. A focus on the interactions between the macrobiological and microbial food web components is also required. For example, biodiversity and the characteristics of (dominant) macroscopic species may determine activities in the microbial food web and vice versa. What is not clear is how changes in biodiversity translate into changes in food web structure and function. An example of long-term variation is found in oligotrophic subtropical waters, which were for many years considered to be a near stable ecosystem with constant chlorophyll concentration and balanced phytoplankton growth and zooplankton grazing. Through the JGOFS time-series studies, it was shown that phytoplankton species composition and the contribution of fixed nitrogen by nitrogen fixers to primary production varied temporally. Such a change in phytoplankton species composition also changes the function of the ecosystem in biogeochemical cycles and influences the stoichiometry of important minor elements in seawater (Figure 6). While such changes have required long-term, careful observations in the open ocean, dramatic changes in food webs at continental margins are obvious, generally reported in fish catch but most likely extending throughout the food web. Changes may occur on a wide range of time scales in response to human activities and inputs, and to short- and long-term natural cycles (Chavez et al., 2003).

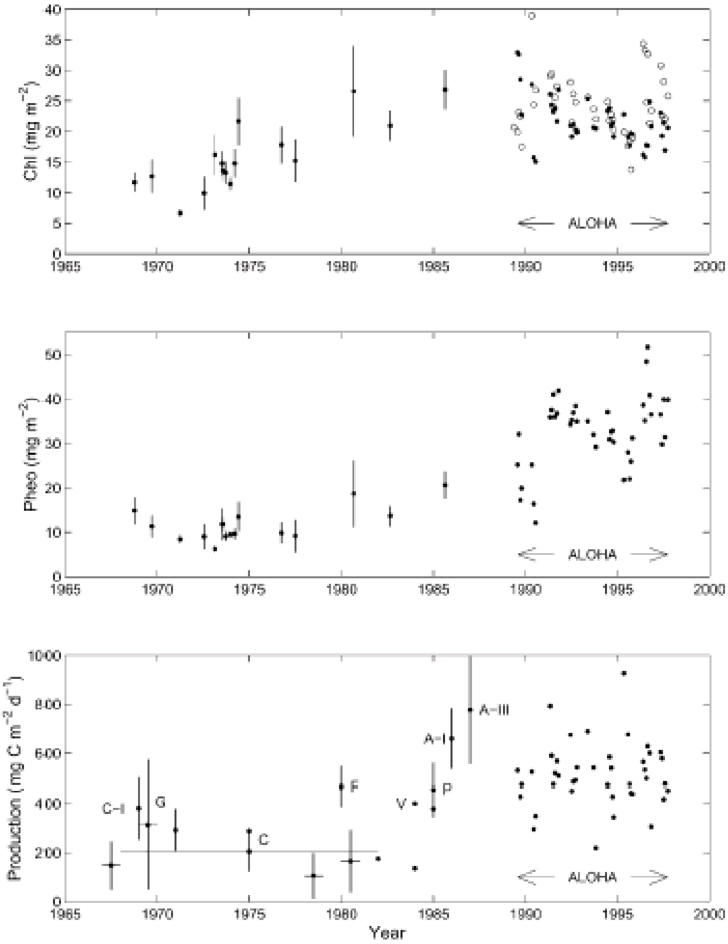

Fig. 6. Composite time-series analysis of phytoplankton community parameters for samples collected in the North Pacific Subpolar Gyre during the period May-October. Measurements include: [TOP] euphotic zone depth integrated chlorophyll concentrations as determined by FL (●) and HPLC (○), [MIDDLE] euphotic zone depth integrated phaeopigment (FL-pheo) concentrations, and [BOTTOM] euphotic zone depth-integrated rates of primary production obtained from numerous sources and locations but derived largely from oceanographic investigations at or near the Climax region and Station ALOHA. Where appropriate, mean values are used (from Karl et al., 2001a).

Another example is the response of HNLC regions to natural and manipulated iron addition. Iron addition changes phytoplankton species composition, abundance and production such that, in turn, dramatic changes in nutrient consumption processes and elemental flux often occur (Wong and Matear, 1999; Bishop et al., 2002).

Priority Questions

- What is the role of biodiversity in the functioning, adaptability, and stability of marine food webs?
- How do key species or functional groups control marine food web stability and key biogeochemical processes?
- Which species interactions define the stability of food web structure and function?

At present, we do not know how differences in the biodiversity of marine communities result in different flows of energy and matter through marine food webs. The main changes we observe in marine species are at the larger end of the size spectrum, that is, benthic organisms, macrozooplankton and fish; however, most of the marine biodiversity probably lies at the other end of the size spectrum, in the viruses, bacteria, algae, and microzooplankton of the microbial food web. We understand very little about how internal and external factors influence biodiversity of these components of marine food webs and the wider implications of these factors.

Research on the link between biodiversity and ecosystem functioning must extend well beyond the food web approach. Both variability in species composition and the impact of biodiversity changes on biogeochemical processes must be better understood. The complexity of marine food webs is highly variable. In high-latitude ecosystems, productivity is relatively high at higher trophic levels and species diversity is low. In the Arcto-boreal area of the northern North Atlantic Ocean, for example, the copepod species *Calanus finmarchicus* comprises up to 90% of the mesozooplankton biomass in the region, and it dominates as a prey species for larval and juvenile fish. Upwelling regions, also rich in marine organisms, are characterised by intermittently high phytoplankton production. But, the trophic transfer up the food web seems to be less efficient in upwelling ecosystems, resulting in substantial sedimentation of organic material that supports a distinct benthic biological system and enhances benthic-pelagic exchange. In general, the proportion of the primary production in surface waters that is exported to deeper water layers depends on the structure and functioning of marine food webs in surface waters and the mesopelagic layer. At a given rate of export, communities that more efficiently recycle organic matter in the near surface layers can maintain higher rates of primary production through regenerated nutrients than those with greater sinking losses. Hence, the structure and function of marine food webs are of particular importance as we try to understand more clearly the impacts of global change on marine ecosystems.

Changes in biodiversity, from plankton to higher organisms, may provide critical sources of information on pre-anthropogenic ecosystem evolution. Species that do not leave an obvious fossil record, such as cyanobacteria and phytoplankton species such as *Phaeocystis*, must also be considered because they may be indicative of past physical and chemical environmental conditions, and tools for their detection in the sedimentary record should be developed (Wakeham et al., 1997). Documenting shifts in marine ecosystems and understanding the causes of such shifts, combining insights from modern oceanographic experiments and multiproxy sedimentary records at key sites, will provide insights into biogeochemical feedback processes that control the carbon cycle.

Identifying the factors that control the distribution of key species in the ocean and how they are likely to respond to global change is critical to our ability to predict the likely impacts of global change on marine ecosystems and biogeochemical cycles. Species characteristics are important in determining energy flows in the food web. For example, some species of copepods change their feeding behaviour from suspension feeding to ambush feeding as a function of prey composition and turbulence, thus changing their ecological function from herbivore to carnivore (Saiz and Kiørboe, 1995). The dinoflagellate *Prorocentrum minimum* is usually autotrophic in conditions favourable for photosynthesis, but can also feed on other phytoplankton to obtain limiting nutrients (Stoecker et al., 1997). Investigating the functional switch/flexibility of species, especially behaviour-related, is important to understand the structure and function of the marine food web.

Another difficulty in prediction of food web response to global change is the invasion of so-called exotic species and the emergence of rare species to become dominant species. For example, the mesoscale iron fertilisation in the western subarctic Pacific increased the abundance of a previously rare centric diatom *Chaetoceros debilis* by a factor of 10^5 within 10 days (Tsuda et al., 2003). Similar changes in the food web components and structure by the increase of rare species are often observed during toxic algal blooms in coastal ecosystems.

The role of biological control in determining food web structure and function is not well understood. Studying the interaction between zooplankton and primary producers is important because this link represents a crucial step in the transfer of organic matter from the photic zone to deep waters or higher trophic levels. Although significant knowledge has been gained on growth rates of marine organisms through experimental and modelling studies, we know very little about mortality induced by predation, grazing, viruses, bacteria and parasites (Ohaman and Wood, 1995). We need to quantify the role of grazers and mortality on food web structure and the recycling of nutrients and carbon.

Regions subjected to heavy fishing pressure provide examples illustrating the complex linkages between food web composition and energy transfer between trophic levels. In these regions, the main societal concern is the availability of new production to higher trophic levels. In order to move to ecosystem-based management of the ocean and its resources, good estimates of the portion of primary production ultimately available to fish, marine mammals, and other top predators will be needed. Physical forcing shifts the ecosystem structure, which alters the export ratio and can further affect species composition. Thus, changes in production do not translate simply into corresponding changes in yields of fish and top predators, for example, pelagic and demersal fish, or downward carbon flux. Conversely, changes in the abundance and distribution of top predators in marine food webs, such as fish and marine mammals, may alter the abundance of prey organisms and cascade down food webs, changing their structure. The sea otter/sea urchin/kelp forest cascade of western North America is an example from coastal waters (Dayton, 1985). Do these changes have impacts on the microbial components in food webs through release from top-down control? Or do transport from the large zooplankton (copepods) and detritus act as “choke points”, partially decoupling feedback in the food web? Or is this distinction a result of the dichotomies in the way we structure our research, rather than reflecting real effects? Another consideration is that ecological control may be “wasp-wasted”. In this case species richness in the mid-trophic levels (such as small pelagic fish) is lower compared with lower and higher trophic levels, with pressure potentially being exerted both up and down from an intermediate trophic level (Cury et al., 2000).

Promising Scientific Approaches

The biodiversity, structure, functioning, and stability of marine ecosystems vary substantially among ocean regions, provinces, and climate regimes. Although studies will need to be tailored to each area, comparative studies among various areas will contribute to the basic understanding of generic processes and mechanisms. Sustained observations at designated sites will be required to follow energy flow and environmental conditions associated with anticipated future regime shifts in these ecosystems. IMBER research also needs to embrace existing molecular techniques (Barcode of Life, FISH (Fluorescent In Situ Hybridisation), DNA micro-arrays, gene probes etc) that can be used to identify key species and/or functional groups and utilize these effectively to increase our knowledge of the structure and function of marine food webs. Our approach to modelling food web structure and function also needs development. The first step will be the coupling of life history models developed by GLOBEC with the generic models developed for primary producers. This approach will require the development of nested suites of models and expansion of ecosystem models to basin scales. Many early insights in marine ecology were gained through manipulations of intertidal benthic marine ecosystems (Paine, 1994). Mesoscale and mesocosm manipulation experiments in which predators have been excluded or the size and number of individuals of key species are changed, will lead to new knowledge. Other insights could be gained by involving scientists who have studied similar questions in terrestrial system

Issue 3. Interactions between biogeochemical cycles and the structure, function and dynamics of marine food webs

Introduction

Organisms continuously require a complex series of inorganic and organic substances that they obtain from their environment. During the millions of years of evolution in the ocean, more and more complex life forms have evolved and this evolution was largely driven by the selective advantage of obtaining the basic requirements for maintenance and reproduction by capturing and ingesting other organisms. Organic matter is continuously transferred from lower to higher trophic levels. This continuous transfer and transformation from inorganic to organic substrates and back in the food web is why biological processes drive almost all biogeochemical cycles.

Marine food webs consist of individual organisms, which are adapted to a certain set of environmental conditions, where they interact with other organisms and the physical and chemical environment in which they live. In the past, food webs have been studied by looking at “state variables” such as populations, species, and trophic levels, in which the properties of organisms are aggregated, and by quantifying the flows of energy and matter between them. This simplification has allowed development of a large body of scientific knowledge that can be coupled in a straightforward way to elemental cycles, especially where processes involving nutrients and lower trophic levels (phytoplankton and bacteria) are considered. For zooplankton and fish, the emphasis has been more on population-level biological processes, such as recruitment, competition and predation, in an implicit or explicit evolutionary context. Simultaneous top-down (by predation) and bottom-up (by nutrient availability) control of marine food webs may confound attempts to establish the relative importance of the macrobiological versus the microbial food webs.

We currently have general descriptions of the cycling of many essential elements (carbon, oxygen, nitrogen, phosphorus, silicon) in selected marine ecosystems as well as many of the fundamental processes such as photosynthesis, respiration, nitrogen fixation, and denitrification (Fasham et al., 2001). Because ecosystems respond to environmental conditions, it is important that studies be extended to regions such as polar and high-latitude ecosystems, continental margins (especially those that exhibit strong coastal upwelling) and the mesopelagic layer.

Through the use of remote sensing and decades of shipboard expeditions, we now have measurements for a number of variables in nearly all areas of the global ocean. Biogeographical provinces have been described for all ocean basins (Longhurst, 1995) although new species, particularly within the microbial and benthic realms, continue to be discovered and described.

In evolutionary time, the emergence of organisms with a key function, such as photosynthesis, N_2 fixation/nitrification, denitrification, silicification, and calcification, repeatedly induced dramatic changes in marine biogeochemistry and Earth System chemistry (Holland, 1984). Palaeoceanographic records suggest large variations in marine food webs in the past that are correlated with changes in the marine chemical and physical regimes. For example, several proxies show glacial-interglacial fluctuations in temperature, salinity, pCO_2, and sediment redox states, synchronised with changes in composition of planktonic and benthic organisms (Figure 7). Processes that control the formation of hypoxic and anoxic water masses must also be understood because these processes also considerably influence metabolic processes such as denitrification and chemical processes responsible for trace element mobility and reactivity.

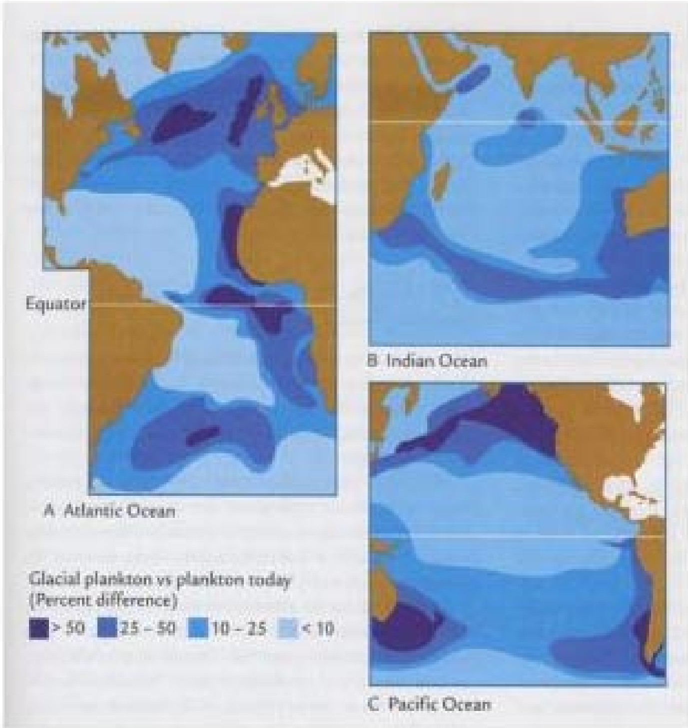

Figure 7. Reconstructed differences in planktonic species assemblages between glacial and interglacial periods (adapted from Moore et al., 1981).

Such ecosystem-biogeochemistry interaction is also observed over shorter time scales. The biological activity related to nutrient uptake influences marine physical and chemical systems, for example, by releasing radiatively active gases (Charlson et al., 1987); converting photon energy absorbed by pigments to heat in the euphotic layer (Nakamoto et al., 2001); changing N:P stoichiometry by N_2 fixation and denitrification (Karl et al., 2001b), changing ratios between macro- and micronutrients by differential uptake, regeneration, and export rates (Takeda, 1998); and by carrying particle reactive micronutrients and isotopes across isopycnals (Butler, 1998). Another example is iron supply that may have increased the abundance and production of diazotrophs, inducing changes in N:P stoichiometry in the equatorial Pacific Ocean ecosystem with a time scale of less than a few decades (Karl et al., 2001a) (Figure 8).

Iron, zinc, and other micronutrients are essential for enzyme activity and protein-dependent processes. Micronutrient limitation causes various stresses on phytoplankton and bacteria by decreasing metabolic and enzyme activity, for example, electron transfer efficiency in Photosystem II, and decreasing uptake of nitrate compared to ammonium because nitrate reductase and nitrite reductase require iron (Raven et al., 1992). Phytoplankton requirement of iron relative to the other elements varies by species; for example diatoms requires more iron than coccolithophorids for growth (Muggli and Harrison, 1997). Iron availability also influences N_2 fixation, for example, by *Trichodesmium* sp*.,* because the functioning of nitrogenase and the other N_2 fixation processes require more iron than do ammonium and nitrate uptake (Kustka et al., 2003). N:P stoichiometry in the marine ecosystem is influenced by the amounts of N_2 fixation and denitrification in the benthic and hypoxic mesopelagic layer. Thus, abundance and bioavailability of micronutrients are critical factors in assessing food web structure, transfer of organic matter to the mesopelagic zone, and metabolic pathways.

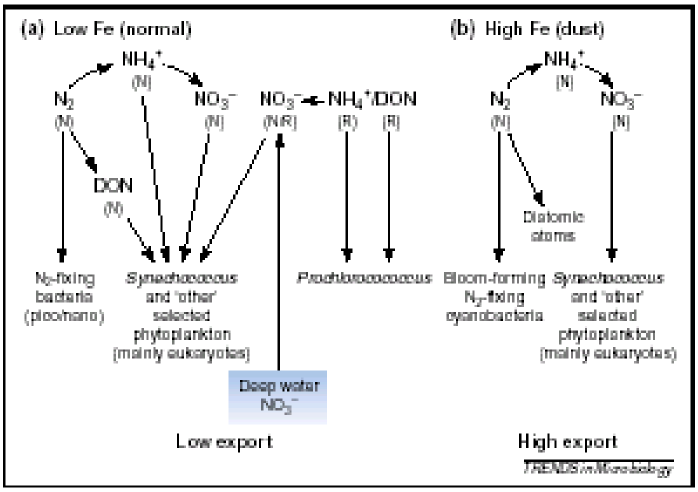

Figure 8. Revised conceptual view of new (N) versus regenerated (R) nitrogen based on observations from the Hawaii Ocean Time-series (HOT) program in the North Pacific subtropical gyre. (a) Shows the normal, low-Fe condition that is observed during most of the year. N_2-fixing pico- and nanoplankton incorporate new N_2, part of which cycles locally through new ammonium (NH_4) to new nitrate (NO_3); new dissolved organic nitrogen (DON) is also produced during this process. All of these substrate pools are used for photosynthesis by the various groups of photoautotrophs (Karl et al. 2001a).

There exists a rapidly growing but fragmented body of knowledge on the connections between biological, physical, and chemical regimes influencing nutrient uptake and remineralisation in the ocean. A holistic view of the impact of macro- and micronutrients on overall food web structure and function in different ocean regimes is therefore within reach, but although the basic processes of production and breakdown of organic matter are well known, their interconnectedness and overall regulation require more study.

Priority Questions

- What controls the rates of and interactions between production, transfer and breakdown of organic matter in marine food webs?
- How does biogeochemical recycling of organic matter in the mesopelagic layer and in shelf and slope sediments impact food web structure and function in surface waters?
- What are the key functional groups, species, and genes that control biogeochemical cycles and what is the role of biodiversity and functional diversity in biogeochemical cycles?
- How do macro- and micronutrient availability impact the structure and function of the entire food web?
- How are specific biogeochemical processes and food web structures recorded in palaeoceanographic proxies?

Factors that control the production of organic matter must be further elucidated. The traditional view of marine food webs often considers the production of organic matter by diverse autotrophic communities to be limited by a single factor (e.g., light, nutrients) and does not consider the interactions between forcing functions or the characteristic temporal and spatial scales of processes. Food web structure is usually described in static terms and does not consider, for instance, the large differences in characteristic time and space scales of the mode of operation at different trophic levels, for example, bacteria operating at microns and whales at thousands of kilometres. It is therefore important that the characteristic scales of variability in the components be resolved.

To understand how food web structure and function may impact production, mineralisation, transport, and transformation of organic matter into macro- and micronutrients in marine ecosystems, the relationships between the genetic, morphological, physiological, and behavioural characteristics of organisms and the interrelated major biogeochemical cycles must be better described. Grazing and predation relationships and the rates of predation among key species need to be measured and analysed quantitatively, taking into account morphological and behavioural characteristics of species and transfer efficiencies between predator and prey. We must explicitly address the fact that predator-prey and plant-herbivore interactions have an evolutionary component, and that because of selective pressures the fundamental characteristics of these interactions may change over relatively short time intervals. As the primary currency for the transfer of energy within marine food webs, we need to understand, at the molecular level, the nature of the particulate organic carbon (POC) and dissolved organic carbon (DOC) pools. Food web transfers represent an organic to organic transition, but also impact the partitioning between POC, DOC, and dissolved inorganic carbon (DIC) pools, for instance, through the fraction of organic material that is respired or lost during feeding. In addition, quantifying food web transfers is critical to elucidating secondary productivity and export from surface waters.

Remineralisation of organic compounds and inorganic shell (calcareous or siliceous) material within the mesopelagic layer, is largely dependent on microbial activity, which plays a critical role in controlling rates of new production and the species composition of the euphotic zone community. Globally, the residence time of carbon in phytoplankton is only a few weeks, whereas the turnover of carbon and nutrients via export, remineralisation, and water mixing in the mesopelagic layer occurs on seasonal to decadal time scales. Changes in surface water circulation driven by climate affect mesopelagic water masses, their chemistry, and nutrient content on decadal to centennial time scales. Therefore, on a global scale, the vertical and horizontal redistribution and return of nutrients to the euphotic zone control the biological state and processing in the upper ocean on these time scales, not only the nutrient concentrations themselves, but also the ratios of nutrients supplied to the euphotic layer (Dugdale and Wilkerson, 1998). Food web structure, from organisms as small as viruses to as large as whales, influences the depth and rates at which particulate organic matter (POM) is recycled in the mesopelagic layer by controlling remineralisation rates and the sinking speed of cells, fecal pellets, and aggregates (Beaumont et al., 2002). Also, the nature (e.g., size, masses, elemental composition, reactivity, and bioavailability) of POM and biominerals produced in the overlying euphotic zone are altered in the mesopelagic layer by biological and abiotic processes.

Remineralisation processes are difficult to quantify, and it is important to determine roles of particular species, functional groups, and specific gene expressions for remineralisation processes. The mesopelagic layer has a high biodiversity of bacteria, zooplankton, and nekton. Activities of zooplankton and nekton are important for fractionating, repackaging, and decomposing POM (Banse, 1995) and microorganisms are key factors in remineralisation. Information about the structure, biodiversity, function, and stability of the mesopelagic ecosystem is essential to understand remineralisation processes and the role of the mesopelagic layer in ocean biogeochemistry (Azam and Long, 2001; Karl, 2002). The physiology and ecological niche of many species are unidentified, and we do not know their roles in the ecosystem and biogeochemical cycles. Moreover, one of the most challenging aspects of food web and biogeochemical studies alike is that important components of marine food webs, and therefore new and possibly important biogeochemical processes, remain to be discovered. This is true for both the micro- and the macrobiological components in the surface, but especially in deeper waters. Examples include pelagic Archaea in meso- and bathypelagic microbial communities, organisms capable of anaerobic ammonium oxidation, and the widespread occurrence of symbiotic and parasitic relationships.

Many different types of benthic communities exist on the continental margin, and they are usually highly diverse. Benthic ecosystems also exhibit dramatic small-scale and temporal variability in areal coverage and activity. The role of these ecosystems in biogeochemical processes is not well known because of their complexity and variability, and the lack of large-scale studies of these systems. Estimates of primary production in the coastal zone based on phytoplankton are between 375 to 575 Tmol yr^{-1}. This estimate does not include primary production from benthic microalgae (Jahnke et al., 2000), macroalgae, coral reefs, seagrasses, marshes, and mangroves, which may account for as much as half of the total coastal primary production. While most studies report global coastal benthic respiration rates of 150 to 200 Tmol C yr^{-1}, these studies clearly underestimate total coastal benthic respiration by a factor of 3 to 4 if reefs, macroalgae, seagrasses and other macrophyte communities also are considered. The question of how benthic communities and other continental margin-specific communities (such as coral reefs, mangroves, and seagrasses) contribute to cycling of nutrient elements (such as Fe/N/P/Si) and the ecosystem functioning as a whole clearly needs more attention.

Because of the high diversity of marine organisms, our understanding of species composition and structure of many marine food webs is still limited. It is estimated that as many as 5,000 fish species may be undiscovered (http://www.coml.org/medres/Census_public102303.pdf). Our knowledge is even more limited for the mesopelagic food web than for the surface waters. Representation of food web structure as a restricted number of "functional groups" that have similar ecological or biogeochemical roles in the ecosystem is a promising approach. However, more information on physiological characteristics, such as nutrient uptake and mineralisation rates of at least the dominant species at various physical conditions (e.g., light, temperature, turbulence), is needed to define "average" characteristics of each functional group. Such information is also useful to understand the potential responses of each functional group to variations and changes in environmental conditions. Detection of genes that activate key metabolic functions would also be useful to this approach. Some functional groups play a dominant role in the structure and functioning of particular ecosystems (e.g., N_2 fixers, top predators, primary producers). How these key functional groups and key species are related to and regulate fluxes of organic matter and associated elements remains to be assessed. Further investigation is required to establish whether key functional groups, key species, or genes exert a dominant control on biogeochemical cycles.

In recent years it has become clear that many characteristics of global elemental cycles depend on the characteristic properties of key species that dominate food webs in certain parts of the ocean. The reasons why a few species are dominant and why most are rare are unclear and the consequences of this situation for biogeochemical cycles have received little attention. For example, variations in community composition and resulting production and metabolic pathways may produce deviations from the Redfield ratio (Redfield, 1934), with consequences for export ratios and remineralisation length scales (Karl, 1999). Imbalances in nutrient use and regeneration within the pelagic food web propagate with depth, with consequences for the biological carbon pump. The role of interfaces, especially between the euphotic surface layer and the mesopelagic layer, between continental margins and the open ocean, and within the benthic boundary layer, are important.

The temporal stability of marine food webs and their succession over time are generally not known. Specifically, we do not know whether present-day communities are in balance with present-day conditions and how organisms and the food web structure over time may adapt to new nutrient or temperature regimes. The time-series data available, in most cases, are not extensive enough to predict species or functional group succession in response to changes in nutrient or physical regime characteristics and are presently limited to a very narrow range of ecosystem types. In order to predict how marine ecosystems and biogeochemistry will respond to future global change, we need palaeo-records that give us details of past communities and key controls, trigger points and hotspots in biogeochemical cycles and ecosystems. The search for palaeo-proxies that would extend the record of such factors as the effects of climatic and biogeochemical variability and changes of the structure, function and dynamics of marine food webs is important in developing a predictive understanding of marine biogeochemical cycles and ecosystems.

Responses of food web structure and biogeochemical cycles to climate variability on decadal time scales as indicated in climate indices such as the PDO, NAO, and El Niño-Southern Oscillation (ENSO) are only poorly known. Palaeoceanographic records, suggest large past variations in marine food webs that are correlated with changes in the marine chemical and physical regimes. For example, several palaeo-proxies show cyclical fluctuation in temperature, salinity and pCO_2 and synchronised change in plankton composition in the last 400,000 years. At longer time scales, some major shifts in climate are correlated with mass extinctions. Understanding past climate change as well as shorter time scale variability as indicated in the PDO, NAO, ENSO indices and their impacts on food web structure and biogeochemical cycles are critical to predicting the impacts of global change. Development of high-resolution palaeo-proxies and their calibration are essential to understand past interactions between biogeochemical cycles and marine food web structure and dynamics.

Promising Scientific Approaches

Laboratory experiments to evaluate the biology and physiology of individual species and functional groups in relation to varying macro- and micronutrient concentrations and ecological interactions, such as grazing, predation, and parasitism, will be important. Recent advances in molecular biological techniques provide powerful tools to identify species and functional groups. Coupling results from both approaches is essential to understand sensitivity of species and functional groups to chemical forcing. Additionally, isotopic studies, such as the study of ^{15}N distributions in different organisms, may provide unique insights to the trophic transfer of energy and biomass.

The different time scales associated with biogeochemical cycles and ecosystems mean that long-term monitoring of selected ecosystems is important. Sustained observation sites that monitor food web composition and function and biogeochemical exchanges are needed, not only in subtropical regions, but also for other domains such as continental margins and high-latitude and polar regions. Moored instruments are useful for finer time scale monitoring. In order to develop our understanding of biological and chemical processes in the mesopelagic layer, attaching newly developed biological/chemical sensors to Argo floats and other drifting and self-propelled autonomous vehicles and moorings (Bishop et al., 2002) is one of the desirable strategies. For larger spatial scale monitoring, volunteer observing ship (VOS) participation and satellite remote sensing will be critical.

Combining complementary results from laboratory experiments and field experiments and observations is essential to accelerate the development of our understanding of nutrient-food web interactions. Process modelling using parameters obtained in these observations and experiments, and advancing numerical simulations is also important for synthesis and prediction. Results obtained by process modelling should feedback to planning for future field observations and laboratory experiments. Mesoscale perturbation experiments (iron fertilisation experiments are one potential example) may also be a useful strategy to advance our understanding of marine ecosystems and biogeochemical cycles. Conducting process studies during natural events, such as hydrothermal “megaplume” events and floods, will yield useful information, if rapid response to such events is feasible.

Improvement of chronology and calibration for marine palaeo-proxies with instrumental records is necessary to better interpret the palaeoceanographic records from sediments, corals, and other sources. Multiple proxies that reveal synchronous variations in food web composition and function and nutrient distribution will be particularly useful. These palaeo-proxies have provided information about changes in the atmosphere, ocean, cryosphere, biosphere, and the dynamics of interactions among them. However, palaeoenvironmental reconstruction requires that the properties measured in natural archives be quantitatively translated into environmental parameters. Even well-established proxies such as $\delta^{18}O$ and $\delta^{13}C$ have not fully overcome limitations in their use. Documenting shifts in ecosystem states and understanding their causes by using modern oceanographic experiments and proxies from palaeo-records will provide insights into the physical and geochemical processes that drive ecological change and biogeochemical feedback. Moreover, this will allow us to test current hypotheses of the linkages between ocean biogeochemical cycles and climate. In turn, accurate interpretation of palaeorecords can extend the temporal baseline of observations to times before human influences dominated planetary chemical cycles, and will enable the prediction of the impact of anthropogenic disturbances in the context of natural variability.

Collaborations for Theme 1

The overall implementation strategy will be to advocate an increase in the number of time-series research locations and combine these with detailed process studies. Top priority locations for new time-series locations should be continental margin and high-latitude and polar regions areas not represented by current day time-series sites. In addition to and in conjunction with other research programs, such as repeat hydrographic surveys and GEOTRACES, basin-wide hydrographic sampling should be conducted. Where possible, these transects should connect time-series locations. Many of the important inputs, outputs, and sources of variability are at interfaces between the ocean and other Earth System components, such as the atmosphere and land. These interfaces are the focus of major IGBP/SCOR projects (SOLAS and LOICZ). For example, the interaction between N-fixation and dust/Fe deposition is of particular interest to SOLAS. IMBER will collaborate with these projects to avoid duplication of effort and avoid gaps. In addition, there is a strong need for IMBER studies to be placed in a long-term temporal context and within the context of global change and human interactions. Cooperative activities with GLOBEC will be particularly important for research that considers the end-to-end food web from microorganisms to top predators. Close collaborations with the PAGES project and its IMAGES activity on the development of palaeo-proxies will also be important. SCOR and IMAGES are co-sponsoring two working groups, Working Group 123 on reconstruction of Past Ocean Circulation and Working Group 124 on Analyzing the Links Between Present Oceanic Processes and Palaeo-records. These working groups will expand the knowledge of palaeo-proxies for ocean circulation and other ocean features and processes. Close interaction and joint implementation with Theme 2 within IMBER will also be important to ensure effective use of resources.

Theme 2: Sensitivity to Global Change: How will key marine biogeochemical cycles and ecosystems and their interactions, respond to global change?

Introduction

IMBER must focus not only on observation and analysis of marine biogeochemical cycles and ecosystems, but also on understanding and predicting how these respond to the complex suite of forcings associated with global change. Identification of components of biogeochemical cycles and ecosystems that may respond most directly to global change is important. In this section, we have partitioned such responses into three categories: effects of climate-induced changes in the physical dynamics of the ocean; effects of increasing CO_2 levels and decreasing pH; and effects of changes in macro/micro nutrient inputs to the ocean.

IMBER studies will investigate how large-scale climate phenomena affect the ocean by altering the physical forcing on seasonal to inter-decadal time scales, and how these oceanic changes can directly alter the distribution of carbon and nutrients in the upper ocean. IMBER studies must also consider how changes in pH and carbon system parameters can alter ecosystems (including organismal physiology, population levels, and food web composition and structure) and biogeochemical cycles. Further, we must examine how global change will impact the controls on biological growth and related biogeochemical processes exerted by oceanic distributions of macro- and micronutrients, as well as the complex roles of iron and other micronutrients. These issues must be considered from diverse perspectives, with scientific approaches guided by carefully defined objectives and implementation strategies.

Issue 1. The impact of climate-induced changes in circulation, ventilation, and stratification on marine biogeochemical cycles and ecosystems

Introduction

Biogeochemical cycles and ecosystems in the ocean are strongly affected by a wide range of physical processes, including horizontal and vertical transports, entrainment, and upwelling and mixing of deep water. The critical time scales of biogeochemical and physical processes are not necessarily matched, leading to intrinsic spatial and temporal variability in ocean biology. Moreover, coupled ocean-atmosphere models predict significant decadal-to-centennial time scale changes in ocean circulation on space scales ranging from regional to global. Such changes will result in modification of both the mean state and the spatio-temporal variability of the uptake, distribution, and sequestration of biologically important substances throughout the ocean. These modifications have been linked to changing atmospheric composition and subsequent climatic effects in the past through proxy records, such as the Vostok Ice Core. In addition to alteration of the mean state, climate changes may induce changes in temporal and spatial variability in physical forcing, which is probably just as important in controlling species' distributions and adaptations. The physical processes controlling major ecosystem processes and elemental fluxes, whether through physical transport or physical environment, must be identified and quantified.

Our incomplete physical understanding of the evolution of atmosphere-ocean interactions and the potentially highly non-linear ecological and biogeochemical responses to global changes hinder our ability to create accurate scenarios of the future effects of climate change on marine ecosystems. Predictions of how changes in climate will affect marine ecosystems and biogeochemical cycles will require a much better understanding of (1) how climate change will affect physical conditions in the ocean and (2) how specific changes in these physical conditions will affect processes important to biogeochemical cycles and ecosystems. Particularly important will be better understanding on the effects of changes in ocean physics on carbon exchange, transport, and storage; dynamics of key species and functional groups (e.g., biodiversity, biogeographical ranges, blooms of gelatinous zooplankton, migration and transport pathways of organisms); organismal metabolic processes and life history strategies; and benthic-pelagic and continental shelf-ocean coupling.

Priority Questions

- How do changes in physical properties of the ocean affect biogeochemical cycles and ecosystems, and how will these linkages be impacted by global change?
- What are the impacts of extreme events (e.g., hurricanes, floods) and episodic events (e.g., blooms) on biogeochemical cycles, fluxes, and ecosystems?
- Which components of physical variability (including climate modes) impact most on biogeochemical cycles and ecosystems?
- What are the key physical factors regulating macro- and micronutrient flux between different parts of the ocean (e.g., between the mesopelagic layer and surface ocean; the continental margin and open ocean; and the sediments and overlying waters)?

Physical properties have direct impacts on marine ecosystems, including changes in biodiversity, species extinctions, and biogeographical ranges. Temperature changes shift seasonal cycles of abundances of planktonic and benthic species (Greve, 2001), growth (Brander, 1995) and recruitment (Sundby, 2000) of fish, and food web dynamics (McGowan et al., 2003). Range displacements resulting from temperature change have been reported from diverse marine organisms (Nakken and Raknes, 1987; Southward et al., 1995; Molenaar and Breeman, 1997; Beaugrand et al., 2002; Parmesan and Yohe, 2003) and have been inferred from population genetic analysis (Bucklin and Wiebe, 1998). Marine organisms are directly impacted by changes in light intensity (Huse, 1994; Macy et al., 1998), which can alter ecosystem dynamics (e.g., trophic and competitive interactions: Fiksen et al., 1998). Biological, biogeochemical, and molecular processes are significantly altered by changes in ultraviolet radiation, resulting from both natural and anthropogenic causes (Boucher and Prezelin, 1996; Shick et al., 1996; Speekmann et al., 2000; Grad et al., 2001; Helbling et al., 2001). At higher latitudes global warming seems to result in increased wind mixing (Debernard et al., 2002; Danard et al., 2003) and turbulence influences plankton contact rates and growth (Rothschild and Osborn, 1988). All these physical properties are linked and they partly influence marine organisms directly, but also to a large extent indirectly through the food web (Sundby, 2000). It is clear that food web structure and biogeochemical cycles respond on annual and decadal time scales to natural changes in ocean circulation and resulting changes in supply of macro- and micronutrients to the euphotic zone.

Evaluation of the physical mechanisms that control biogeochemical cycles of major elements and distributions of key species is important. To develop predictive capabilities, we must identify the forcing factors (e.g., variability of large-scale circulation; temperature, light, turbulence and vertical structure of the water column; mesoscale and sub-mesoscale motion in terms of fronts and eddies; coastal upwelling and filaments) and their thresholds that yield strong biological responses, including regime shifts. Can the shifts recognised in present-day variability of ocean climate and their associated impacts on marine ecosystems be used effectively to predict future changes in elemental cycling and biological processes?

Some insights into the coupling of physical, chemical, and biological processes can be gained by evaluation of changes in biogeochemical processes and food webs as recorded in the palaeoceanographic record. Late Pleistocene El Niño-Southern Oscillation (ENSO)-like records indicate decade-to-century time scale changes in ocean-atmosphere interactions. The late Pleistocene history of seawater temperature and salinity variability in the western tropical Pacific Ocean warm pool has, for example, been reconstructed from oxygen isotope and magnesium/calcium composition of planktonic foraminifera (Stott et al., 2002). The results reveal a dominant salinity signal that varied with Dansgaard/Oeschger cycles over Greenland. Salinities were higher at times of high-latitude cooling and lower during interstadials. The pattern and magnitude of the salinity variations imply shifts in the tropical

Pacific Ocean/atmosphere system analogous to the modern ENSO. El Niño-dominated conditions correlate with stadials at high latitudes, whereas La Niña conditions correlate with interstadials. Millennial-scale shifts in atmospheric convection away from the western tropical Pacific Ocean may explain many palaeo-climate observations, including lower atmospheric CO_2, N_2O, and CH_4 during stadials, and patterns of extratropical ocean variability.

The state of climate modes controls the frequency, location, and strength of extreme events, such as hurricanes and floods, which may have a great impact on ocean ecosystems and biogeochemical states. For example, the ocean surface "scar" imposed by a hurricane, a path outlined in satellite sea surface temperature images, may be enriched in nutrients due to enhanced upwelling from the mesopelagic layer, thus impacting the local biological system. Episodic events in the ocean may cause a disproportionately large fraction of the variability in ecosystems and related biogeochemical cycles. For example, unpredictable and infrequent salp blooms have been estimated to play an important role in highly efficient scavenging of biomass from the water column, speeding delivery of carbon to the ocean depths with particularly large fecal pellets (Naqvi et al., 2002). Diazotroph blooms, or periods of extended diazotrophy, will force changes in the grazer food web, the stoichiometry of remineralisation, and remineralisation length scales. These presently unpredictable, episodic events (Justic, 1997), probably affected by changes in oceanographic conditions such as water column stability, must be evaluated. We must understand which episodic and extreme events have the most impact on marine ecosystems, and which of these will be most impacted by changing ocean physical conditions. Changes in the frequency, duration, and strength of these physical events ripple through the ecosystem, but how far and with what result?

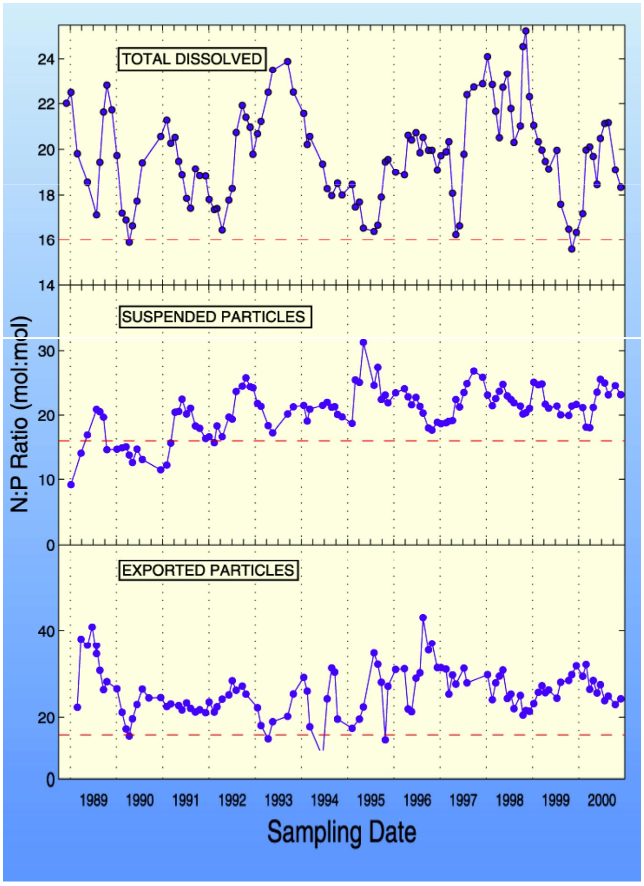

Figure 9. Shifts at ALOHA station over time between P-limitation regime and N-limitation regime. The red dashed line corresponds to classical Redfield ratio, Points above this line correspond to P-limitation, below the line to N-limitation, after Karl et al. (2003).

Insights into the controls of organic matter fluxes, and how these controls may modify marine food webs and biogeochemical conditions in the future, can be evaluated in the light of present-day climate phenomena or shifts. Climatic conditions favouring stratification, for example, may shift the balance in sources of new nitrogen from vertically mixed nitrate (and phosphate) to fixed atmospheric nitrogen, with commensurate shifts in food web structure. Such shifts will be reflected in the magnitude, form, and fate of organic matter constituting the biological pump, and will resonate throughout the ecosystem over seasonal to decadal time scales. The redistribution of nutrients and changes in circulation and stratification will lead to alteration of the rates, modes, and patterns of biological production (Boyd and Doney, 2003). For example, changes in subtropical and tropical circulation related to ENSO have been implicated in significant biological and biogeochemical shifts in the Pacific Ocean (Karl, 1999; Karl et al., 2001b) (Figure 9). Long term evolution of nutrients in response to change in physics are also observed off Japan (Ono et al., 2002). Such climatic oscillations result in the decoupling of major nutrient cycles (particularly N and P) and imply a previously unexpected fluidity in the large-scale elemental cycles. In addition to such shifts, significant large-scale changes in the magnitude of new production in the Equatorial Pacific Ocean may be in response to ENSO forcing (Turk et al., 2001). Moreover, ENSO-related changes in ocean margin upwelling substantially alter productivity and denitrification rates (Morrison et al., 1998). These changes propagate into the ocean interior and ultimately throughout the entire marine system. Although such regional-scale perturbations have been observed, extrapolation to basin and global scales is not practical within our current understanding and given our existing level of observations of basic biological, physical, and biogeochemical processes.

Decadal climate modes (e.g., ENSO, the North Atlantic Oscillation (NAO) and Pacific Decadal Oscillation (PDO: Figure 10) and related teleconnections are likely to introduce other signals into the ocean system, such as variations in heat content (Levitus et al., 2000), carbon storage in the subtropical thermocline (Bates et al., 2002), and changes in iron

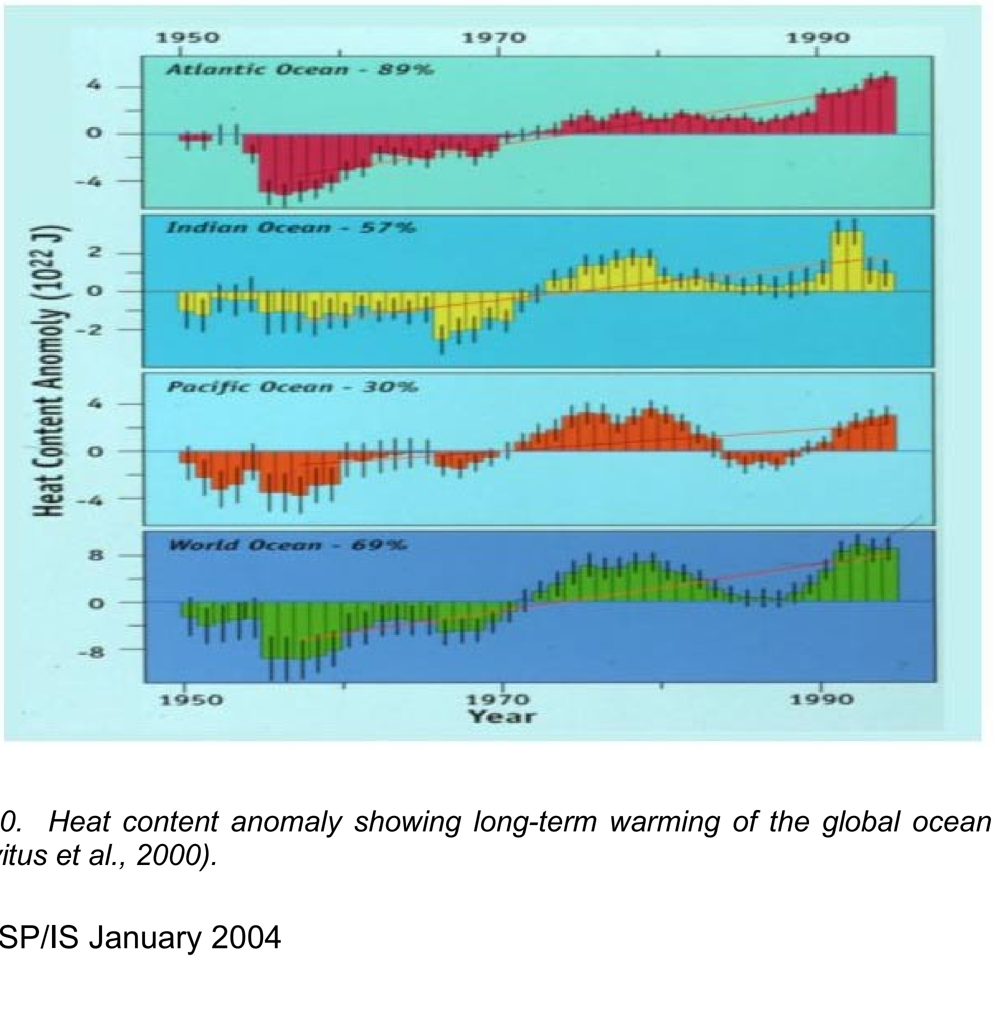

Figure 10. Heat content anomaly showing long-term warming of the global ocean (Figure from Levitus et al., 2000).

delivery as dust (Prospero, 1999). The magnitude of coastal flooding also can be controlled by the state of climate modes. For example, ENSO events change the locations and amounts of precipitation on the U.S. West Coast, impacting riverine inputs to the ocean margin (Pavia and Badan, 1998). Flooding delivers buoyancy, nutrients, particulates, organic matter, and pollutants to the ocean margins, thus impacting directly, broadly, and immediately the margin ecosystems (Justic, 1997).

It is likely that human-induced climate change will alter ocean circulation and its variability. For example, idealised simulations of the climate effects of increased CO_2 by Sarmiento et al. (1998) predict reduced thermohaline circulation and meridional heat transport, less vigorous wind mixing, and greater stratification in the future, leading to reduction in global new primary production, but with complex regional patterns (Bopp et al., 2001; Snyder et al., 2003).

Promising Scientific Approaches

Research on the impacts of physical variability on ecosystems and marine biogeochemical cycles will require strong contributions from sustained observation systems for physical, chemical, and biological factors at comparable time and space scales. Such observations should include time-series observations extending over several decades, augmented by comprehensive data mining. Sustained observations are required to capture the unpredictable, extreme and episodic events that have significant impacts on ecosystems and biogeochemistry; they will provide new insight into potential effects of longer-term global change on marine ecosystems and biogeochemical cycles. Properly designed, sustained observations will capture variability on time scales from hours (sensors on moorings), to events (e.g., salp or diazotroph blooms), to seasons (e.g., monsoons), to interannual and longer (e.g., variability associated with climate modes such as ENSO and NAO). Sustained observation efforts require persistence to observe low-frequency and slowly evolving modes of variability. While important sustained observation programs already exist, it is necessary that these be augmented with new efforts, particularly at high latitudes and in the continental margins. The International Time Series Science Team sponsored by the Partnership for Observations of the Global Oceans has recommended moorings in sites that could be useful for IMBER research (see www.oceantimeseries.org/globalnetwork.htm).

Process studies will be required to target resources on specific research questions, focusing on mechanisms, interactions, fates, and sources. These studies should be co-located and integrated with the sustained observation programs, to ensure that measurements are comparable and the data can be integrated for more comprehensive understanding.

Extrapolation of observations and research results from specific sites to the global ocean will require integration with ongoing and planned hydrographic surveys in all major ocean basins over the coming decades, including measurements relevant to IMBER on CLIVAR and GEOTRACES transects. Data collected along these cross-ocean transects (e.g., nutrients, gases, carbon system parameters, transient tracers, hydrography), as well as data from additional survey lines focused on micronutrient distributions turnover, will be invaluable for extending the findings from sustained observations and process studies to the global scale.

Modelling and model/data synthesis, using both historical and newly acquired data, will also be essential for global-scale extrapolations. Future simulations should incorporate appropriate biogeochemical and physical processes, to enable accurate models of potential oceanic responses under changing forcing. These responses may include the development of mechanisms involved in the reflux of remineralised nutrients from the mesopelagic to the euphotic zone, and organismal adaptations to temperature, light, and other physical forcings. Research conducted as part of IMBER should assist the development of more accurate representation of processes in the models.

New insights will derive from rescue, integration, and synthesis of existing datasets and advanced modelling efforts to understand systems, based on both current knowledge and new results of the sustained observation and experimental process studies. Combining the insights developed by observation, laboratory and field experiments, process studies, modelling, and collection of samples for palaeo-proxy analysis will both extend our interpretation of past occurrences and provide a context for predicting future change and its impacts.

Issue 2. Response of marine biogeochemical cycles, ecosystems, and their interactions to increasing anthropogenic CO_2 and changing pH

Introduction

Seawater is strongly pH buffered, mainly due to the high content and chemical speciation of dissolved inorganic carbon. In contrast to freshwater systems, its natural pH range is, therefore, rather small, and most present surface waters fall into a pH_T range of 8.1 ± 0.1 (Figure 11). Even glacial-interglacial pH changes, as driven by variations in atmospheric CO_2 concentrations, represent a comparatively small perturbation to the oceanic pH regime. Equilibrium pH changes between glacial and interglacial (e.g., late Holocene pre-industrial) atmospheric CO_2 levels are on the order of 0.10-0.15 pH units. During the past 23 million years, the atmospheric CO_2 concentration probably never exceeded 300 ppmv (Pagani et al., 1999; Pearson and Palmer, 1999; Petit et al., 1999). Therefore, marine organisms had a long time to adapt to a rather narrow pH range with a peak-to-peak variability of not more than 0.15 pH units.

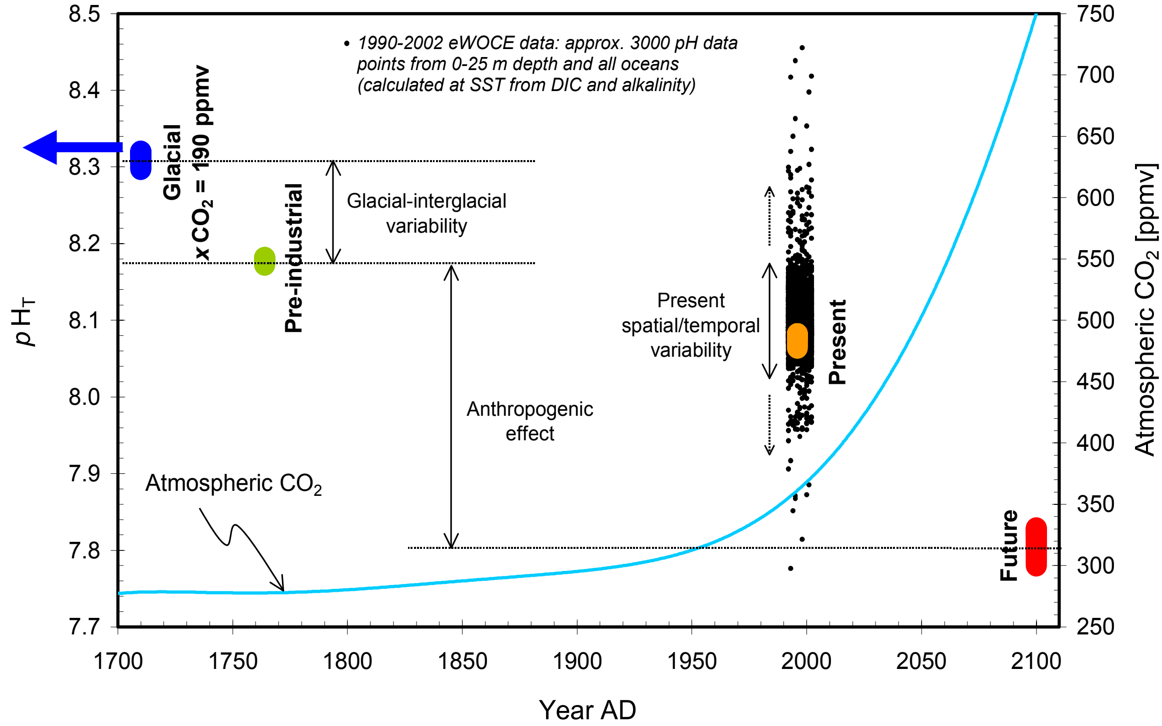

Figure 11. Present (1990-2002) surface seawater pH_T values from all oceans (3000 data points from the upper 25 m, pH_T was calculated from measured DIC and alkalinity). The majority of the data fall into a rather narrow pH-range of 8.1 ± 0.1. Also shown are typical pH ranges of glacial, pre-industrial, present, and future (year 2100) surface seawaters resulting from the observed and predicted increase in atmospheric CO_2 levels (blue line with exponential increase) as obtained by simple scenario calculation (Table 1) (prepared by Arne Körtzinger on the basis of WOCE data: Schlitzer, 2000).

The anthropogenic increase in atmospheric CO_2 concentrations from a pre-industrial value to the present level represents a chemical forcing to surface ocean pHof the same size as the glacial-interglacial change. Due to the anthropogenic perturbation, surface ocean pH values have already dropped by about 0.1 since the onset of the Industrial Revolution. A projected future increase of the atmospheric pCO_2 concentration to about 750 ppmv by the end of the 21st Century (Houghton et al., 2001) will cause a total pH drop on the order of 0.35-0.4 pH units. Such pH changes are well in excess of the natural variability during at least the last 400,000 years ecosystems and marine biogeochemical cycles and perhaps even 23 million years, and thus represent a major perturbation to marine

Table 1. Sample calculations illustrating the magnitude and direction of glacial-interglacial and "Anthropocene Era" variations in the properties of the marine CO_2 system. fCO_2 = CO_2 fugacity (≈ CO_2 partial pressure), A_T = total alkalinity, DIC = dissolved inorganic carbon; pH_T = pH value on total scale [µmol kg^{-1}], [C] denotes concentration of C [µmol kg^{-1}], Ω = solubility ratio defined as the ratio of the ion product and the solubility product of the respective mineral phase. The SST of a pre-industrial surface water at 20°C was varied assuming a 4°C glacial-interglacial temperature shift, the observed 0.6°C increase in sea surface and near-surface land air temperatures since 1880 (Jones et al., 2001)and a projected temperature increase of 4-6°C by 2100. A glacial increase of 3% in salinity (and A_T) was included in this scenario calculation. All calculations were made assuming equilibrium between ocean and atmosphere and should not be regarded as precise reconstructions or predictions.(Prepared by Arne Körtzinger).

Parameter	**Glacial**	**Pre-industrial**	**Present**	**Year 2100**
Temperature (°C)	16	20	20.6	25
Salinity	36	35	35	35
Atmospheric CO_2 (ppmv)	190	280	375	750
Equilibrium seawater fCO_2 (µatm)	185	273	365	725
A_T (µmol kg^{-1})	2369	2300	2300	2300
DIC (µmol kg^{-1})	1963	1964	2020	2115
pH_T (µmol kg^{-1})	8.32	8.18	8.08	7.82
[HCO_3^{2-}] (µmol kg^{-1})	1676	1720	1809	1953
[CO_3^{2-}] (µmol kg^{-1})	280	235	199	141
[CO_2(aq)] (µmol kg^{-1})	6.7	8.8	11.6	20.6
Ω_{Calcit}	6.6	5.6	4.8	3.4
$\Omega_{Aragonit}$	4.3	3.6	3.1	2.2

A better understanding of the effects of changing pH and carbon system parameters on marine biogeochemical cycles and organisms is urgent, because of the suggestions of some scientists, companies, and nations that increases in atmospheric CO_2 concentrations could be mitigated by purposeful sequestration of carbon in the ocean. The impacts of such activities on biogeochemical cycles and ecosystems could be substantial, however our current limited understanding of pH and CO_2 effects do not allow evaluation of different scenarios of CO_2 increase and mitigation strategies.

Priority Questions

- What are the effects of CO_2-driven changes in carbonate chemistry on biogeochemical cycles, ecosystems, and their interactions?
- Which organisms and metabolic processes are most sensitive to pH change, and how will this sensitivity affect biogeochemical cycles, ecosystems, and their interactions?
- How, and to what extent, can organisms adapt and/or evolve in response to changes in pH and CO_2 concentrations?

The chemical speciation within the marine CO_2 system is the major determining factor for seawater pH. A scenario calculation for typical surface ocean seawater under a variable atmosphere and with typical sea surface temperature (SST) changes between the glacial, pre-industrial, present, and future situation (Table 1) shows the substantial predicted decrease in surface ocean pH_T due to the uptake of anthropogenic CO_2 as manifested in the concurrent DIC increase. The significant acidification of the surface ocean will cause major shifts in the speciation of the marine CO_2 system, namely a marked increase in the CO_2(aq) and strong decrease in the carbonate ion (CO_3^{2-}) concentration. The latter would reduce the supersaturation of surface waters with respect to calcium carbonate mineral phases (calcite and aragonite) by about 40%. Such expected dramatic changes in pH and the marine carbonate system are very likely to affect marine organisms and metabolism in various ways, possibly leading to shifts and changes in biogeochemical cycles, ecosystems, and their interactions.

Several direct effects of increasing CO_2(aq) on the biological pump have been recognized:

- There is potential for growth rate limitation of phytoplankton either by CO_2 diffusion (Riebesell et al., 1993; Wolf-Gladrow et al., 1999) or sub-optimal functioning of the carbon concentration mechanism (Morel et al., 1994), although there is contradictory evidence about whether increasing CO_2(aq) concentrations could indeed enhance oceanic productivity (Hein and Sand-Jensen, 1997). Observed taxon-specific differences in CO_2 sensitivity suggest that changes in CO_2 availability may influence phytoplankton species succession and distribution (Rost et al., 2003).
- Despite the expected rigidity of elemental ratios of production and respiration of organic matter, the so-called Redfield ratios species-specific deviations from these ratios (Geider and La Roche, 2002), as well as deviations in space and time, have been observed on many occasions (Körtzinger et al., 2001). Furthermore, CO_2-dependent changes in C:P ratios have been observed in culture experiments (Burkhardt et al., 1999), challenging the commonly accepted notion of CO_2-independent Redfield ratios. Flexibility in these ratios allows for the possibility of CO_2-related changes in the stoichiometry and strength of the biological carbon pump.

As its carbonate ion concentration decreases, surface seawater becomes less supersaturated with respect to calcite and aragonite mineral phases (Table 1), simply as a consequence of the uptake of anthropogenic CO_2. There is strong evidence that such decreases in calcite and aragonite in seawater have negative impacts on calcification success of corals and coralline macroalgae (Figure 12) (Kleypas et al., 1999; Langdon et al., 2000); as well as coccolithophorids (Riebesell et al., 2000). It remains to be seen how this will affect net community production (Langdon et al., 2003) in the marine environment as well as the $CaCO_3$ dissolution at depth and feedbacks to atmospheric CO_2 concentrations (Zondervan et al., 2001). Furthermore, changes in marine calcification may directly impact organic carbon export via the proposed role of $CaCO_3$ as mineral ballast in POC export (Armstrong et al., 2002; Klaas and Archer, 2002).

The pH of seawater is a “master variable” in the marine system. Changes in pH may therefore constitute a significant impact on marine ecosystems via a number of possible mechanisms, many of which are understood poorly. The importance of pH is illustrated by the following effects:

- the pH dependence of enzymes, especially those with exogenous substrates. Depending on an enzyme’s pH optimum, decreasing seawater pHmay increase or decrease enzyme activity.
- Concentrations of micronutrients may be influenced by pH changes through pH-dependent sorption-desorption equilibria (Granéli and Haraldsson, 1993), which may either enhance or inhibit marine phytoplankton production.
- The speciation of elements may be affected by pH changes (Kester, 1986) with both beneficial (e.g., Co, Fe) and inhibitory consequences (e.g., Cu) for biological productivity.

- Maintaining a specific optimal intracellular pH may cause cells to use more (or less) energy under conditions of changing ambient pH (Raven and Lucas, 1985) and may affect a cell's overall performance.
- Isotopic compositions of planktonic foraminiferal shells are influenced by pH (Spero et al., 1997). Strong isotope dependence on the pH would require correction of the $\delta^{18}O$ and $\delta^{13}C$ of shell material during glacial time (about 0.2‰ more negative for the atmosphere's CO_2 content to 30% lower during glacial time), demanding surface ocean pH 0.15 units higher. Hence, if the pH dependence were to prove universal, then a 1°C cooling would have to be added to the glacial to interglacial temperature difference derived from $\delta^{18}O$ of planktonic foraminifera. If such a correction only applies to planktonic organisms, but not to benthic organisms, the 0.2‰ $\delta^{13}C$ correction would increase the surface-to-deep carbon isotope difference, thereby increasing the apparent magnitude of the strengthening of the biological pump during glacial time. It will be interesting to learn the cause of the pH dependence and thereby how it might change with species and growth conditions of the shells.

These examples demonstrate that changing pH will affect food webs by multiple mechanisms simultaneously, in different directions and to variable degrees. An extensive review of the effects of pH on coastal phytoplankton by Hinga (2002) revealed significant differences in pH sensitivity and pH ranges, sustaining optimum growth rates while allowing only slight insight into the underlying mechanisms of pH effects.

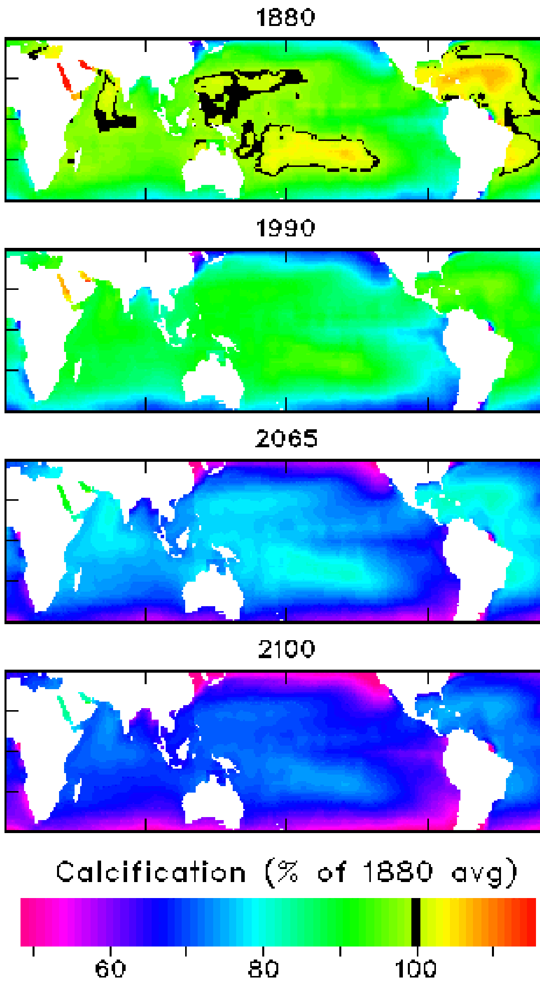

Figure 12. Projected change in coral reef calcification rate based on average calcification response of two species of tropical marine algae and one coral in a marine mesocosm (Kleypas et al., 1999).

Recognising the strong potential impact of pH changes on marine organisms and ecosystems, it will be important to develop ideas and techniques to investigate the adaptive capabilities of marine biota to a low pH environment. Predictions of the impacts on marine systems of decreased pH will depend critically on whether adaptation of organisms can keep pace with predicted pH changes. An important feature of such research would be to attempt to determine the physiological and genetic components of organismal adaptation to pH changes.

We need to develop a broad understanding of the pH sensitivity of marine biogeochemical cycles and ecosystems, including organisms and their metabolic processes, in the entire food web. We currently lack understanding of how changes in the marine CO_2 system will impact the broad spectrum of biological processes, such as primary and secondary production, key species dynamics, and energy flow in food webs. Such changes will likely stimulate a multitude of responses, caused and controlled by mechanisms that may not yet be understood or anticipated (e.g., Engel, 2002). On the basis of such knowledge, it will be essential to develop better understanding of the integral effects of pH and CO_2(aq) changes on the quantity and quality (e.g., organic/inorganic carbon ratio, opal/carbonate ratio) of the biological pump and the resulting potential feedback on atmospheric CO_2 concentrations. IMBER will need to work with SOLAS to create a coherent research effort on the effects of pH on key aspects of marine biogeochemistry, organisms, and ecosystems.

Promising Scientific Approaches

Effects of pH change on biogeochemical cycling and food web structure in the euphotic zone will propagate into the ocean, especially into the mesopelagic layer and could affect benthic–pelagic coupling in the continental margins. Research approaches will need to be designed to develop a better understanding of how the influence of surface ocean acidification extends beyond the ocean surface. Some particularly sensitive or threatened ocean ecosystems, such as coral reef communities, deserve special attention in IMBER research. Previous LOICZ research has involved coral reefs and IMBER will seek LOICZ collaboration on these studies.

To understand the complex action and interaction of pH effects, a multitude of approaches will be needed, ranging from small-scale laboratory experiments and large-scale in situ manipulative experiments to analysis of existing and newly generated field data from hydrographic surveys (e.g., carbon measurements on CLIVAR repeat hydrographic lines and carbon data from VOS and other routine measurements) and dedicated process studies. Traditional culture experiments will be an indispensable tool; however, we should also aim for larger-scale mesocosm and open ocean manipulation experiments, similar to the iron fertilisation experiments (e.g., Iron Experiment (IronEx), South Ocean Iron Release Experiment (SOIREE), Southern Ocean Iron fertilisation Experiments (EisenEx), etc.), but focused on pH and CO_2 effects. New facilities (e.g., artificial ecosystems) will be required to study marine ecosystems under sustained low pH conditions. In addition it may be useful to develop a marine analogue to the “Free Air CO_2 Enrichment” (FACE) experiments carried out by the terrestrial research community (Hendrey, 1992). Preferable sites for this new and technologically challenging approach would include coral reef and $CaCO_3$-dominated shelf ecosystems. But ultimately, a mesoscale open ocean CO_2 or acidity enrichment experiment should be considered as a new joint approach of IMBER and SOLAS to overcome the inherent limitations of laboratory and mesocosm experiments.

These approaches should be embedded in and accompanied by a suite of modelling studies from process to Earth System scale, and should be complemented by careful examination of palaeorecords for evidence of the adaptation potential of marine ecosystems to major pH shifts.

Issue 3. Response of marine biogeochemical cycles, ecosystems, and their interactions, to changes in inputs of macro- and micronutrients

Introduction

Exogenous forcing of the ocean system, both natural and anthropogenic, occurs primarily through physical and chemical fluxes across oceanic boundaries. Human activities have been modifying chemical transfers across the ocean-land and ocean-atmosphere boundaries for decades. We need to develop a quantitative understanding and predictive capability of the coupled responses of marine biogeochemical cycles and ecosystems to such anthropogenic additions of both macro- and micronutrients to the ocean.

Macronutrients generally occur in seawater in rather constant ratios that can be altered by anthropogenic additions. Currently, inputs of nitrogen and phosphorus from land to ocean are probably two to three times their natural values, although damming of rivers has resulted in entrapment of nutrients, especially silicon, in reservoirs (Rabalais and Nixon, 2002). Another two-fold increase in these fluxes is projected to occur by the middle of this century (e.g., see Figure 13 for nitrogen transport by rivers). The human alteration of nutrient fluxes has been geographically uneven, with the largest changes occurring in areas of the highest population density and agricultural production, and within marginal seas and over continental shelves. Further changes in these ratios can be brought about by shifts in biogeochemical processes in the ocean itself. For example, continuing global expansion of oxygen-depleted zones resulting from eutrophication (Diaz and Rosenburg, 1995) is expected to lead to an increase in pelagic denitrification rates. This change will be associated with remobilisation of phosphorus and micronutrients from continental shelf sediments, resulting in a decrease in the N:P ratio in the water column and greater availability of micronutrients in forms that can be assimilated by organisms.

Time-series observations in the North Pacific Ocean suggest that changes in nitrogen fixation may be associated with alternating nitrogen and phosphorus controls of production on decadal time scales. Decoupling of macronutrient cycles in the ocean (in which micronutrients probably play key roles) is now widely regarded to be of key ecological importance (Karl et al., 2001a) (Figure 14).

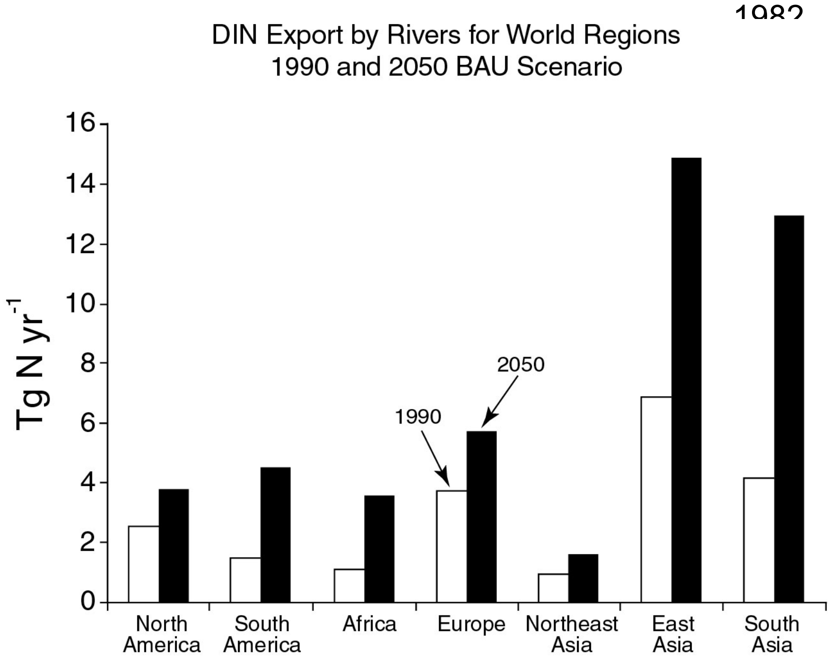

Figure 13. Model-predicted riverine fluxes of dissolved inorganic nitrogen (DIN) for various regions in 1990 and 2050 for the business-as-usual scenario (Seitzinger et al., 2002).

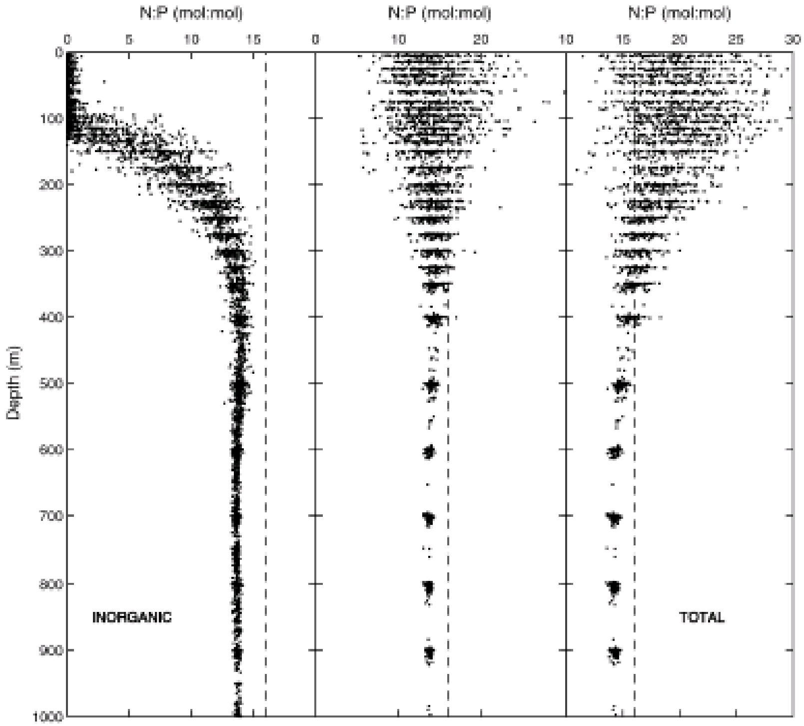

Figure 14. Nitrogen-to-phosphorus (N:P) ratios versus water depth for samples collected at Station ALOHA during the period Oct. 1988 to Dec. 1997. (Left) Molar N:P ratios for dissolved inorganic pools calculated as nitrate plus nitrite: soluble reactive phosphorus (SRP). (Center) Molar N:P ratios for the corrected total dissolved matter pools. (Right) Molar N:P ratios for total dissolved matter pools, including both inorganic and organic compounds, calculated as total dissolved nitrogen (TDN): total dissolved phosphorus (TDP). As a point for reference, the vertical dashed line in each graph is the Redfield-Ketchum-Richards molar ratio of 16N:1P (from Karl et al., 2001a).

Priority Questions

- How will changes in macro/micro nutrient inputs to the ocean affect the abundance, distribution, and stoichiometry of these elements?
- How will changes in macro/micro nutrient inputs to the ocean affect food web structure and function?
- What effect will changes in macro/micro nutrient inputs to the ocean have on benthic/pelagic coupling and biogeochemical cycles?

The effects of increased inputs of macro- and micronutrients from land to ocean (via the atmosphere, freshwater runoff, and submarine groundwater discharges) on elemental fluxes and food web structure in the ocean are not well known. There are unanswered questions about the net effect of counter-balancing processes, including nitrogen loss through denitrification, which raises P:N ratios and sets the stage for nitrogen fixation, versus stimulation of nitrogen fixation, which lowers P:N ratios. What will be the net effect of these opposing processes on the global fixed nitrogen inventory, and how will this affect fluxes and the stoichiometric composition of organic matter in different ocean domains, including continental margins and the open ocean, as well as surface waters and the deep sea? Changes in the structure and dynamics of marine food webs will impact and be impacted by altered chemical forcing (i.e., changes in the quality and quantity of macro- and micronutrients from land, atmosphere, and seafloor). Since species differ in their nutrient requirements, we can expect changes in the levels and ratios of nutrients entering the ocean to change the relative abundance of different species. Modified nutrient ratios significantly impact marine food web structures and biodiversity (Sterner and Elser, 2002). Under conditions of abundant silicon, diatoms may become the dominant primary producers, and food webs will support commercially important fisheries. Where diatom productivity is limited by a low Si:N ratio, the food web is more complex, with a smaller fraction of diatom production reaching the highest trophic levels (Turner, 2002). Food web structure also determines the extent of export from the surface layer (Michaels and Silver, 1988). Other consequences of eutrophication and associated changes in relative abundance of nutrients in coastal waters may include increases in the number and severity of blooms of dinoflagellates and other harmful algal species (Anderson et al., 2002) and shifts in the abundance, diversity, and harvest of fishes in affected regions (Breitburg, 2002). The impacts of increased terrestrial supply of dissolved and particulate matter may extend from shallow waters to well offshore. The nature and extent of such changes and the possible feedback loops of biological processes to chemical forcing remain open questions.

An important effect of inputs of macronutrients to the ocean is the stimulation of primary production. The respiration of additional organic matter may lead to hypoxic and anoxic conditions in the water column. Thus, nutrient over-enrichment may be responsible for recent discoveries of hypoxia in coastal waters in regions not previously known to experience oxygen depletion (Hearn and Robinson, 2001; Rabalais and Turner, 2001; Weeks et al., 2002). These conditions can impact both biogeochemical cycles and ecosystems. There are several important, yet poorly understood, aspects of coastal anoxia and hypoxia, including how exposure of sediments to reducing conditions facilitates mobilisation of redox-sensitive metals (notably Fe and Mn). Aside from serving as an unquantified source of these elements to surface and intermediate waters, such mobilisation may also affect the nitrogen cycle. This linkage between the nitrogen and trace metal cycles occurs because, while both Fe and Mn in their lower oxidation states can interact with oxidised nitrogen species, the reduced nitrogen form (NH_4^+) can react with iron and manganese in their oxidised states (Luther et al., 1997). The contribution of such interactions to the nitrogen cycle should be evaluated.

Hypoxia and anoxia in coastal waters has significant impacts on marine biota, including organismal metabolic changes, species distributions, biodiversity, and food web dynamics (Ross et al., 2001; Breitburg, 2002; Cooper et al., 2002; Baden and Neil, 2003). Linkages should be explored among nutrient inputs, oxygen concentration of coastal waters, biogeochemical cycling, and ecosystem processes (Justic, 1997; Rabalais and Turner, 2001). The rate of organic carbon accumulation per unit area of the seafloor is 8-30 times higher in coastal areas than in the open ocean (Chen et al., 2003). Eutrophication and related hypoxia and anoxia in coastal waters may be expected to favour even greater preservation of carbon in the marginal sediments, and possibly its export to the ocean interior. However, sedentary benthic animals cannot benefit from the enhanced food availability, due to hostile conditions arising from the absence of oxygen (Rabalais and Turner, 2001). Moreover, the lower pH in anoxic areas suppresses the growth of benthic animals with calcareous shells. The lower benthic biomass will alter the benthic-pelagic coupling and transfers across the sediment-water interface over continental margins. While the greater carbon supply to sediments is expected to support sedimentary denitrification (and sulphate reduction), the decreased oxygen penetration to sediments arising from both lower bottom water oxygen concentrations and less bioturbation will limit nitrification-denitrification coupling and consequently nitrate availability for denitrification. Thus, the extent to which sedimentary denitrification can serve as a buffer to increased nitrate loading in coastal waters is unclear.

The relationship of remineralisation depth to the vertical scales of stratification, circulation, and isopycnal ventilation determines the various time scales of nutrient and carbon sequestration and reflux. Boundary scavenging (or input from the continental slopes) with isopycnal mixing to the ocean interior is still a poorly quantified process, although this may play a major role in biogeochemical cycling and food web structure in the ocean interior.

Effects of changes in the quality and quantity of the organic matter exported to the mesopelagic layer on remineralisation of nutrients and secondary production need to be evaluated.

Our present understanding of the role of microbes in biogeochemical transformations is incomplete. How do the composition and function of microbial populations respond to changes in the chemical environment? What are the factors that control the activities of enzyme systems responsible for important biogeochemical transformations (e.g., denitrification)? These are questions that have yet to be answered satisfactorily. We know little about major groups of these organisms, for example, the Archaea, and many marine microbes cannot be cultured at present. New approaches, including molecular characterization (DNA sequencing and microarrays), should be utilised to gain new insights into microbial ecology and functional biodiversity.

Promising Scientific Approaches

Marine biogeochemical and ecosystem responses to anthropogenic inputs of nutrients are complex and diverse, and can only be evaluated through integrated multidisciplinary studies that allow observation and analysis of the target process in the context of the system and its feedbacks. Such studies should include laboratory, mesocosm, and field observations and experiments, as well as comprehensive observation and modelling of biological, chemical, and physical processes.

Studies should identify sites that are most sensitive to changes in chemical forcing, where, for example, enhanced inputs of macro- and micronutrients can bring about large changes in community structure, export production, and CO_2 sequestration. These include HNLC regions, coastal upwelling zones, continental margins and marginal seas receiving large river runoff and nutrients. Ocean domains that are less well studied, including high-latitude and polar regions, and the mesopelagic layer, are also priorities.

Technical advances will greatly benefit IMBER, including sensors for coastal waters, devices for making in situ measurements during extreme events and in areas of strong boundary currents, devices to address benthic-pelagic coupling in space and time, tools for rapid surveys of slope regions in steep gradients, and algorithms for ocean colour in coastal waters (e.g., Sathyendranath, 2000). Observations from ships of opportunity and ongoing ocean monitoring programs, including the Continuous Plankton Recorder Survey (Batten et al., 2002; Edwards et al., 2002), should be explored as cost-effective approaches for biological data collection.

The results of iron fertilisation experiments and time-series studies have led to a general appreciation of the significance of micronutrients in ecosystem dynamics and biogeochemical cycling. These studies should be continued and used to address the priority questions above. Micronutrients should also be explored as proxies of palaeo-chemical environments. For example, records of lattice-bound Cd in banded corals can help reconstruct patterns of anthropogenic additions of fertilisers to the sea, on time scales ranging from annual to centennial. Similarly, down-core changes in polyvalent metals in high-sedimentation continental margin sediments should be utilised to study recent variation in biogeochemical processes in benthic communities and environments. These studies should be supplemented by other palaeo-proxies (e.g., organic carbon, stable isotopes, biomarkers for specific groups of organisms).

Collaborations for Theme 2

Collaboration with CLIVAR will be needed to address Issue 1, in both understanding the physical drivers and carrying out common experimental and modelling efforts. Furthermore, analysis and re-analysis of ocean states provided by the Global Ocean Data Assimilation Experiment (GODAE) will bring new insights about patterns of physical forcing. Impacts of physical processes on marine organisms will be explored in close collaboration with GLOBEC, in order to understand biological and biogeochemical effects on all levels of organization, from individuals to ecosystems. PAGES and IMAGES research provides information on how changes in the physical system and geochemical processes affect ocean biogeochemical cycles, as reflected in the sedimentary record, and IMBER will provide information on how to interpret the palaeo-proxies. Joint implementation with research being undertaken to address IMBER Theme 1 issues will also be important to ensure effective use of resources.

IMBER collaboration with SOLAS and LOICZ are of particular importance for Issue 3, since the proposed research is focused on the fates of nutrients reaching the ocean through the air, and surface and groundwater inputs. IMBER will design complementary research with these projects to extend studies of flux effects in the euphotic zone, and to the mesopelagic layer and the open ocean and will focus on the interaction between biogeochemical cycles and food web structure and dynamics. IMBER will collaborate with LOICZ on studies focusing on the significance of submarine groundwater discharge for biogeochemical and biological processes in continental margins. The recently completed report of SCOR/LOICZ Working Group 112 on Magnitude of Submarine Groundwater Discharge and its Influence on Coastal Oceanographic Processes (Burnett and Chanton, 2003) may be useful to guide development of this area of research. Joint implementation with research being undertaken to address IMBER Theme 1, issues will also be important to ensure effective use of resources.

SCOR and IOC are planning a symposium on “The Ocean in a High-CO_2 World” in May 2004 that will bring together ocean scientists to discuss what we can predict regarding how the ocean carbon system might evolve under a variety of atmospheric CO_2 concentrations, and the effectiveness, and potential chemical and biological effects, of purposeful ocean carbon sequestration. This symposium may provide an opportunity for the SOLAS and IMBER to further develop joint activities in ocean carbon research.

Theme 3: Interactions with the Earth System: What is the role of ocean biogeochemistry and ecosystems in regulating climate?

Introduction

This theme will focus on key issues to address the present and future capacity of the ocean to control the climate system via atmospheric composition as well as ocean heat storage. These important research topics will be approached by assessing (in the context of global change) the varying capacity of the ocean to store anthropogenic CO_2; the role of hypoxia/anoxia in the nitrogen cycle; and how changes in ecosystem structure modulate solar heating of the upper ocean and consequently physical structure. Modelling the potential feedbacks from marine biogeochemical cycles and ecosystems to the Earth System will require detailed understanding of local and regional manifestations of global change in the ocean and their interactions with other parts of the Earth System. Some aspects of global change, such as land-use changes, are already occurring, leading to changes in the distributions and physico-chemical forms of macro- and micronutrients, the consequences of which are modified fluxes of radiatively active gases. Oceanic storage of anthropogenic CO_2 is likely to be affected by temperature and alkalinity effects, in addition to changes in ocean circulation and mixing, which is predicted to affect the interactions between marine biogeochemical cycles and ecosystems, and the Earth System (Sarmiento and Wofsy, 1999; Levitus et al., 2001). IMBER will work with SOLAS and LOICZ to integrate on air-sea fluxes of gases and particulates, and land-sea fluxes of carbon, respectively.

In recent decades, increasing density of observations of the ocean, atmosphere, and biosphere have shown that the Earth is an integrated system with variability, internal and external forcings, regional and global responses, and feedbacks among its components. As human activities continue to impact land-ocean-atmosphere interactions, the impact on the Earth System is manifest in terms of global change. Earth System responses in terms of increasing global mean temperature and changing precipitation, the rate of these changes and, more importantly, local and regional manifestations of these changes, depend crucially and inextricably on how the components of the Earth System respond individually and together. Studies of pre-industrial conditions highlight the variability, forcing, and response of the Earth System. We must use these data and our present knowledge to develop a modelling capacity that will enable prediction of the impacts of global change on the Earth System. This necessity requires dynamic, process-based models that are able to capture the range of possible changes (Goddard and Graham, 1999; Stocker, 1999; Knutti and Stocker, 2002). Developing, validating, and testing the predictions of such models are impossible without a solid understanding of the interactions and feedbacks among the components of the Earth System. This understanding can only be achieved with extensive, well-planned observational programs supported by modelling and data assimilation activities.

As an important component of the Earth System, the ocean itself is a complex system, dominated by non-linear processes, time-delayed feedbacks, and chaotic behaviour (Patten et al., 1995). One of the consequences of perturbations to such a system are regime shifts in ecosystems (Hare and Mantua, 2000), which may lead to altered efficiency and strength of the carbon biological pump, rates of primary and secondary production, and release of radiatively active gases such as N_2O. While it is generally believed that the ocean acts as a buffer in the dynamics of the Earth System due to its capacity to absorb atmospheric heat and CO_2 (i.e., a negative feedback mechanism), it is evident that such a complex system with the characteristics described above may also be a trigger in the evolution of global change trajectories, leading to positive feedbacks and amplifying global change. Solar penetration into the mixed layer is significantly affected by absorption of infrared radiation by organic and inorganic particles. Therefore, ecosystem dynamics and properties could contribute significantly to stratification of the upper ocean and consequently affect the entire climate system (Murtugudde et al., 2002). Factors controlling marine biogeochemical cycles and ecosystems under global change must be understood in order to predict feedbacks to the other components of the Earth System.

Impacts of climate change on the ocean are already occurring (Levitus et al., 2000). Conversely, the ocean is regulating climate by its heat capacity and its ability to sequester carbon. In addition to its intrinsic complexity, the ocean has a high dynamic range of physical, biogeochemical and biological characteristics that vary over multiple time and space scales. These characteristics result in known “hot spots” and “choke points” and, undoubtedly, some that are not yet known. High-latitude ocean areas could be important choke points in marine biogeochemistry, with significant potential for positive feedback to the coupled climate system, for example, through oceanic regulation of atmospheric CO_2 as in the glacial periods (Sarmiento and Toggweiler, 1984). Coastal zones are important hot spots for biogeochemical and ecosystem feedbacks to the Earth System. The predicted sea level rise over the next century (Houghton et al., 2001) will affect different coastal benthic ecosystems (e.g., coastal wetlands and coral reef communities) in different ways. The biogeochemical and ecosystem feedbacks could be manifested through reduction-oxidation (redox) state changes, and related impacts on nitrogen cycle, water quality and habitat changes, and fish populations.

We must describe the most significant feedback loops for guiding observational and modelling activities. Here we describe key interactions and feedbacks to be addressed by IMBER between the Earth System, and marine biogeochemistry and ecosystems.

Issue 1. Oceanic storage of anthropogenic CO_2

Introduction

The most direct and probably the strongest feedback from marine biogeochemistry and ecosystems to the Earth System will occur through oceanic regulation of atmospheric CO_2. Presently, the ocean absorbs around one-third of the anthropogenic CO_2 emissions (Houghton et al., 2001); however, the assumption that the ocean will continue to be such an efficient sink of anthropogenic CO_2 may not be correct. It is within this context that IMBER will study the capacity of the ocean to store anthropogenic carbon.

Atmospheric CO_2 concentrations are now higher than at any time in the past 20 million years (Pagani et al., 1999; Pearson and Palmer, 1999; Petit et al., 1999). The anthropogenic increase of atmospheric CO_2 has led to enhanced accumulation of carbon in the upper and intermediate ocean (Gruber and Sarmiento, 2002) (Figure 15). The variability of atmospheric CO_2 associated with natural modes of climate variability such as ENSO is not well constrained by available observations (Keeling et al., 1995; Bousquet et al., 2000; Le Quéré et al., 2000; Feely et al., 2002) and palaeo-environmental data indicate surprisingly small fluctuations of atmospheric CO_2 since the last glacial period (Indermühle et al., 1999). However, we are now in a period in which the atmosphere and ocean are out of equilibrium in respect to CO_2 levels.

The anthropogenic perturbation of atmospheric CO_2 concentration is taking place on a time scale of decades to centuries, which does not allow the equilibration of the atmosphere with the deep ocean or marine sediments. We are therefore witnessing a non-steady state situation that is driven by a complex combination of the kinetics of the processes involved. These include the major carbon pumps operating in the ocean; that is, the physical (or solubility) pump driven by intermediate and deep water formation and the biological pump, which can be separated into soft tissue (or organic carbon) and hard tissue (or alkalinity/carbonate) pumps.

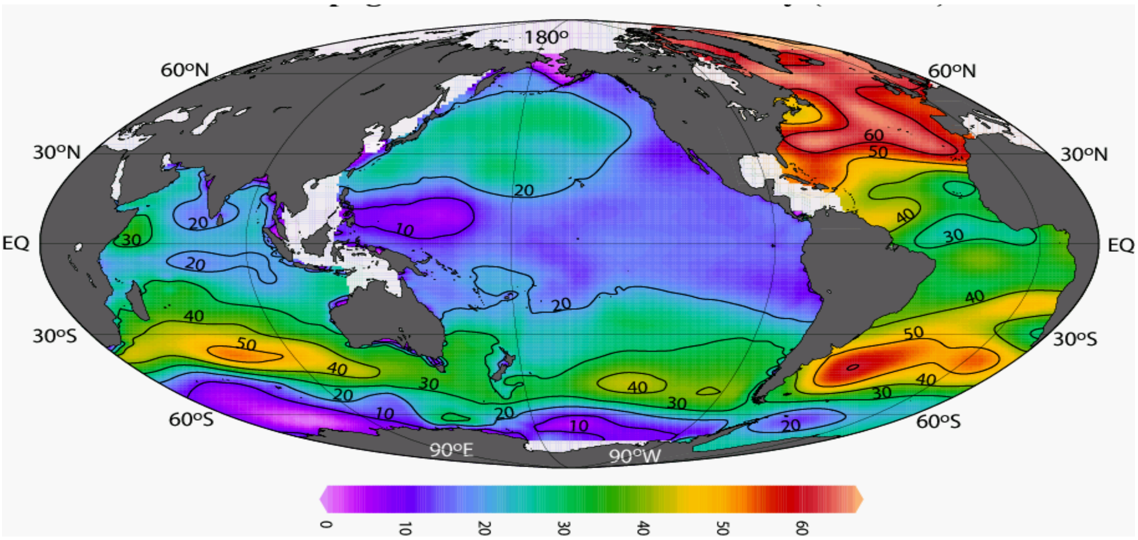

Figure 15. Anthropogenic CO_2 column inventory (mol m^2)(from Sabine et al., 2003).

Global change is already affecting the ocean in many ways, encompassing central parameters of physical (e.g., temperature, salinity, winds, precipitation) and chemical (e.g., pH, CO_2 system speciation, fixed nitrogen input, macro- and micronutrient input) forcing. Such changes are likely to have an impact on the ocean's carbon cycle that could be mediated in many ways, including vertical supply of nutrients; high-latitude convection activity and the strength of the thermohaline circulation; changes in calcification, efficiency, and elemental composition of the biological pump; and the supply of macro- and micronutrients to the ocean. It is presently unclear, quantitatively or even qualitatively, what the integrated effects of such changes will be on the ocean carbon cycle and how these will feed back to atmospheric CO_2 concentrations.

Regarding longer time scales, the correlation between glacial-interglacial changes in temperature and atmospheric CO_2 concentrations is striking; the radiative forcing due to CO_2 probably accounts for a significant part of the glacial-interglacial climate change. Even today, despite the obvious importance of such knowledge, it remains unclear whether CO_2 is a secondary amplifier or a primary driver of the glacial cycles. Although it is clear that the ocean is the most likely driver of CO_2 changes observed in glacial cycles, the mechanisms are not understood (Archer et al., 2000). Competing hypotheses abound, employing a wide range of mechanisms, from physical changes to changes in the soft tissue pump or the carbonate pump. Therefore, we need to better understand the mechanism(s) responsible for glacial-interglacial CO_2 cycles. Moreover, analysis of short-term transients, such as during Dansgaard/Oeschger or Heinrich events, should provide key insights on responses at decadal or centennial time scales. Although the Earth System is currently operating in a non-analogue state, the perspectives gained from palaeo-proxies is likely to provide important insights into the functioning of the Earth's climate system, which will certainly help in interpreting the comparatively fast changes of the Anthropocene Era (Crutzen and Stoermer, 2000).

Priority Questions

- What are the spatial and temporal scales of storage of CO_2 in the interior of the ocean?
- How will global change affect carbon transformation and storage in the mesopelagic layer and how will these changes be communicated to the surface ocean?
- What is the role of the continental margins in ocean carbon storage under global change?

Long time series and repeat transects over recent decades have shown an increase in the total DIC in the upper ocean. Beyond this direct geochemical impact, the Anthropocene Era is also characterised by significant human-driven changes in physical forcing of the Earth System, more of which are likely to become detectable during the next decade. Modelling studies have illustrated the feedback potential of the ocean carbon cycle under global change (Friedlingstein et al., 2001; Plattner et al., 2001). Methods to evaluate changes of anthropogenic CO_2 inventories have been developed, but will require continued improvement and testing. Over the past decade ^{13}C and O_2 have proven to be very useful in the interpretation of long-term trends of atmospheric CO_2. Changes in the carbon cycle may be understood better by observing the ocean's oxygen reservoir, which is one order of magnitude, smaller than the carbon reservoir, but tightly coupled to biological and hydrographic processes. There is growing evidence that the ocean's oxygen reservoir has been decreasing during recent decades. Regional trends of as much as a few tens of µmol kg^{-1} (Kim et al., *2000*) and basin-wide changes of several µmol kg^{-1} (Emerson et al., 2001; Keller et al., 2002) have been detected, primarily in intermediate waters. Only one-fifth of these changes can be explained by ocean warming (Bopp et al., 2002; Keeling and Garcia, 2002), with the remainder attributed to changes in the ventilation of these waters and/or the efficiency of the (soft tissue) biological pump (Keller et al., 2002). Jointly, oxygen and carbon dioxide may therefore be the best parameters to measure for detecting Anthropocene Era trends of the ocean's carbon cycle.

We know that changing physical and chemical forcing will induce a multitude of responses of the carbon cycle in the ocean. These changes range from large-scale effects due to circulation and ventilation changes to molecular-scale effects on phytoplankton due to changes in pH, river inputs (Fe, P, N, Si), and perhaps increasing anoxia. The role of ocean circulation in the meridional and zonal transport of carbon is starting to be assessed directly using interior ocean measurements of carbon-related tracers (Holfort et al., 1998; Schlitzer, 2000). These oceanic transports of carbon, together with measured gradients in atmospheric CO_2, provide independent information on the overall source, sink, storage, and transport behaviour of the land-atmosphere-ocean system (Sarmiento et al., 2000; Wallace, 2001). Although some of the biological effects have been documented in specific experiments (e.g., the effect of pH on calcification: Riebesell et al., 2000) we presently don't know how these effects will interact (perhaps with synergistic side effects) and feed back to the atmosphere. Understanding these processes is crucial to understanding oceanic carbon storage.

Our current global ocean biogeochemistry models do not resolve ocean margins, nor do they appropriately include the exchange between the coastal and the open ocean. Inclusion of this zone in carbon models is necessary because the outer coastal zone is likely to be net autrophic, taking up carbon dioxide (due to upwelling along the ocean margin) and fuelling (after lateral exchange) the heterotrophic processes in the open ocean. Feedback from the mesopelagic layers to the upper ocean in terms of carbon regulation will be better understood through observational, modeling and synthesis activities. National and international policy decisions and government actions will depend on the outcome of the carbon cycle research. The synthesis of these data into models (e.g., by the Global Carbon Project) to make future projections will reduce the uncertainties that are often the basis of non-action or delayed policy decisions. As already seen from JGOFS synthesis activities, continued carbon-related observations, along with hydrographic data, will aid in the assessment of the absorption and storage of anthropogenic CO_2 into the ocean (Gruber and Sarmiento, 2002) and assist in closing the carbon budgets on global scales. The benefits may not always be quantifiable or immediately evident in terms of reduced risk and cost of future corrective actions required to mitigate the impacts of changes in oceanic regulation of atmospheric CO_2. Specific data assimilation and biogeochemical reanalysis, taking into account climate variability and change, are necessary.

Promising Scientific Approaches

The need for further observations cannot be overemphasised, especially for understanding the potential for release of CO_2 by the ocean under global warming and change, providing a positive feedback to the climate and the Earth system. Continuation of repeated hydrographic lines are required to determine the anthropogenic CO_2 storage. CLIVAR plans such repeated lines, and IMBER will work with CLIVAR to measure carbon (and other key elements) on these lines. Such repeat hydrography lines should be an important approach to IMBER observations, particularly if enhanced in terms of biogeochemical and ecosystem measurements. Hydrographic lines alone cannot readily address time-dependent aspects of the ocean circulation that may also be extremely important for carbon uptake and transport. The extent to which more continuous observational initiatives (e.g., the Argo float program) might benefit ocean carbon cycle science requires careful assessment. Developments with the Argo profiler network, which is providing excellent physical oceanographic data, suggest that Argo or similar drifting profilers should be considered for marine biogeochemical profiling (Bishop et al., 2002). Oxygen sensors should be the first biogeochemical sensor added to Argo-type floats, followed by sensors for optical properties and specific nutrients.

More broadly, ocean carbon surveys within GOOS and other projects that use time-series stations and moorings in the open and coastal ocean, will be important to IMBER research. Novel towed and autonomous instruments that can achieve better accuracies of pCO_2 measurements will also advance IMBER research. Observations, data synthesis and modelling will require close cooperation with SOLAS, to enable carbon cycle features from air-sea CO_2 exchange to carbon sequestration to be considered effectively.

Space-based sensors that measure surface chlorophyll and other biogeochemical quantities, should be strongly supported by national space agencies. Particularly relevant are new approaches being developed to estimate ecosystem state (particulate/dissolved matter: Loisel et al., 2002) and main taxonomic group (diatoms, coccoliths, nitrogen fixers: Iglesias-Rodriguez et al., 2002a; Iglesias-Rodriguez et al., 2002b; Subramaniam, 2002).

State-of-the-art inverse and forward modelling approaches are able to quantify the anthropogenic CO_2 invasion into the ocean with reasonable accuracy. These models need to incorporate advances in estimating the state of the ocean, and ocean reanalyses will provide the groundwork for future estimation of marine biogeochemical states. As computers become more efficient and powerful, coupled climate models are evolving toward coupled climate and biogeochemical models or Earth System models, allowing incorporation of biological feedbacks to climate that will enhance our ability to quantify the oceanic regulation of atmospheric CO_2. This major goal can only be met if knowledge can be gained from IMBER, SOLAS and other projects is fully incorporated into the work of the Earth System Science Partnership and the Global Carbon Project.

Finally, to evaluate the robustness of the modelling approaches, interpretation and simulation of palaeoenvironmental data should be undertaken. Palaeoceanographic data indicate that synchronous food web changes occurred in association with marine biogeochemical and physical regimes with cyclical fluctuations in temperature, salinity, dust, and CO_2 in the past 400,000 years (Petit et al., 1999). Particularly important will be a focus on decadal-to-centennial time scales, to accurately time synchronise the various records before they are reanalysed, with specific objectives of determining the feedbacks from marine biogeochemistry and ecosystem changes to other components of the Earth System.

Issue 2. The role of hypoxia/anoxia in the oceanic nitrogen cycle

Introduction

The ocean plays a major role in Earth System function not only as a massive heat and carbon regulator, but also as a major biogeochemical reactor that contributes significantly to global budgets of radiatively active gases such as N_2O. Physico-chemical changes in the marine environment arising from human activities have the potential to greatly affect the structure and functions of the microbial community involved in the production and

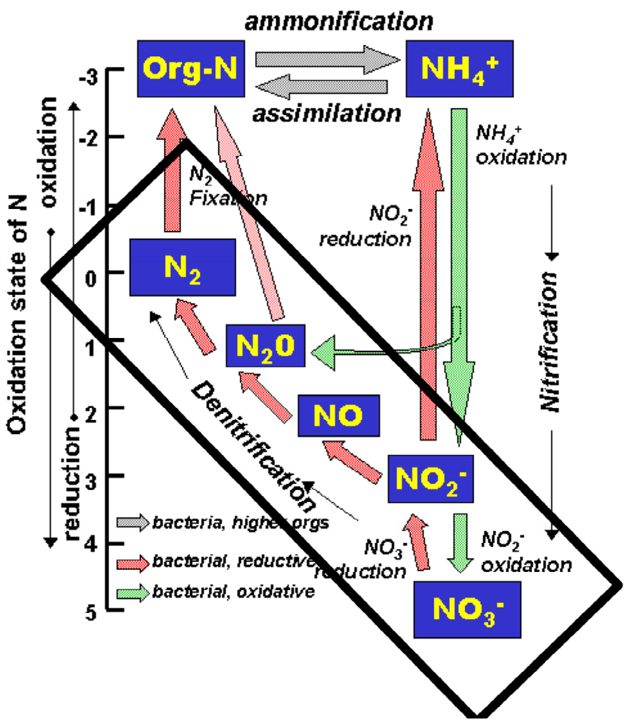

Figure 16. The nitrogen cycle including microbial pathways of production and consumption of N2O (*adapted from Capone, 2000).*

consumption of these gases. The biologically mediated redox transformations of nitrogen, particularly those involving N_2O, a potent, long-lived (150 y) greenhouse gas, are especially sensitive, in unpredictable ways, to the ambient O_2 concentration in the low range (<25 µM; Codispoti et al., 1985). Changes in oceanic distribution of O_2 are most likely to occur in the future in response to global warming and eutrophication. It is crucial to understand how and to what extent these changes will affect the part of the ocean nitrogen cycle involving N_2O.

Some of the most important redox transformations of nitrogen occur in hypoxic/anoxic water and shallow sediment layers. Production of N_2O can occur through both oxidative and reductive pathways, that is nitrification (Dore et al., 1998), as well as denitrification (Capone, 2000; Naqvi et al., 2000); both processes are mediated by bacteria (Figure 16). While denitrification is obviously favoured by low ambient O_2 levels, the yield of N_2O during nitrification also increases in hypoxic waters (Goreau et al., 1980). The impending global warming is expected to lead to increased stratification of the upper ocean (Sarmiento et al., 1998) as well as a reduction in the strength of the thermohaline circulation (Houghton et al., 2001). Such changes will cascade through both large- and meso-scale physical structures of the ocean, in turn affecting nutrient transport and cycling, and consequently ecosystem structure and functioning. In a more stratified ocean, primary producers are likely to be adapted to a more regenerative system (Bopp et al., 2001; Karl et al., 2001b) involving small phytoplankton (flagellates or cyano-bacteria) instead of larger diatoms. Moreover, the sea-to-air flux of O_2 is expected to increase at the cost of its supply to subsurface waters (Bopp et al., 2002; Joos et al., 2003). This in conjunction with increased nutrient loading from land is expected to result in an expansion of the hypoxic/anoxic zones within the mesoplelagic layer and the continental margins, affecting nitrogen and sulphur cycles. Loss of NO_3^- through denitrification can ultimately lead to conditions favourable for N-fixation in some areas, and in the occurrence of NH_4^+ as the dominant fixed nitrogen species in others (where sulphate reduction takes place). In both cases, the phytoplankton community structure will be greatly modified, in turn affecting the organic carbon export. More importantly, the hypoxic/anoxic conditions will affect the remineralisation of biologically important elements and alter the strength of oceanic N_2O source strength (Naqvi et al., 2000). The magnitude of this process and the potential for feedback to the Earth System are largely unknown.

Priority Questions

- What processes are responsible for the formation and maintenance of hypoxic/anoxic conditions?
- To what degree are N_2O concentrations and related rates of nitrogen cycling in the ocean altered by changes in microbial community structure and function?

The coupled biogeochemical-ecosystem response to global change, especially in ambient O_2 concentrations, is inherently non-linear, with an abrupt switch over from the oxic to hypoxic (reducing) conditions occurring at an O_2 concentration of approximately 1 µM (Morrison et al., 1999). These effects imply that even minor changes in forcing processes may bring about large changes in chemical fluxes. The N_2O cycling is especially sensitive to O_2 concentrations in the vicinity of this threshold value, with both the highest and the lowest N_2O concentrations found within a narrow range of 0-5 µM O_2. The pattern of N_2O cycling differs significantly between the deeper open ocean and shallower shelf hypoxic zones in that while a net consumption of N_2O invariably occurs within the open ocean denitrification zones, denitrification sometimes leads to enormous build-up of N_2O in shallow hypoxic systems (Naqvi et al., 2000). This difference probably arises from the variable activity of N_2O reductase, but it is not known what factors control the activity of this enzyme. In fact, microbial ecology of hypoxic systems, including the identity of organisms that mediate transformations involving N_2O, is still an almost unexplored area of research. Understanding the mechanisms and identifying the organisms responsible for N_2O production are central to predicting how global change may affect the oceanic production and cycling of N_2O. There is a growing interest in biochemical characterization of nitrification and denitrification and the underlying genetics. Evidence is now emerging linking the activities of the enzymes involved in transformation of nitrogen oxides with the availability and redox chemistry of Fe, Mn and Mo. Combining molecular biological techniques (DNA- and RNA-based) with activity measurements (using isotopic tracers) to relate phylogenetic diversity with N_2O cycling, is a promising avenue of research.

To examine the priority questions, rates of O_2 consumption and supply as well as key N_2O-producing organisms should be identified and quantified. Understanding shifts in the O_2 distribution pattern and their effects on the nitrogen cycle in the ocean will be critical to prediction of future climate scenarios. IMBER will encourage an integrated end-to-end approach to food web structure and function in the open ocean and the continental margins, placing emphasis on hypoxic/anoxic regions. Including N_2O in the context of these efforts is important.

Promising Scientific Approaches

Consolidated datasets of physics, O_2, nitrogen biogeochemistry, and phytoplankton composition are essential. Sustained observations are required to detect human-induced changes that need to be resolved from natural variability. A first step would be to focus on key areas that have undergone particularly great stratification changes, or have been subjected to extreme nutrient/sediment loading by rivers. Atmospheric reanalyses (Kalnay et al., 1996) provide a next step in reconstructing the last decade's variability of whole ocean physics. It should also allow the exploration of seasonal to decadal variability and regime shifts of the physical and biogeochemical environments over the past 50 years (Chai et al., 2003). Extension of such approaches to studies of O_2 and N_2O cycles should also be attempted.

Integrating experimental and modelling efforts from the onset of IMBER research will be absolutely essential for success. Complex food web models should be verified with experimental and observational measures of key chemical and biological species that can be compared directly to model predictions. Nitrogen cycling with special attention to how biogenic gases relate to evolution of food web structure and function, should be incorporated into these efforts for model validation. Models that include key phytoplankton groups/species driven by nutrient co-limitation (N, P, Si, Fe, etc.), with embedded nitrogen cycle and shallow sediment schemes, should be used to study the impact of eutrophication on hypoxia/anoxia and N_2O emissions. Key systems for study should be continental margins exposed to large riverine inputs as well as the permanent mesopelagic hypoxic zones. Sensitivity testing should be systematically conducted to explore potential feedbacks of N_2O to climate. These studies could be used to identify key ecosystem processes for in-depth study within IMBER Themes 1 and 2.

Issue 3. Direct ecosystems feedback on ocean physics and climate

Introduction

Marine organisms may modify global temperature by affecting the heating of the upper ocean due to absorption of heat by chlorophyll and related pigments of phytoplankton. These pigments absorb approximately half of the incoming solar radiation in the spectral range of 350 to 700 nm. The effect of this absorption on ocean temperature is dependent on the relative depth of radiation attenuation and the depth of the mixed layer. If the mixed layer is shallow, absorption is particularly sensitive to changes in phytoplankton biomass.

Existing coupled physical-biological models have become relatively sophisticated since the seminal works of Fasham et al. (1993) and Sarmiento et al. (1993). However, the intrinsic nonlinearities of the system often make it difficult to distinguish the feedbacks between biological and physical processes (see Miller et al., 2003 for a review). It has been known for decades that marine biota affect the penetration of incident radiation and thus have the potential to affect water column temperature (Denman, 1973). Despite the heuristic perspective on the magnitude of such a feedback (Lewis et al., 1990; Sathyendranath et al., 1991), the traditional approach to its inclusion in state-of-the-art coupled climate models has been rather simplistic, with a constant attenuation depth (Schneider and Zhu, 1998). This may have been partly due to one-dimensional ocean studies (Simpson and Dickey, 1981a; b), which failed to capture the dynamic feedbacks that can result from ecosystem-related radiative feedbacks. With the availability of remotely sensed global surface chlorophyll concentrations, the impact of ecosystems on radiative attenuation are being addressed again in ocean general circulation models (Nakamoto et al., 2001; Murtugudde et al., 2002).

Recent studies indicate that the chronic ”cold-tongue” problem, which afflicts nearly all state-of-the-art coupled climate models and forced ocean models, is related to misrepresentation of the biological feedbacks in these models (Murtugudde et al., 2002). The boreal spring warming of the sea surface in the eastern equatorial Pacific Ocean cold-tongue region is not simulated by any of the coupled climate models or forced ocean models. During March-April, when the sunlight is increasing and the winds are at their weakest, mixed layers in the cold tongue tend to be shallow, with very weak surface entrainment. The thermocline relaxes from the strong upwelling of the previous boreal summer/winter seasons with both the thermocline and the nutricline still in the euphotic zone. This leads to a subsurface chlorophyll bloom and a heat source just below the mixed layer. Existing models do not include this natural heat source, which restratifies the water column during boreal spring months, instead simulating colder-than-observed temperatures below the mixed layer and excessive surface cooling due to the entrainment of these cold waters. Accurate representation of the radiative penetration thus leads to a nearly 70% reduction in SST errors. The ecosystem feedbacks thus not only have the potential to control the annual cycle, but also affect the Bjerknes feedback during ENSO events, thus modulating the ENSO amplitude and frequencies (Marzeion et al., 2003).

Figure 17 illustrates both change in temperature and horizontal transport due to the space and time variability of solar absorption by marine life.

Priority Questions

- How do marine food web structure and variability affect ocean physics?
- Do marine food webs affect the large-scale climate via heat control in the upper ocean?

The vertical distribution of phytoplankton species not only depends on supply of macro- and micronutrients but also on the availability of light. The distribution of light is modified by vertical distribution of light absorbing/reflecting species and, in turn, feeds back to ocean physics through conversion of light to heat. The impact of such a conversion will occur locally as stratification changes, which will cascade into dynamic feedbacks on local and regional scales. This two-way interaction between the marine food web structure and ocean physics has the additional aspect of the impact of global change on both ocean physics and the food web structure.

The dynamic feedbacks in the ocean do impact sea surface temperatures, a key variable for driving the atmospheric temperature. Even if it is not yet proven that climatically significant biological effects on ocean physics occur outside of the eastern equatorial Pacific Ocean, preliminary studies using coupled ocean-atmosphere models indicate that biologically mediated SST warming amplifies the seasonal cycle of the lowest atmospheric layer temperature (an average magnitude of 0.3°C, but may reach over 1°C locally: Shell, 2003), tending to indicate a broad influence on climate via atmospheric teleconnections (Figure 18). The impacts of changes in light attenuation within the mixed layer due to chlorophyll have also been reported to affect El Niño and La Niña in an asymmetric way (Timmermann and Jin, 2002). Also, Nakamoto et al. (2001) show significant impacts in the Arabian Sea. All these results must be studied by in-depth studies and ultimately model ensembles should provide estimates of the robustness of such direct biological feedback on the climate.

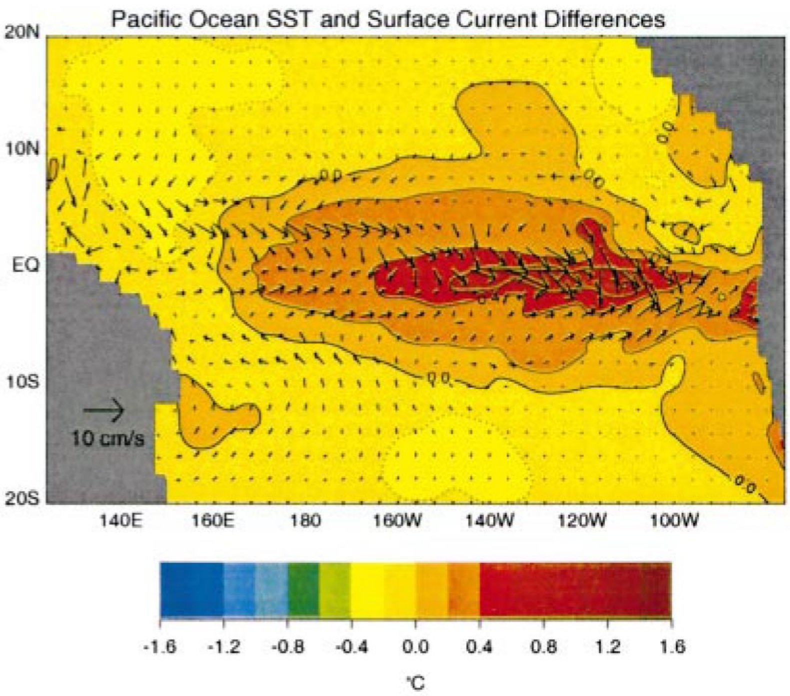

Figure 17. Annual mean differences in surface currents (vectors: cm.s^{-1}; scale is located in lower left corner of panel) and temperatures (colours) for variable and constant attenuation of light with depths (from Murtugudde et al., 2002)

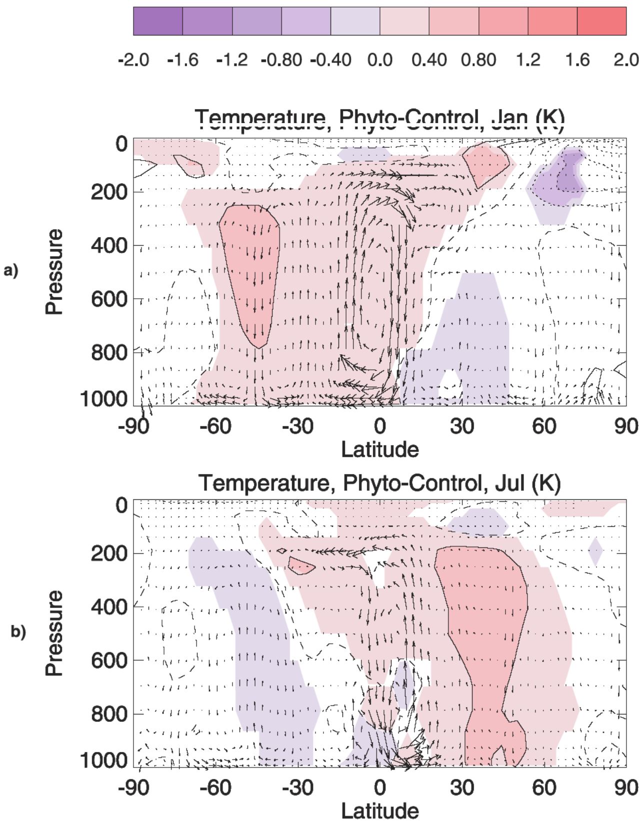

Figure 18. Difference between phytoplankton and control runs for (a) January; and (b) July, longitudinally averaged air temperature (coloured contours) and circulation (arrows). Solid contours correspond to positive temperature differences, while dotted contours indicate negative temperature differences. The dashed line follows the zero contour. Temperature differences with a significance of at least 95% are shaded. (from Shell, 2003).

Promising Scientific Approaches

Feedbacks to climate due to changes in marine ecosystems could, in principle, be addressed using suites of models of various complexities. Beyond being tools to investigate propagation of perturbations into the climate system, coupled or intermediate complexity models must be (1) based on key processes that interface the different sub-systems and (2) evaluated by model/model and model/data intercomparisons of some key variables and in relation to regime shifts. In brief, the study of feedbacks to the Earth System should integrate and synthesise the various knowledge bases developed during the activities designed to investigate the Themes 1 and 2 of the IMBER project.

Thus, studying the feedbacks from the ocean to the Earth System will require the development of a hierarchy of models. First, integration of simple plankton representation into physical ocean and ocean-atmosphere models is crucial to quantify the direct impact on stratification and circulation patterns at different space and time scales. Second, the use of coupled ocean-atmosphere system models will help to identify positive or negative feedbacks between ecosystem response and climate variability and change. Third, sensitivity studies on evolving scenarios of climate variability and global change, with or without feedbacks with marine biogeochemical and ecosystem models, will provide a way to assess the weight of direct marine ecosystem feedbacks on climate. Innovative laboratory experiments to measure physical control by plankton activity should be strongly encouraged.

Key systems for both modelling and process studies would be (1) high-latitude and polar areas particularly sensitive to climate change, such as the Arctic Ocean and shelves; (2) the tropics, which could amplify the feedbacks through coupled ocean-atmosphere interactions and global teleconnections; and (3) continental margins where large bloom patterns occur, and which are sensitive to river input.

Collaboration for Theme 3

Joint implementation of research on carbon cycle and N_2O production will be undertaken by both the IMBER and SOLAS scientific steering committees (SSCs) via a joint IMBER/SOLAS Implementation Planning Group. This joint work is essential if feedback between marine food webs and climate through the production of atmospherically important gases is to be examined fully. Repeat hydrographic lines planned by CLIVAR, including ocean carbon measurements will be especially important for studying changes in ocean carbon storage and will be organized jointly with IMBER to integrate key biogeochemical components.

Improving global biogeochemical models, including micronutrients, carbon, oxygen, and nitrogen cycles, that interact with ocean physics and climate is a key aim. To achieve this, the results of a suite of sensitivity tests should be used to help design and prioritise experimental and modelling activities within the IMBER project. Understanding and modelling the complex system of biogeochemical and ecosystem feedbacks is an important integrating activity across disciplines that address components of the Earth System. Various modelling activities, including data assimilation, should be conducted in collaboration with GAIM, CLIVAR, GODAE, and PAGES, with GCP leading on synthesizing global carbon data and coordinating the development and intercomparisons of global carbon models.

Because feedbacks to climate via gases (CO_2, N_2O) and optical properties often have a large-scale impact, comprehensive monitoring of these key cycles at appropriate spatial and temporal resolution, in key areas and at selected sites, is important. It will require a strong and concerted international effort to maintain and considerably expand the present ocean observing system. These efforts should be conducted in a proactive integrated strategy with SOLAS, LOICZ, CLIVAR, GOOS, IOCCP, and the Integrated Global Observing Strategy (IGOS-P) Ocean and Coastal Themes.

Studies of the feedbacks from the marine system to climate will allow IMBER results to be used to develop a more integrated view of the Earth System. The quantitative understanding and consequent development of predictions of the feedbacks cannot be achieved without strong connections with other international initiatives, since the sign, magnitude, controls, thresholds, and runaway modes of the feedback system cannot be completely answered within the auspices of IMBER. IMBER will need to work closely with other IGBP and SCOR projects, CLIVAR, IHDP, and DIVERSITAS in the context of GCP's activities, to integrate efforts in synthesizing data and modelling to understand oceanic feedbacks to the Earth System.

Theme 4: Responses to Society: What are the relationships between marine biogeochemical cycles, ecosystems, and the human system?

Introduction

This theme focuses on interactions between the human and ocean systems. The motivation for such a theme lies in recognition that humans not only influence ocean systems, but that humans also depend on ocean systems for goods (e.g., fish, oil, gas, and minerals) and services (e.g., weather mediation, regulation of local and regional water quality, transportation, dumping of waste, and global regulation of atmospheric concentrations of CO_2 and O_2). A number of interactions between humans and natural systems are already included within the previous three themes, particularly addressing the human system as a cause of change in the ocean system (e.g., as a source of nutrients and contaminants), as well as the role of the oceans in human-induced climate change. The possible effects of changes in the marine system and their implications for the human system (e.g., loss of biodiversity, loss of coral reef systems, decreased productivity of fish and seaweeds, introduction of new plankton and fish species, reduced CO_2 buffering, long distance effects of anoxia) receive less emphasis in the other themes.

The overall goal of this theme is to promote understanding of the multiple feedbacks between the human and ocean systems, and to clarify what human institutions can do either to mitigate human-caused perturbations in the ocean system or to adapt to system changes. The achievement of this goal depends on inputs from both the natural and social sciences. The major challenge of this theme will be to bring together scientists from a wide range of disciplines to identify areas of joint concern and interest and to create an ongoing community of those with expertise on both sides of the natural-social science divide. These scientists must be capable of communicating not only within their own specialist disciplines, but also across disciplines and with policy makers. Since this theme has not achieved the level of detail of Themes 1, 2, and 3, its development requires several initial steps prior to the start of implementation.

The first goals in bringing a range of disciplines together are identification of common issues of interest and concern, and development of a common language and concepts. Current multi-disciplinary, interdisciplinary and perhaps even transdisciplinary research is slowly building on a common language. This theme can be expected to benefit from these efforts, and to make its own contributions to them. With regard to common concepts, the Driver-Pressure-State-Impact-Response (DPSIR) framework is offered as a means of structuring this research theme, and helping scientists to understand their contribution (Figure 20). The DPSIR framework is the causal framework for describing the interactions between society and the environment and has been adopted by the European Environment Agency (EEA) as a basis for analysing the inter-related factors impacting the environment. It is an extension of the Pressure-State-Response (PSR) model developed by the Organisation for Economic Cooperation and Development (OECD).

Examples of *Drivers* include consumer preferences, economic growth, the effects of globalisation, and transportation and energy production infrastructure and processes. *Pressures* are typically sources of nutrients and contaminants, but also include the effects of harvesting and use of the marine environment in general. *State* relates to the quantity and quality of various environmental components, for example, chlorophyll concentration, stocks of fish, and biodiversity. Changes to environmental States can lead to *Impacts*, which may be positive for people or ecosystems, but are more often negative. Environmental quality targets may not be met, or perhaps fish stocks decline below levels needed to support those dependent on them, or the relative abundance of stocks is altered towards less valuable species (Pauly et al., 1998).

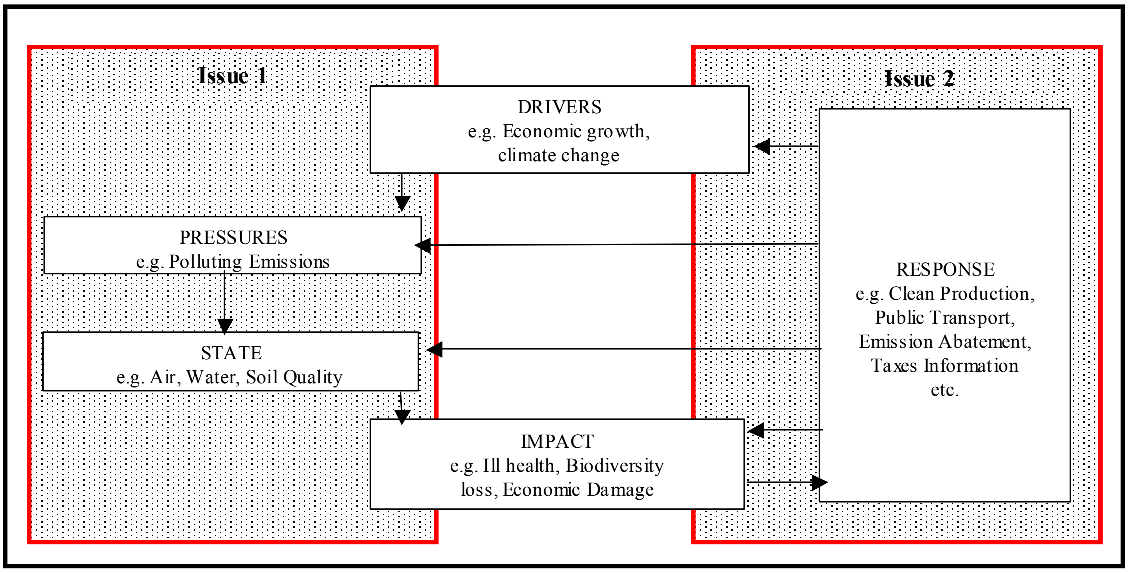

Figure 19: The DPSIR framework with overlay of the IMBER Theme 4 issues. (adapted from http://org.eea.eu.int/documents/brochure/brochure_reason.html)

The severity of negative impacts determines whether or not a response is required. *Responses* may attempt to mitigate adverse environmental Impact, usually by reducing pressures either directly (e.g., emission abatement) or indirectly (e.g., influencing Drivers such as consumer preferences). Responses may also attempt to restore environmental States (e.g., dredging to remove stocks of nutrients in lake sediments) and even ecosystems (e.g., mangrove reforestation and wetland creation). Responses may also involve adaptation, helping humans accommodate to, and perhaps even benefit from, State changes. Implementation of this framework by the EEA has focused on the development of indicators, particularly for the Driver, Pressure, and State components. This framework has been used in environmental analysis (Turner et al., 1999; Kannen et al., 2003).

IMBER has identified two research issues, as indicated in Figure 19. It is considered too early for IMBER to attempt to apply the whole of this framework. The reason is, in part, that IMBER does not yet encompass the appropriate scientific community. Application of this framework requires contributions by social scientists and close cooperation between natural and social scientists as well as between science and policy. The two issues are housed in different parts of the DPSIR framework, and make different contributions toward creating this community. Issue (1) is centred on the Pressures and State components, and the link between them. Research being undertaken within other IMBER themes will provide much initial information. It is within this issue that cooperation between natural and social scientists is to be stimulated. Issue (2) is centred on Response, which is in the domain of the social sciences. While cooperation with natural scientists will be promoted, the focus of this issue is more towards the Science-Policy interface.

Both issues will follow a similar, cautious strategy, which explicitly addresses known difficulties in creating a multi-disciplinary and policy-oriented research community. The aim in this first IMBER phase is to make small but concrete steps based on good science. Each issue will elaborate its particular DPSIR element (Pressures-State or Response), and then build outward toward the adjacent elements, namely Drivers and Impact. Select studies may go further and attempt more of, even the whole of, the DPSIR, although this is by no means required. The priority is to build toward Drivers, in response to currently perceived policy needs. Cooperation with other programs, such as IHDP, will be needed. Building toward Impact has a lower priority, and will require close cooperation with other projects, such as GLOBEC and DIVERSITAS. It is recognised that Impact overlaps, in many instances, with research activities within these projects.

There is the potential with this approach for a mismatch between the results of the two issues, because of their different perspectives on Drivers and Impact. Mismatch is expected to be less of a concern for Drivers. Research on developing and testing scenarios is relatively new and, if anything, is likely to benefit from diversity in approach. Mismatch within Impact is likely because it is the element of DPSIR, which involves natural and social sciences as well as science and policy. IMBER intends to address this element of the DPSIR at a later stage. Studies from both themes would be used to give structure to and priorities within a future issue.

Issue 1: Human lifestyle effects on the state of the ocean

Research outlined in previous themes will contribute to our understanding of the sources and nature of change in the ocean system. This issue provides the framework for drawing this research together, and for stimulating additional research, to provide a cohesive picture of how human lifestyles have affected, or may affect, the state of the ocean. This issue will elaborate on current knowledge of the relationships between Pressures on and the State of the marine environment, derived from other IMBER themes, to estimate the consequences of existing and historic patterns of human behavior on the ocean system and the implications of those consequences for human welfare.

Four broad activities can be identified:

- development of cross-sectional and time-series indicators of major State changes in the ocean that are either currently taking place or have taken place in the recent past;
- clarification of the major Impacts those State changes have had or are having on human welfare, broadly defined;
- identification of the Pressures (both anthropogenic and natural) on the oceanic environment causing these state changes; and
- identification of the socio-economic and natural system Drivers that cause these pressures.

Research on this issue recognises that Drivers reflect prior Responses and Impacts but, for analytic purposes, treats Drivers as independent variables or givens whose influence is to be assessed. This issue will seek to bring together existing, and develop new, data and indicators of Pressure, States, Impacts, and Drivers. These indicators will be selected for their ability to identify or refute existing claims about whether and how socio-economic Drivers contribute to environmental Pressures that alter ocean States, with Impacts on the human system and human welfare. In addition, this research will engage those familiar with integrated assessment techniques and modelling. It will seek to address the complex interactions between the plethora of human Drivers relevant to any given marine environmental problem (as well as various sources of natural variation), which create environmental Pressures and exacerbate or dampen trajectories and variance in State variables and have important implications for (and Impacts) on economic, social, political, and cultural values. For example, understanding the likely Impacts for the human system of the types and rates of various biogeochemical cycles and the response of marine ecosystems to those changes (i.e., State variables) requires accounting for human Drivers such as food production (agriculture and fishing), manufacturing, and transportation in order to understand changes in Pressures such as over fishing, freshwater diversion, eutrophication, and pollution by oil and heavy metals.

These activities will not only draw on research activities in other IMBER themes, they will also draw on other IGBP and international projects including LOICZ, Land-Use Cover Change /New IGBP Land project (LUCC/LAND), GLOBEC, and IHDP projects at large.

Issue 2: Mitigation or adaptive policies that could reduce the impact of global change on society

This issue builds on Issue 1 by looking at Response and its link to Drivers and Impact. The focus lies with the influence of Response on Drivers. Issue 2 examines the Responses of humans and human institutions to the experienced or expected Impacts of particular changes in the state of the ocean system and the effectiveness of those Responses at altering the anthropogenic Drivers of particular environmental problems. The research would primarily focus on how well policy Responses adopted by human societies, through their institutions, manage to reduce or mitigate the socio-economic behaviors that are Drivers of the environmental Pressures that alter the States of ocean systems. This issue examines the efforts of human institutions to respond to past changes in ocean systems to reduce current perturbations of ocean systems by human behaviors and thereby reduce the impacts of perturbations of the ocean system on human societies. The main objective of analysis in this issue is to improve our understanding of how to design human institutions to better manage human interactions with the marine system.

The increasing present experience and future expectation of Impact requires the development of effective Responses by either developing new or redesigning existing human institutions. For IMBER purposes, human institutions are considered to consist of any consciously organized efforts by humans to respond to Impact at a level above the individual. These include not only international, national, provincial, and local government policies and regulations, but also the efforts of corporations (whether multinational or single country) as well as nongovernmental organizations (NGOs) to prompt behavioral changes. This issue also will pay analytic attention to informal and less self-consciously guided institutions. These include economic markets, social norms, and cultural preferences and practices to determine how such informal institutions, as well as more formal ones, contribute to mitigating or exacerbating the impact humans have on the ocean and the responses they use to adapt to ocean changes. An important aspect of this research involves addressing the ways in which the incentives, pressures, and ability of human institutions to adapt depends considerably on how Impacts are experienced and understood. At the abstract and global level, these questions have been investigated by a variety of organisations, most notably the Intergovernmental Panel for Climate Change (IPCC). IMBER will contribute to these larger scale efforts by bringing together natural and social scientists to identify selected cases that capture, at smaller temporal and spatial scales, both the major institutional (Responses) and behavioral (Drivers) dynamics of human systems. Cases selected and explored as representative microcosms of human-ocean interactions during the first several years of Theme 4's implementation will provide insights that may be valuable at larger scales and also provide opportunities to develop interdisciplinary research methods and form interdisciplinary research teams that can undertake larger scale efforts over the longer term.

Accurately evaluating the effects and effectiveness of institutions, particularly institutions that address environmental problems, raises challenging methodological obstacles. Assessing the environmental impacts of a particular human institution requires understanding the complexities of the human sphere, the complexities of the environmental sphere, and the complexities of the interaction between those spheres. It requires clearly identifying what factors made adoption of new institutions possible, defining what behavioral changes are expected, identifying the state of behavioral changes that would have occurred even without the institution's influence, identifying which of the myriad aspects of the institution were responsible for whatever success it achieved or failed to achieve, and determining whether the institution's success can be applied in a wider context (e.g., other countries, other environmental problems, other locations). Care needs to be taken not only to identify intended, direct, and positive institutional effects but also unintended, indirect, and negative institutional effects, and to take into account the interplay between the institution being examined and the many other institutions whose actions influence ocean changes.

Crucial elements in conducting research on the effects of institutions that seek to mitigate or adapt to ocean change will be the ability to bring together research teams whose members can understand, make use of, and integrate knowledge, models, and methodologies from both the natural and social sciences. For example, studies of the effects of global change on coral reefs would require research teams that bring together modellers of tropical ecosystems, marine biologists and animal physiologists, physical and chemical oceanographers, and social scientists who study how the use of reef systems is governed by local norms and rules and how the health of those systems affect local lifestyles. Research that is likely to be most convincing to policymakers as well as most innovative scientifically is likely to consist of projects that incorporate quantitative and qualitative variables into system models, that make use of place-based and illustrative case studies, and that take into account feedbacks from the ocean system to humans and from humans to the ocean system. Particular analytical value might be achieved by looking at how the responses and effectiveness of those responses (whether involving mitigation or adaptation) vary between different cultures, different national or local governments, or different corporate or nongovernmental efforts. Equally important insights might be gained by examining how societies differ in their responsiveness to given changes in the natural environment, that is, how sensitive they are to particular impacts and how responsive they are upon experiencing such impacts. "Hotspots" where human environmental impacts on ocean systems, the impact of changes in ocean systems for human societies (particularly innovative human institutions), or some combination of these features, may prove particularly useful sites for collaborative research. Identifying factors that best explain why otherwise similar cases demonstrate significantly better or worse performance could provide valuable insights into strategies to adopt and strategies to avoid, as well as contexts that facilitate or hinder such efforts. A final, but important, aspect of evaluating institutional effects involves identifying ways to evaluate the impact of institutions relative to other causes of variation in human behaviors. This involves determining, as accurately as possible, whether self-conscious efforts to mitigate human impacts on the ocean environment offer a solution that can reduce 50% of human impacts, 5% of human impacts, or 0.5% of human impacts, especially when compared to the impacts of non-self-conscious institutions such as economic markets that may have far more significant influences.

Within the IMBER mandate, research might involve investigation of such issues as waste disposal at sea, or extraction of non-living resources such as oil and minerals from the ocean. These areas involve existing activities that have already been recognized as issues and have been the target of local, national, and international efforts to mitigate human impacts on ocean systems. Beyond these existing interactions of humans with the ocean system, emerging interactions are also a potential area of interest under this theme, including large-scale use of ocean thermal differentials to produce energy, large-scale desalination efforts, and intentional iron fertilization and injection of CO_2 into the deep ocean for carbon sequestration efforts. Research on the consequences of changing fish stocks on coastal communities are already underway in GLOBEC.

Collaborations for Theme 4

The development of Theme 4 will require identifying natural and social scientists who will work together to develop a common language and common set of concepts that can be used to engage such scientists in identifying foundational questions that must be answered before Issues 1 and 2 can be addressed. IMBER will seek funding for a workshop in 2005 focused on bringing the natural science communities (including GLOBEC) and social science communities together, and will build on the work of other initiatives including those of the IHDP project Institutional Dimensions of Global Environmental Change programme (IDGEC). IHDP will be an important partner in the development of this theme. After the key questions have been identified, an implementation plan for this theme will be developed. This may involve the development of a pilot project to take this initiative forward.

Key to the success of implementation of this theme will be identifying and engaging a core group of natural scientists (representing topics of biogeochemical cycles and end-to-end food webs) and social scientists who are already literate in, or open to and interested in, the methods, insights and approaches of those on the other side of the natural-social science divide and who are also comfortable with the issues raised by research that attempts to study and engage the policy world while simultaneously retaining analytic distance from it. In particular, co-chairs, one representing the natural sciences and one representing the social sciences will be identified to take this theme forward. Outreach efforts would be made to identify from the range of natural scientists already involved through the other three IMBER themes those who are interested in engaging with the issues raised in Theme 4. These outreach efforts will also target economists, sociologists, anthropologists, geographers, lawyers, and political scientists among others who are engaged in research on ocean-related issues and who can see the value of engaging with natural scientists in further investigation of these issues.

Cross-cutting Science Activities

Sustained Observations

In situ Observations: The JGOFS strategy of sustained observations (i.e., time-series studies) resulted in a significantly increased understanding of the links between biogeochemistry and ecosystems (Steinberg et al., 2000). Similarly, IMBER requires long-term observations to monitor and interpret seasonal, annual, and decadal variability in biogeochemical cycles and ecosystems. This data will form a critical foundation for developing a predictive capability for the impact of global change on the ocean system. This strategy requires sustained observation sites as central components around which other investigations, such as process and experimental studies, will be clustered.

Development of new, additional sustained observation sites in areas such as the continental margins, high-latitude and polar ocean areas, and within the mesopelagic layer, will be required. The development of new sites must consider the time and space scales relevant to the questions being addressed. Likewise the nesting of sites and transect designs will need to be considered. IMBER will encourage the use of a wide range of measurement platforms, such as remote sensing, floats, autonomous underwater vehicles (AUV), moorings, volunteer ships of opportunity, repeat hydrographic lines, and new platforms as new technologies are developed.

IMBER will not develop a sustained observation capability in isolation, but will form close collaborative links with ongoing sustained observation programmes at international, regional, and national levels. These programmes include the Global Ocean Observing System (GOOS), the International Ocean Carbon Coordination Project (IOCCP), current time-series stations such as Hawaii Ocean Time Series (HOT), Bermuda Atlantic Time-series Study (BATS), and the Kyodo North Pacific ocean time-series station (KNOT), global plankton repeat surveys, and many more regional and national initiatives. Close collaboration with GOOS must include an active dialog to determine priorities for variables to be measured, the time and space scales required for measurements, and the research and development needs of the system. Development of long-term, cost-effective sustained observations of the ocean, particularly the measurement of a wide range of biogeochemical and biological variables, is in an early stage of development. IMBER must play an active role in this development and take advantage of developments as they occur.

Satellite observations are a central component of sustained observations. Satellite sensors measure scattered, reflected and 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 have been developed by researchers to use ocean colour as a proxy for surface chlorophyll. Coordinated international activities have been undertaken with the sponsorship of organisations such as WCRP, IGBP, the International Ocean Colour Coordination Group (IOCCG), and national space agencies. While significant progress has been made, this process needs to continue beyond the present generation of satellites (SeaWIFS, MODIS, MERIS, OCTS, POLDER), to obtain higher ocean coverage (60% global, over a 3-5 day timeframe) and move toward an operational system. To achieve this goal, IMBER will work collaboratively with SOLAS, and with IGOS-P in the development of the IGOS-P Coastal Theme and the review of the IGOS-P Ocean Theme.

Beyond surface chlorophyll, the development and testing of a new generation of ocean colour remote sensing algorithms is required to cover others aspects of the ecosystem structure. Recent developments are able to detect different phytoplankton functional groups (i.e., coccolithophorids, diatoms, cyanobacteria), 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 to support on-going and new satellite ocean colour analysis. Long-time series will be particularly important to quantify and merge ocean colour products remotely sensed from different platforms.

Emerging Technologies

Given the dynamic nature of the ocean and its strong spatial and temporal (both periodic and episodic) variability, our ability to answer the pressing global change-related questions are severely limited due to under-sampling. Extending the quantity and quality of measurements of critical variables is thus of prime importance for the scientific goals of IMBER. 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.

A variety of *Platforms* form the backbone of any ocean observation system. Often a nested approach, combining platforms of different types such as Eulerian platforms (moorings, buoys, bottom landers, offshore platforms, etc.), Lagrangian platforms (drifters, floats), and other platforms (volunteer observing ship (VOS) and AUVs) may need to be taken. However, all these platforms can only be helpful to research if adequate chemical and biological sensors or autonomous sampling devices are available. Clearly, the field of physical oceanography is well ahead in using such platforms for observational programmes. Similar biogeochemical and ecosystem studies have so far been limited severely by the limited availability of chemical and biological sensors that are sufficiently miniaturised and have low power requirements.

Sensors suitable for the platforms mentioned above 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 rather 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; electrochemical: pH glass electrode) are not yet available, miniaturised systems based on more classical chemical methods have been developed (e.g., nutrients, pCO_2). The application of these systems, however, is more restricted since their size, power requirement and cost 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. Again, these techniques need to be further developed and adapted to the challenging requirements of use on autonomous platforms.

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 sensor and analyser techniques may not suffice to fulfill all measurement needs. In this case, autonomous in situ sampling devices (e.g., trace metal clean samplers) may be able to fill this gap to some extent. The whole issue of emerging new platforms and sensors and their future potential has been discussed in detail by Dickey (2001).

Molecular biology and genomics: In recent years, oceanographers have come to appreciate the value of subcellular investigations (including molecular biology and genomics) for identifying, quantifying, understanding, and predicting biological patterns and processes at organismal, population, community, and ecosystem levels. DNA-based characters can define species boundaries, reveal cryptic species, and accurately estimate biodiversity for marine organisms from microbes to whales (Hebert et al., 2003). These same protocols can be used to identify prey species amid gut contents; DNA can provide a means of documenting trophic relationships in complex food webs. Molecular genetic analysis can reveal underlying population dynamics (patterns of recruitment, dispersal, and mortality), as well as species' evolutionary history and responses to climatic variability. 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). Recent studies using microsatellite DNA markers for Atlantic cod has linked individual fish to their population of origin (Nielsen et al., 2001).

Rapid advances in genomics (i.e., study of genes 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 animals. Such techniques allow us to identify groups of organisms that perform certain functions within food webs, 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, 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. We may soon be able to assemble and sequence whole genomes of microorganisms from natural samples, and may discover novel genes and functions in biogeochemical cycles.

Mesoscale Ocean Manipulation Experiments

Small-scale manipulation experiments, such as predator exclusions, have been an important research approach over the past several decades, to test various hypotheses regarding the structure and function of marine food webs. Many early insights in marine ecology were gained through manipulations of intertidal benthic marine ecosystems (Paine, 1994). An important development of the past decade of ocean biogeochemical research was the implementation of large-scale manipulation experiments to test hypothesis about the role of iron in marine ecosystems (e.g., IronEx, EisenEx, SOIREE). These experiments were necessary to test the results that had been obtained in flask incubations and mesocosms. The nature of biogeochemical cycling and the physical dynamics of pelagic ecosystems required that manipulation experiments on limiting nutrients take place on scales of tens of square kilometers.

The success of mesoscale ocean manipulation experiments on the impacts of iron additions suggest that this approach might be useful for studying other aspects of ocean biogeochemistry and ecosystems. Additional experiments are still needed to study the effects of iron on carbon export from different ecosystem types and to study the ecosystem effects of iron (e.g., species successions and biodiversity effects) and how iron-enrichment feeds back to the atmosphere (an area of particular interest to SOLAS). Similar approaches with other limiting micronutrients (e.g., Zn, Mn, Cu and Mo) could help us better understand the role of these elements in marine systems. Other manipulation experiments might be used to study

- how macronutrient concentrations and ratios change the abundance of individual species and functioning of marine ecosystems;
- effects of low oxygen on ocean biogeochemical cycles and ecosystems ;
- effects of sustained pH decreases on biogeochemistry and ecosystems (this may require the construction of large-scale artificial ecosystems);
- effects of CO_2 enrichment, such as through a marine analogue to the "Free Air CO_2 Enrichment" (FACE) experiments carried out by the terrestrial research community. Preferable sites would include coral reef and $CaCO_3$-dominated shelf ecosystems. A

mesoscale open ocean CO_2 or acidity enrichment experiment should be considered by IMBER and SOLAS to overcome the inherent limitations of laboratory and mesocosm experiments;

- top-down, bottom-up, and “wasp waisted” controls in ecosystems. There may be opportunities to combine nutrient addition and predator exclusion studies in mesocosms or large-enclosed ocean areas to study these control factors; and
- triggers of blooms of specific types of phytoplankton and zooplankton species.

Such manipulation studies will be very useful for testing the level of our understanding about how biogeochemical cycles and ecosystems work.

Palaeoceanography

The importance of palaeoceanography to the IMBER project is demonstrated by its integration throughout this document. Effective use of data from palaeoceanographic studies allows the extrapolation of our relatively short time series backward through time and to separate the effects of environmental variability versus directional changes, as well as to facilitate the separation of natural versus anthropogenic changes. Such backward extrapolation is necessary to allow development of models to predict the potential effects of global change on future ocean biogeochemistry and ecosystem states. These goals can only be achieved if accurate and understandable proxies of important variables are available. Particularly important for IMBER purposes will be palaeo-proxies that allow us to understand how the physical, chemical, and biological environment affect ocean biogeochemistry and ecosystems. Examples include palaeo-proxies for understanding

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

Multiple proxies are needed to reveal synchronous variations in biogeochemical and ecosystem parameters.

Development of palaeo-proxies will require laboratory experiments and testing of correlations on samples from sediment cores, corals, and perhaps other sources. Biologically important isotopes, trace metals, and unusual remnant organic molecules (“biomarkers”) should be explored. If possible, new proxies should be related to existing proxies whose behaviour is well understood. IMBER will work with IMAGES and other groups, such as the two relevant SCOR/IMAGES working groups, to advance the availability of useful palaeo-proxies.

Data Management

The collective value of data is greater than its dispersed value. The development of an appropriate IMBER data management plan is a fundamental and critical activity upon which the ultimate success of IMBER will depend. Data management and exchange are therefore important components of IMBER research projects and should be addressed by each proposed IMBER activity.

To ensure effective data management within the IMBER project a small IMBER Data Management working group will be formed. The first task for this group will be to develop a data management policy and plan for the project based on the recommendations by the SCOR/IOC Meeting on Data Management for International Marine Research Projects held in Liverpool in December 2003 (Appendix 2). The working group will also have an ongoing role in IMBER, assisting IMBER activities and the IMBER international project office (IPO) with data management issues.

Synthesis and Modelling

Process studies, sustained observations and modelling have progressed tremendously over the past decade. It is now crucial to link these three complementary research approaches in a continuous, coherent, and synthesised manner. In the long term, reliable prognostic ocean models including biogeochemical cycles and ecosystems are required to predict the impact of global change on the ocean as a component of the Earth System. Such models critically depend on the continued existence of observational data and process studies, which contribute to model development, diagnosis, evaluation, and validation.

Models provide a suite of tools to investigate hypotheses, analyse and extrapolate data both in space and time, help gather data efficiently through observational system simulation experiments, and last, but not least, identify crucial gaps to be filled by new observations and research to reduce uncertainties in our knowledge. To achieve such interactions, a synthesis and modelling framework must be set up and active from the beginning of the IMBER project to integrate knowledge and to refine the implementation strategy.

To accelerate progress in IMBER-relevant models, we need to encourage innovation in biological, geochemical, and physical modelling. Improvements are likely come from recent progress in

- the reconstruction and forecast of space and time variability of physical ocean states made by CLIVAR and GODAE communities;
- identifying nutrient sources and sinks, including both macro- and micronutrients, the remineralisation loop, and exchanges with continental margins, sediments and the atmosphere;
- functional group representations, for key microbial and phytoplankton species, allowing simulation of both quality and quantity of food as well as the export of organic carbon and the production of gases by organisms;
- understanding trophic level interactions, leading to coupling of life-history GLOBEC-type models for large feeders (mesozooplankton or small fish) to generic non life-history JGOFS-type models developed for primary producers and microbial processes.

Model hierarchy will need to range from diagnostic models for hindcast and nowcast purposes, to prognostic models for forecasting ocean conditions. These models can be of different complexity in both their mathematical framework and in their biogeochemical and ecosystem representation, as needed for addressing a particular question. Their spatial coverage should range from global scale to regional scale, using various coupling or nesting schemes to ensure propagation of non-linear perturbations within the different components. This point is particularly important to address open ocean-ocean margin coupling, as well as benthic-pelagic interactions, from synoptic events to decadal and global change time scales. As an example, IMBER will greatly benefit from modelling initiatives already underway, such as Green Ocean Modelling (plankton functional group approach for primary producer), the SCOR-IOC Basin Scale Modelling Group, and the Climate Impacts on Oceanic Top Predators project (CLIOTOP) approaches to end-to-end food web modelling.

In addition to several coordinated, high-resolution modelling activities based on research and operational oceanography, we need computationally economic and process-oriented intermediate complexity models that are easy to use and readily available to both modellers and observationalists in the research community. Furthermore, simplified versions of first-order process-based models will play an essential role for the development of Earth System Models of Intermediate Complexity (EMIC) in cooperation with the Global Carbon Project (GCP) and the GAIM project. Such models will likely be the primary tool for assessing the impact of human activities on the Earth System, and thus the potential feedbacks to human societies. Model development and research should be an iterative processes; good models will suggest what is needed from observations and good observations will help refine models.

It must recognised that continuous synthesis of the available information can only be achieved if interconnected databases are constructed, quality controlled, shared in a common format and updated in near real time, jointly for biological, geochemical, and physical variables. As IMBER covers time scales up to decades and longer, systematic data mining (including estimated uncertainties) will be strongly encouraged, with ocean biogeochemical reanalyses as one of the goals. Over millennial time scales, high-density sampling and synchronised palaeo-proxies are critical, as well as development of new palaeo-proxies. Collating and quality controlling data from various sources remains a daunting task for modellers which must be addressed. For new observations, clear procedures and protocols for data quality control and dissemination are at the heart of an emerging sustained observing system for marine biogeochemistry and ecosystems. These activities must be developed in close cooperation with GOOS.

Assimilation of biogeochemical and biological data into models should be encouraged following the strategy developed primarily by meteorology and now by operational oceanography (e.g., GODAE). It is envisioned that in the long term, as ocean modelling becomes operational, the most successful systems will be selected and further developed by explicitly adding biology and biogeochemistry. In addition to these operational systems, diagnostic models will continue to play a major role in addressing research questions associated with network optimisation, parameter estimation studies, etc. New mathematical and conceptual approaches to quantify and model biodiversity, trophic interactions, and impact of global change on food web dynamics and human dimensions will be important for IMBER research.

Overall, an important benefit that will emerge from the use of such a synthesis and modelling framework is that it will provide, through analysis of the misfit between models and observations, a formal way to evaluate the quality and quantity of the data, to assess the adequacy of the processes implemented in the models, investigate the overall quality and validation of the model structure, and most importantly, to enhance our ability to predict the impact of global change scenarios on marine biogeochemistry and ecosystems. The models developed must remain flexible, to make optimal use of new data streams, new parameterisations, and new developments in the mathematical concepts of non-linearity and inverse/assimilation schemes.

Project Organisation and Management

Scientific Steering Committee

The IMBER Scientific Steering Committee (SSC) is responsible for providing scientific guidance and overseeing the development, planning, and implementation of the IMBER project. Figure 20 gives a proposed structure for IMBER management. The SSC will facilitate the publication of IMBER scientific findings, and will encourage active communication among IMBER activities. The SSC will encourage national governments, and regional and international funding agencies to support IMBER research and (in conjunction with the sponsors) will seek funding to support the infrastructure of IMBER. The SSC will facilitate active collaboration between IMBER and other relevant projects and programmes to ensure the goals of IMBER are met. The first task of the SSC will be to respond to reviewers' comments to produce the final Science Plan and Implementation Strategy.

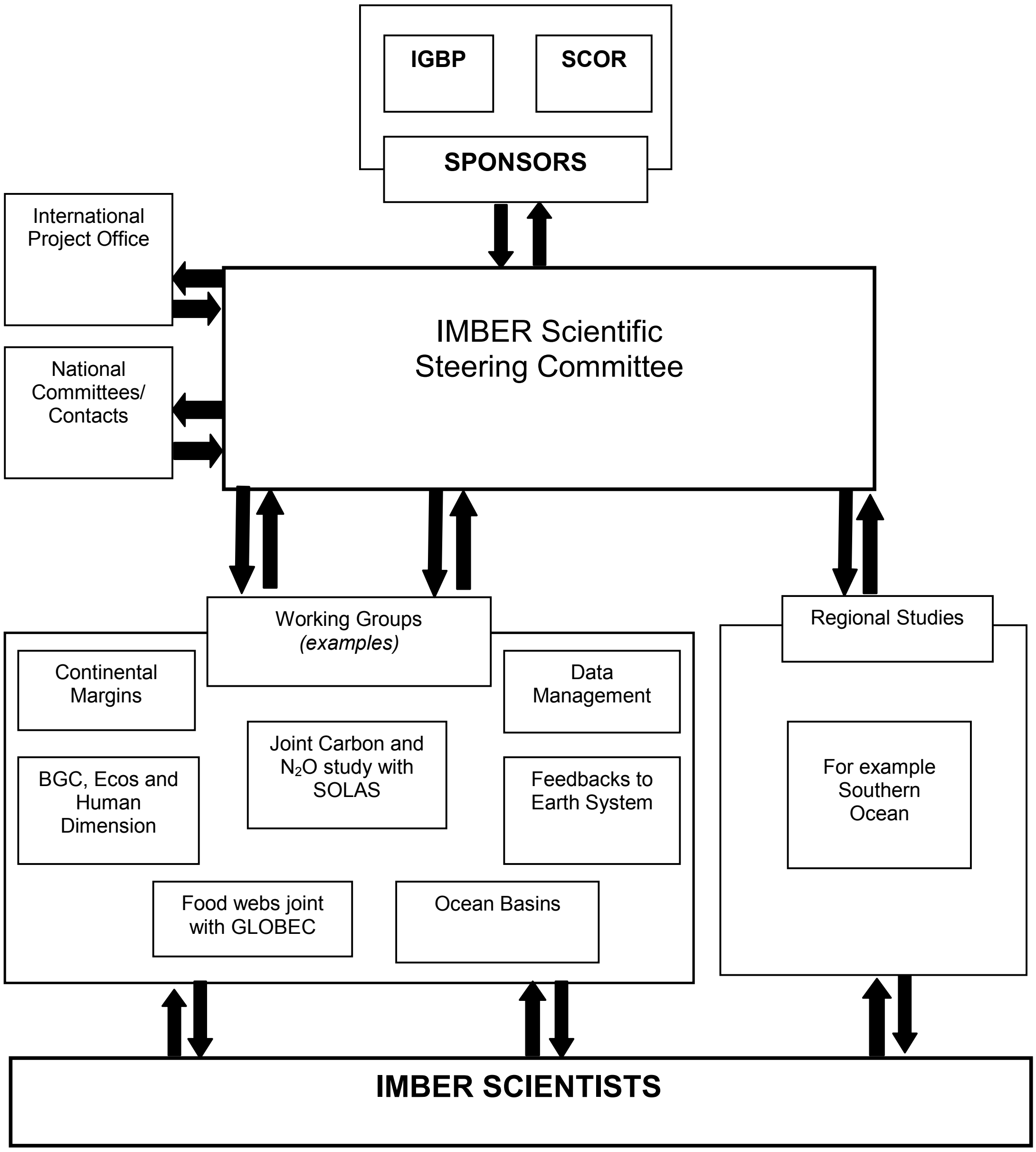

Figure 20. Organisational Structure of IMBER

Working Groups

The implementation of IMBER will be facilitated by working groups, who will focus on implementing aspects of IMBER research. Several key working groups have been identified. These include

- a food web working group, which will be joint with GLOBEC, with co-chairs from each project. This working group will facilitate collaborative research of IMBER and GLOBEC focus on end-to-end food webs;
- a data management working group which will be responsible for data management policy and procedures and will involve data managers, providers, all users; and a carbon and N_2O working group which will be joint with SOLAS and will focus on the seamless implementation of carbon and N_2O in the two projects.

Each working group will have a chair or co-chairs responsible for reporting activities of the group to the SSC on a regular basis. The need for further working groups and the lifetime of the working groups will be decided by the SSC and will vary depending on the focus of the working group and the development of the project.

Regional Projects

The development of regional projects, including time-series and process studies, will be encouraged as a mechanism for implementing global IMBER research in regions of special interest. The regional projects will be encouraged to develop implementation plans to facilitate collaboration and communication between individual and national projects in the region. The SSC will encourage the participation of regional bodies (e.g., International Council for the Exploration of the Seas *(*ICES) and North Pacific Marine Science Organisation (PICES)) in the development and implementation of these projects. The chairs of regional projects will be responsible for reporting to the SSC.

International Project Office

The IMBER SSC, in conjunction with the co-sponsors, will seek financial support for an International Project Office (IPO) for the IMBER project. The IPO will provide day-to-day administrative support for IMBER and support for all SSC activities. The IPO will have a major role in seeking financial support for IMBER activities, facilitating communication both within and outside the project, and ensuring effective data management and archiving of information for the project. The IMBER IPO will be co-located with the GLOBEC IPO: if possible, to assist the two projects work toward a single project after GLOBEC is completed in 2009. The IPO will also be responsible for working with the SSC to ensure that the IMBER project provides a wide range of products to the science community and keeping a record of these products. These are likely to include, books, special journal issues, synthesis papers, and Open Science Conferences. The production of outreach materials aimed at the wider community will also be important and are likely to include books, brochures, science highlight articles, newsletter articles, and an effective Web site.

National Committees and Contacts

There is broad worldwide interest in the IMBER project, with 36 countries being represented at the OCEANS Open Science Conference in Paris in January 2003. To ensure wide international participation in the project, the IMBER SSC will encourage the formation of national committees to support the development and coordination of the IMBER project. National committees will be encouraged to promote and seek funding for IMBER research. They will play an important role in IMBER by coordinating research and communication within countries. National committees will be requested to evaluate projects for recognition as IMBER projects and provide recommendations to the IMBER IPO for consideration by the SSC. These committees will be asked to have clear links with national IGBP and/or SCOR committees in countries where they exist, as these committees will be instrumental in setting up and supporting the national IMBER committees in many countries. In countries where there is not a national IMBER committee, the SSC will seek a national contact person for the project to facilitate communication with the scientific community and may approach this person to form a national IMBER committee if appropriate. Strong and effective national committees will be crucial for IMBER as virtually all research and observation systems are implemented using national funding.

Recognition of IMBER Research

The aim of the IMBER Science Plan and Implementation Strategy is to provide a framework to encourage participation of regional, national and individual research efforts in the IMBER project. Research efforts can be submitted for recognition as IMBER projects. This will ensure that (a) the IMBER SSC knows what research is being conducted under the IMBER label, (b) research carrying the IMBER label falls within the science themes identified in this document, and (c) such research conforms to the scientific approaches outlined in this document, and (d) a data management plan is in place for the activity.

International/regional research groups can submit their project for recognition by the IMBER SSC via the IMBER Web site. National groups and individual Principle Investigators (PIs) should first work through their national IMBER committees or representatives, who in turn will present the application to the international SSC. If the PI or group is from a nation without an IMBER national committee or other formal representation, they may apply directly to the IMBER SSC. Projects seeking recognition from multiple IGBP/SCOR projects are welcome, as the IMBER SSC recognises that many national/regional activities will contain research objectives relevant to more than one project.

The following is a guide to the benefits to, and responsibilities of, recognised projects (adapted from GLOBEC and SOLAS).

Benefits

- Provides the opportunity for participation in the development, planning, and implementation of a collaborative, internationally recognised programme;
- Adds to the scientific value of planned research by providing complementary information, for example, by widening the range of studies and extending their spatial and temporal coverage;
- Promotes rapid communication of ideas and results through meeting and project publications;
- Develops and tests standard methods and protocols for measuring variables, thereby facilitating quality control and meaningful data sharing;
- Makes available data sets collected in component studies and develops a common data management strategy; and
- Enables close working links with other relevant international programmes and projects.

Responsibilities

- Accept general principles and goals outlined in the IMBER Science Plan and Implementation Strategy (this document);
- Carry out a programme in general accordance with the relevant aspects of the IMBER Science Plan and Implementation Strategy;
- Participate in the activities of the project through management bodies, and by assisting in its planning and development as a whole;

- Make data collected within the project available to the wider community, in accordance with the IMBER data policy (to be developed);
- Acknowledge the links with IMBER in the products of the project (e.g., acknowledgement in scientific papers); and
- Assist in the provision of central project services, for example, data management.

Education

The success of IMBER will depend on the participation of scientists from a wide range of regions and scientific disciplines. To achieve a high level of participation it will be important to address a variety of issues, including developing effective ways of interaction and communication between scientists of widely differing disciplines, enhancing knowledge and skills of scientists and students from developing regions, and assisting graduate students to develop interdisciplinary skills. To achieve the required increase in scientific capacity a range of approaches will be required. The SSC will seek financial support for specific training workshops and Web-based training, and will encourage activities such as the exchange of scientists and graduate students between institutions, the development of a summer school similar to the successful SOLAS Summer School, and the provision of berths on cruises for developing country scientists and graduate students.

The IMBER SSC will hold meetings and workshops in a variety of regions to encourage and facilitate broad national and regional participation in IMBER activities and will work with Global Change System for Analysis, Research and Training (START) to develop appropriate training activities in developing regions. The IMBER SSC will also investigate community participation in the project by assessing how local community groups may be able to provide data for the project.

Communication

Clear and effective communication, both within and outside the IMBER project, will play a significant role in the successful implementation of IMBER. The IMBER Web site will be a central source of information, including key planning documents, contact information, and reports of scientific highlights and research activities. It will also serve as a link to working groups and to national and regional activities, and as a portal to IMBER data sets.

Ensuring effective two-way communication between national and regional activities, the SSC, working groups, and the IPO will be an important component of the IMBER communication strategy. Communication with the IMBER science community and with other interested scientists will be facilitated through publication of scientific papers, newsletters and electronic bulletins.

The detailed scientific results of IMBER research will be published primarily in scientific journals. However, it will also be important to ensure that the results of IMBER research are accessible to a broad audience including policy makers, resource managers, teachers, and the public. The IMBER SSC will facilitate the production of appropriate synthesis documents for this broad audience and will encourage IMBER researchers to make their findings available in widely accessible form.

Linkages with Other Projects and Programmes

The IMBER project is being developed in the context of ongoing and new projects sponsored by IGBP, SCOR, IOC, and other organisations. IMBER will develop collaborative activities, which will draw on the expertise of these projects and programmes and will avoid unnecessary duplication. The relationships with these projects and programmes are detailed below (Figures 21 and 22).

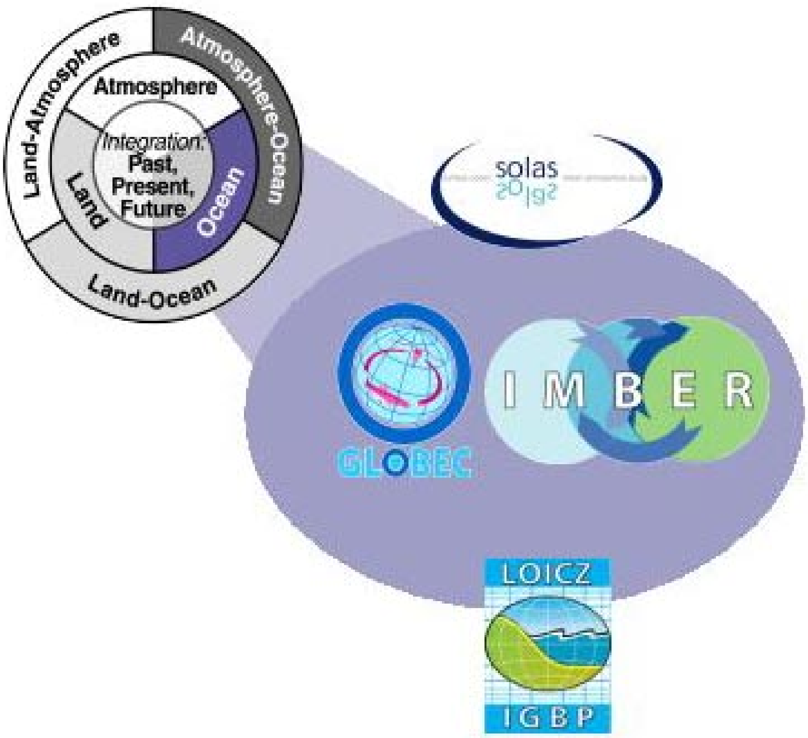

Figure 21. Relationships of IMBER to other IGBPII projects in marine research.

Interaction with IGBP/SCOR Marine Projects

Global Ocean Ecosystems Dynamics (GLOBEC)

GLOBEC is a joint IGBP/SCOR/IOC project running for the period 1999-2009. The primary goal of GLOBEC is "*to advance the understanding of the structure and functioning of global ocean ecosystems, its major subsystems, and its response to physical forcing so that a capability can be developed to forecast the responses of marine ecosystem to global change*". The core activities of most of the regional and national GLOBEC programmes are focussing on the interaction between zooplankton and fish, their trophic interactions, and how this interaction is influenced by ocean climate and physical factors. Some of the activities, however, focus on a broader range of ecosystem components, such as the Southern Ocean GLOBEC, which also studies trophic dynamics at lower levels than zooplankton, up to marine mammals and seabirds.

Together, the scientific approaches of IMBER and GLOBEC will cover the entire range of trophic levels of marine ecosystems integrating the food web from end to end (Figure 23). This will be a joint activity, with IMBER concentrating on the lowest trophic levels up to zooplankton, GLOBEC focusing mainly from the level of zooplankton to top predators. After GLOBEC's completion in 2009, GLOBEC and IMBER scientists will continue this work. The collaborative activities of the two projects must address the interaction between phytoplankton and zooplankton and how this interaction is influenced by physical processes and biogeochemical cycles. This research has not been pursued in any other past or present large-scale ocean research project. Remineralisation processes will be addressed by IMBER in relation to the entire spectrum of trophic levels.

IMBER and GLOBEC have slightly different approaches with respect to types of measurements, measuring techniques and spatio-temporal measuring intervals, because of the different sizes of organism of central interest to each. The collaboration should emphasize process-oriented studies in the field and in mesocosms. Modelling is another area for collaborative activity. An important modelling focus in GLOBEC is individual-based models/circulation models for growth, transport, and survival of zooplankton and larval fish. Individual-based models for copepods are now being developed. However, more work is needed to develop integrated trophodynamic models from phytoplankton to fish. This significant research challenge needs joint work from both the IMBER and the GLOBEC communities.

IMBER and GLOBEC both have high-latitude and polar ocean areas as one of their regional foci, and joint work is already underway and being planned in the Southern Ocean. Another potential joint regional programme between IMBER and GLOBEC is Climate Impacts on Oceanic Top Predators (CLIOTOP), which links phytoplankton, physics and fish in the tropical Oceans.

In summary, GLOBEC and IMBER will work together in joint scientific activities in some regions, in research focussed on end-to-end integration of marine food webs and in ecosystem modelling. The Scientific Steering Committees of IMBER and GLOBEC will form a joint working group to plan integration in areas of shared scientific interest.

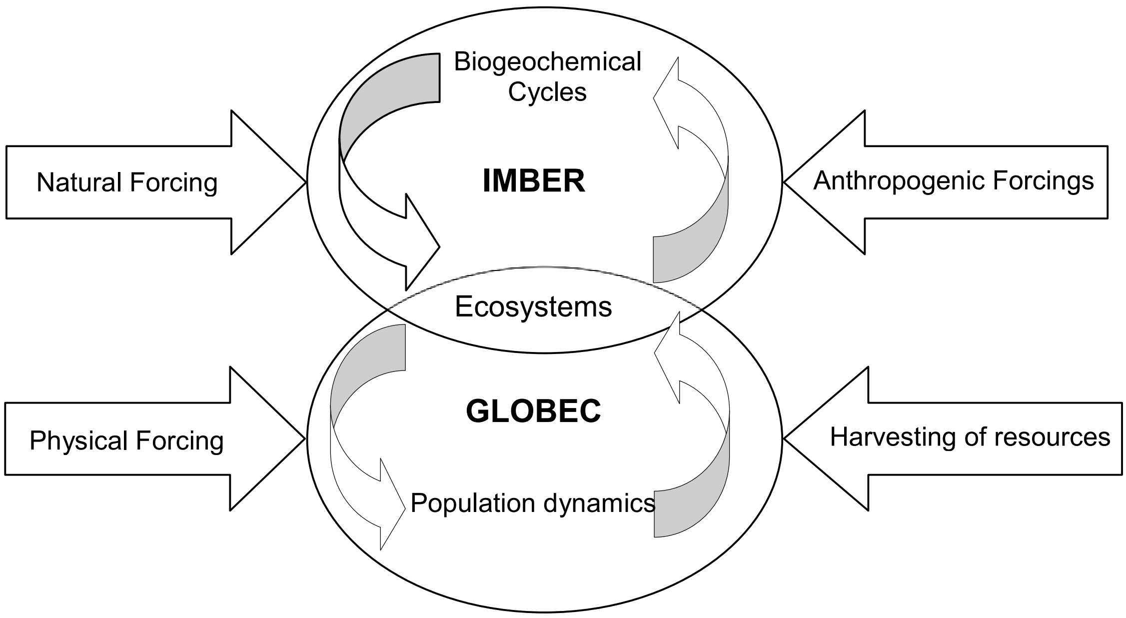

Figure 22. Linkage between IMBER and GLOBEC.

Interaction with IGBP/SCOR Interface Projects

Surface Ocean – Lower Atmosphere Study (SOLAS)

SOLAS is a joint IGBP/SCOR/CACGP/WCRP project, which has as its goal *“To achieve quantitative understanding of the key biogeochemical, physical interactions and feedbacks between the ocean and atmosphere and of how this coupled system affects and is affected by climate and environmental change.”* SOLAS research is centred on three foci: (1) Biogeochemical interactions and feedbacks between ocean and atmosphere; (2) Exchange processes at the air-sea interface and the role of transport and transformation in the atmospheric and oceanic boundary layers; (3) Air-sea flux of CO_2 and other long-lived radiatively active gases.”

Close collaboration between IMBER and SOLAS will be important, particularly in regard to Foci 1 and 3 of SOLAS. To ensure a close and effective collaboration between the two projects in the area of oceanic carbon cycle research, IMBER and SOLAS will develop a joint implementation plan, with SOLAS focussing on the flux of CO_2 between the ocean and atmosphere, and the processes in the euphotic zone that control this flux. In a complementary way IMBER will focus on the carbon cycle in the euphotic zone looking downward (Table 2). The two projects will also jointly implement science activities on N_2O, with SOLAS focussing on surface ocean production, air-sea exchange and climatic impacts, and IMBER focussing on the sediment/water interface, deep production, and transport into the surface ocean.

Table 2. IMBER role in Ocean Carbon Research, in Relation to Other IGBP Projects.

Topic	IMBER Role	Project Links
Vertical and Horizontal fluxes in the ocean	Major	SOLAS
Continental Shelf/Open Ocean exchange	Major	SOLAS/LOICZ
Benthic/Pelagic Coupling	Major	LOICZ
Continental margin carbon cycling	Shared	LOICZ/SOLAS
Carbon fixation/respiration and vertical transport	Major	SOLAS
Food web Dynamics	Major	GLOBEC
Anthropogenic carbon accumulation	Shared	SOLAS/LOICZ
pH and ecosystems	Shared	SOLAS
Temperature effects on photosynthesis and respiration	Major	SOLAS
Impact of macro/micronutrient relationships on vertical export and ecosystems	Major	GLOBEC/SOLAS

Land-Ocean Interactions in the Coastal Zone (LOICZ)

LOICZ is the IGBP II project at the intersection of land and ocean. The goal of LOICZ is to ***“****determine at regional and global scales the dynamic nature of interaction between land, ocean and atmosphere and how changes in various components of the Earth system are affecting coastal zones and altering their role in global cycles.”* This enables assessment of how future changes in coastal areas will affect their use by people and provides a sound scientific basis for future integrated management of coastal areas on a sustainable basis.

LOICZ has identified five themes for the next ten years of its research. These are

1) River basin deliveries to the coastal zone and human dimensions
2) Coastal development and change; implications of land and sea use
3) Fate and transformation of materials in coastal and shelf waters
4) Vulnerability of coastal systems and human safety
5) Towards system sustainability and coastal zone management

The theme "Fate and transformation of materials in coastal and shelf waters" is the research area of LOICZ that mostly closely relates to IMBER. It will be important for IMBER and LOICZ to collaborate in continental margin research. To facilitate this linkage, the leader of LOICZ Theme 3 will be a full member of the IMBER Continental Margins working group and the LOICZ Chair will be an ex-officio member of the IMBER SSC. IMBER will seek funding to hold a joint workshop with LOICZ and Coastal GOOS to develop a detailed implementation plan for continental margin research.

Interaction with IGBP Integration Projects

Past Global Changes (PAGES)/International Marine Past Global Changes Study (IMAGES)

The PAGES goals are *"to provide a quantitative understanding of the Earth's environment in the geologically recent past and to define the envelope of natural environmental variability against which anthropogenic impacts on the Earth System may be assessed*."

IMAGES is the component of PAGES most relevant to IMBER, because of the focus of IMAGES on palaeo-oceanography based on marine sediment coring. Palaeoceanographic information and long-term observations provide key information on different biogeochemical states of the ocean and their temporal and geographic scale of variability. These same data, together with modelling efforts, provide the possibility of identifying key mechanisms driving changes. Substantial effort is needed to develop the use of effective proxies for the quantitative representation of past conditions. This proxy-based approach requires rigorous calibration against direct observations; thus, a fruitful integration between palaeoceanography and ocean biogeochemistry must be an objective of future IMBER/PAGES collaboration. Collaborative activities will be identified, including identifying potential new proxies, improving proxy calibration, and establishing useful chronometers. Participation by the major international projects concerned with obtaining and interpreting sediment cores, in particular IMAGES and International Ocean Drilling Programme (IODP), is expected. Combining the insights developed by observations and modelling will be a vital component of this collaboration.

Global Analysis, Integration and Modelling (GAIM)

GAIM is an integrative Earth system analysis project with the goal to *"advance the study of the coupled dynamics of the Earth system using as tools both data and models".*

IMBER will collaborate in the future modelling frameworks, which will treat the Earth as a system in which biogeochemical and ecosystem interactions and their feedbacks to the Earth System are considered in conjunction with GAIM. Common interests in evolving computer technologies and computational techniques should be used by IMBER and GAIM to examine the role of the ocean in defining the relations between global climate variability/predictions, biogeochemistry, and ecosystem feedbacks.

Interaction with Earth System Science Partnership Programmes

WCRP/Climate Variability and Prediction (CLIVAR)

CLIVAR is a project of the WCRP with the specific objectives to

> "a) *describe and understand the physical processes responsible for climate variability and predictability on seasonal, interannual, decadal, and centennial time scales, through the collection and analysis of observations and the development and application of models of the coupled climate system, in cooperation with other relevant climate research and observing programmes*;
> b) *extend the record of climate variability over the time scales of interest through the assembly of quality controlled palaeoclimatic and instrumental data sets*;
> c) *to extend the range and accuracy of seasonal to interannual climate prediction through the development of global coupled predictive models; and*
> *d) understand and predict the response of the climate system to increases of radiatively active gases and aerosols and to compare these predictions to the observed climate record in order to detect the anthropogenic modification of the natural climate signal."*

CLIVAR has an organisational structure in place, with many of the observational and modelling/synthesis activities already planned. As the IMBER Science Plan and Implementation Strategy evolves, specific efforts must be made to develop linkages into the three streams of CLIVAR, namely the Global Ocean Atmosphere Land System (GOALS), Decadal-to-Centennial activity (DecCen), and Anthropogenic Climate Change (ACC) activities (http://www.clivar.org), and, in particular, CLIVAR's ocean basin panels, so that activities can be blended to avoid duplication of organisational and planning efforts.

IMBER must collaborate closely with CLIVAR on the CLIVAR Repeat Hydrography/CO_2 Lines (Sabine and Hood, 2003). To ensure there is close and effective collaboration IMBER will take responsibility for coordinating the biogeochemical measurements on the CLIVAR Repeat Hydrography Lines. This coordination will be implemented through appropriate membership of the CLIVAR Basin Panels in association with the SCOR-IOC advisory panel on CO_2/GCP International Ocean Carbon Coordination Project.

Various modelling activities in CLIVAR must be considered in detail to identify commonalities that will allow the physical, biogeochemical, and ecosystem modelling needs of IMBER to be addressed to avoid duplication. Common interests in evolving computer technologies and computational techniques should be used by IMBER and CLIVAR to translate climate variability and climate change predictions into biogeochemistry and ecosystem responses and feedbacks. There is also a strong interest for both CLIVAR and IMBER to use data from operational oceanography (in particular GODAE), and in the common definition of ongoing analyses of the climate system. IMBER will consider coordinated activities, in regions and processes that CLIVAR activities are investigating, so that the best possible use of limited resources available for sustained observations can be made (e.g., Time Series Stations, Repeat Hydrography Lines). The interdisciplinary nature of IMBER science necessitates that the organisational structure of IMBER involve members and representatives of the CLIVAR community, where appropriate.

DIVERSITAS

DIVERSITAS, an international programme of biodiversity science, has as its mission statement *"promote integrative biodiversity science, linking biological, ecological and social disciplines in an effort to produce socially relevant new knowledge; and to provide the* *scientific basis for an understanding of biodiversity loss, and to draw out the implications for the policies for the conservation and sustainable use of biodiversity".*

To ensure effective collaboration on biodiversity studies, IMBER will develop project elements relating to biodiversity in concert with DIVERSITAS, using as a model for this coordination the ongoing relationship between DIVERSITAS and the Land Use and Cover Change (LUCC) project of IGBP LAND. That is, DIVERSITAS and IMBER will agree upon a liaison scientist (i.e., a marine biodiversity researcher), who would serve on the DIVERSITAS SSC and the IMBER SSC, and who will be responsible for leading and coordinating marine biodiversity research within IMBER, consistent with the science plans of both programmes.

This structure will ensure that responsibility is shared between IMBER and DIVERSITAS for developing research priorities. The initial intention is that DIVERSITAS will lead the implementation of specific activities, to be developed through workshops and research proposals. These should reflect the science and implementation priorities of IMBER and be consistent with the most pressing issues in biodiversity research, as defined by DIVERSITAS. This coordination is anticipated to be an opportunity for DIVERSITAS, which is still in the early stages of developing marine activities, and will also benefit IMBER, which needs the theoretical foundations of 'state of the art' biodiversity research from DIVERSITAS.

International Human Dimensions Programme on Global Environmental Change (IHDP)

The goal of the International Human Dimensions Programme on Global Environmental Change (IHDP) is *"to describe, analyse and understand the human dimensions of global environmental change".*

Collaboration with IHDP, particularly the Institutional Dimensions of Global Environmental Change (IDGEC) project, will be critical to the development and success of Theme 4 of IMBER. There are areas of joint interest and potential for development of a joint IDGEC and IMBER workshop to identify the key questions to be addressed in Theme 4 and to develop an implementation plan for this work.

Global Carbon Project (GCP)

The Global Carbon Project of IGBP, IHDP and WCRP has developed a research framework for the synthesis of the global carbon cycle cycle data and models. It also assists in the coordination of national programs for global-scale carbon research and facilitates the coupling of carbon research between the natural sciences and the social sciences. It is important that there is an effective collaboration and communication between IMBER and GCP to ensure data and research results from IMBER are integrated into the GCP synthesis.

Interaction with other SCOR Projects

Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB)

The Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) programme, sponsored by SCOR and IOC, has as its goal *"improving prediction of Harmful Algal Blooms (HABs) by determining the ecological and the oceanographic mechanisms underlying their population dynamics, integrating biological, chemical, and physical studies supported and enhanced observation and modelling systems".*

IMBER and the GEOHAB programme have common interests in biogeochemical cycles and ecosystem interactions, particularly in the continental margins region, and how ocean physics, chemistry, and biology control phytoplankton population dynamics. It will be important to both IMBER and GEOHAB that data and scientific results can be shared between the two projects. Mechanisms for achieving this goal are being identified through collaboration of both projects in the development of a common data management strategy for IGBP/SCOR marine projects. IMBER will also seek to develop cooperative research with GEOHAB on controls of phytoplankton population dynamics. GEOHAB's core Research Project on HABs in Upwelling Systems could be a particularly fruitful area for joint work.

International Ocean Carbon Coordination Project (IOCCP)

The International Ocean Carbon Coordination Project (IOCCP) is a joint pilot project of GCP and the SCOR/IOC Advisory Panel on Ocean CO_2. IOCCP was developed in response to scientific and societal interest in understanding and quantifying global reservoirs and fluxes of ocean carbon, with particular attention to its interactions with the terrestrial and atmospheric carbon cycles. With JGOFS ending, ocean carbon research and observations will now be carried out in a number of national and international programmes and projects (e.g., CLIVAR, IMBER, SOLAS, and miscellaneous underway, drifter, or mooring-based pCO_2 monitoring programs).

IOCCP is a coordination mechanism to compile program information and plans, and to address cross-cutting issues common to all ocean carbon research and observation activities, such as methods and best practices, standards, reference materials, data formats, quality control/quality assurance practices, and data synthesis activities. These activities will be addressed through targeted workshops and in close cooperation with the international and regional research programs. IOCCP is also providing a central communications centre through development of a Web site (http://www.ioccp.org) with up-to-date information on repeat lines, underway measurements, time series, and other observation programs as well as modelling and data synthesis groups and projects.

IMBER will be an active cooperating partner in IOCCP to avoid duplications and highlight areas for potential collaboration with other ocean carbon research projects. IMBER and IOCCP will work together to ensure compatibility of ocean carbon data management activities and to encourage data sharing.

GEOTRACES

GEOTRACES is a SCOR sponsored planning group. Its primary objectives are to:

- determine global distributions of selected trace elements and isotopic tracers (TEIs) in the ocean;
- evaluate the oceanic sources, sinks, and internal cycling of TEIs and thereby characterise more completely their global biogeochemical cycles; and
- build and maintain a core community of marine scientists who understand the chemical, physical and biological processes regulating the distribution and properties of trace elements and isotopes well enough to exploit them reliably in future interdisciplinary studies.

The unifying research strategy of GEOTRACES is to develop a global suite of basin-scale sections of trace element distributions, complemented by process studies at key locations in order to better understand the factors controlling the sources, sinks, and internal cycling of trace elements.

Data collected in the GEOTRACES project will be important in addressing IMBER research on understanding biogeochemical cycles and the basin scale distribution of trace elements. In particular, research undertaken by GEOTRACES will be a critical contribution to the implementation of the research to be undertaken in Theme 1, Issue 1 of the IMBER project. IMBER and GEOTRACES will investigate the development of joint studies and field activities. To ensure effective communication between IMBER and GEOTRACES, the Chair of GEOTRACES will be an ex-officio member of the IMBER SSC.

Ocean Observing Programmes

Global Ocean Observing System (GOOS)

The identification of sustained observations as an important component of the IMBER research strategy means that a close collaborative interaction with the Global Ocean Observing System (GOOS) will be important to the success of IMBER.

GOOS is conceived as:

- *"a sustained, coordinated international system for gathering data about the oceans and the seas of the Earth,"*
- *"a system for processing such data, with other relevant data from other domains to enable the generation of beneficial, analytical and prognostic environmental information services, and'*
- *"the research and development on which such services depend for their improvement."*

GOOS has been designed to serve the needs of the research community as well as the needs of a wide range of other end users. GOOS relies on the collection of data from existing observing subsystems, many of which or parts of which, like the Argo profiling float programme, for example, are funded at least partially from research budgets.

GOOS is being designed and planned by two panels, the Ocean Observation Panel for Climate (OOPC), which focuses primarily of physical observations of the open ocean to support climate predictions and ocean and weather services, and the Coastal Ocean Observing Panel (COOP) which is focused on physical, biological, and chemical measurements in the coastal region and biological observations in the open ocean. IMBER must interact with GOOS, both as an end user of data collected by GOOS and as a partner with GOOS in identifying the variables to be measured and the research and development needed to improve the observing system. IMBER and the two advisory panels of GOOS (OOPC and COOP) and the IGOS Steering Committee need to identify mechanisms to enable effective communication and interaction between IMBER and GOOS.

Appendix I - Acronyms

Acronym

ACC	Anthropogenic Climate Change
AUV	autonomous underwater vehicle
BATS	Bermuda Atlantic Time-series Study
CACGP	Commission on Atmospheric Chemistry and Global Pollution
CLIVAR	Climate Variability and Prediction (WCRP)
COOP	Coastal Ocean Observing Panel
DecCen	CLIVAR Decadal-to-Centennial activity
DIC	dissolved inorganic carbon
DIN	dissolved inorganic nitrogen
DIVERSITAS	International programme of biodiversity science
DOC	dissolved organic carbon
DOM	dissolved organic matter
DON	dissolved organic nitrogen
DPSIR	Driver-Pressure-State-Impact-Response
EEA	European Environment Agency
EisenEx	Southern Ocean Iron fertilisation Experiments
EMIC	Earth System Models of Intermediate Complexity
ENSO	El Niño-Southern Oscillation
FACE	Free Air CO_2 Enrichment
FISH	Fluorescent In Situ Hybridisation
GAIM	Global Analysis, Integration and Modelling
GCP	Global Carbon Project
GEOHAB	Global Ecology and Oceanography of Harmful Algal Blooms
GEOTRACES	A collaborative multi-national programme to investigate the global marine biogeochemical cycles of trace elements and their isotopes
GLOBEC	Global Ocean Ecosystem Dynamics
GOALS	Global Ocean-Atmosphere-Land Study
GODAE	Global Ocean Data Assimilation Experiment
GOOS	Global Ocean Observing System
HNLC	high-nutrient low-chlorophyll
HABs	harmful algal blooms
HOT	Hawaii Ocean Time Series
ICES	International Council for the Exploration of the Seas
ICSU	International Council for Science
IHDP	International Human Dimensions Programme of Global Environmental Change
IGBP	International Geosphere-Biosphere Programme
IGOS-P	Integrated Global Observing Strategy Partnership
IMAGES	International Marine Past Global Changes Study
IMBER	Integrated Marine Biogeochemistry and Ecosystem Research
IOC	Intergovernmental Oceanographic Commission
IOCCG	International Ocean Colour Coordinating Group
IOCCP	International Ocean Carbon Coordination Project
IODP	International Ocean Drilling Programme
IPCC	Intergovernmental Panel for Climate Change
IPO	International Project Office
IronEx	Iron Experiment
JGOFS	Joint Global Ocean Flux Study
KNOT	Kyodo North Pacific Ocean time-series station
LAND	New IGBP Land project
LOICZ	Land-Ocean Interactions in the Coastal Zone
LUCC	Land-Use Cover Change
NAO	North Atlantic Oscillation

NGOs	non-governmental organisations
OECD	Organisation for Economic Cooperation and Development
OOPC	Ocean Observing Panel for Climate Change
PAGES	Past Global Changes
PDO	Pacific Decadal Oscillation
PICES	North Pacific Marine Science Organisation
POC	particulate organic carbon
POM	particulate organic matter
SCOR	Scientific Committee on Oceanic Research
SOIREE	South Ocean Iron Release Experiment
SOLAS	Surface Ocean – Lower Atmosphere Study
SSC	scientific steering committee
SST	sea surface temperature
START	Global Change System for Analysis, Research and Training
TEIs	trace elements and isotopic tracers
VOS	volunteer observing ship
WCRP	World Climate Research Programme

Appendix II - Data Policy Template for IGBP and SCOR Large Scale Ocean Research Projects

Recommended by the SCOR/IOC Meeting on Data Management for International Marine Research Projects held in Liverpool December 2003.

Data Policy Template for IGBP and SCOR Marine Projects

Scientific data and information derived from large-scale research projects with oceanic components are critical to project success and are an important legacy of these projects. Project data should be available for assessment and use by independent scientists, including, initially, other project scientists and later by external scientists. To ensure long-term survival, integrity, and availability of project data and models, a workable plan, policy, and associated infrastructure must be established early in the life of a project. Project data, as well as model code and model output, must be made available to the community.

A data management policy and plan should (1) encourage rapid dissemination of project results; (2) ensure long-term security of key project data, as well as model-related information; (3) protect the rights of the individual scientists; (4) treat all involved researchers equitably; and (5) reward openness. IGBP and SCOR affirm the data policy of their parent organization, the International Council for Science (ICSU):

> "ICSU recommends as a general policy the fundamental principle of full and open exchange of data and information for scientific and educational purposes." [ICSU General Assembly Resolution 1996]

Participants at the December 2003 meeting on Data Management for International Marine Research Projects recommend that all IGBP/SCOR large-scale marine research projects adopt the following essential elements in their data policies. Also listed are additional considerations for the development of project data management systems.

Essential Data Policy Elements

- Project endorsement requires a credible commitment to the timely submission of data to a project-approved database to ensure long-term archiving of the data.
- Discovery Metadata (what was collected where, when and by whom) should be submitted by project scientists to the International Project Office on the shortest feasible time scales. Failure to do should be considered reason to remove project endorsement.
- Model code and documentation, initialisation, boundary conditions, forcing and output resulting in published results ("definitive runs") must be submitted to project-approved databases in forms which allow assessment of key findings.
- Timelines for data and model sharing, as well as protocols associated with intellectual property rights of different data types and models, should be defined. Currently accepted guidelines are that data should enter the public domain after a maximum of two years after data become available to the PI.
- Quality control of metadata[1], data and model output needs to be addressed.
- Each project should form and support a Data Management Committee. The three primary functions of Data Management Committees are to:

    (1) make sure that data are available for project scientific purposes and ensure that data management meets the scientific need.

[1] Metadata are information about data, including information that allows data sets to be located (discovery metadata: what was measured, when and where), information that enhances human understanding of the data and the uses to which it can be put (semantic metadata) and information that allows software agents to access the data (technical metadata).

(2) oversee the compilation of data from individual PIs and national projects into a long-term data set
(3) address the involvement of scientists without access to effective data management infrastructure.

- Projects must adopt or establish a credible data management infrastructure.
- Projects should adopt metadata standards (content and controlled vocabularies[2]) and agreed data formats both within and among projects to facilitate data interoperability.
- Project Data Management Committees should consider how to get appropriate project data into operational data streams[3] and appropriate operational data streams into the project domain.

Additional Considerations

Project SSCs and Data Management Committees should create their project data policy, considering the following issues.

The project SSC should:

- create a Data Management Committee with adequate representation of project science, a balance between project scientists (including modellers), national and international project data managers, and consideration of outreach functions to countries without data centres.
- consider providing access to project-related publications through a publication database, such as that used by GLOBEC.

The project Data Management Committee[4] should:

- develop a process to ensure that metadata and data are submitted, monitor the compliance of project scientists to the policies, and refer failure in compliance to the project SSC.
- specify how project data will be quality controlled.
- specify incentives to encourage project scientists to submit metadata and data to the IPO and a long-term data repository, respectively. ("One carrot is worth ten sticks.") These incentives may include citation of data in a peer-reviewed journal, access to other project data during "an embargo period" before public access, tools for use of data in the data archive (e.g., data merging, plotting, spatial visualisation and modelling tools), and help from international data managers in submitting data, accessing data, and using analysis tools. Proper incentives will reduce the efforts needed by data managers to get data into project data systems and increase participation in the project.
- determine the variables most likely to be measured and the expected data volumes, and specify project data products.
- address how non-geo-referenced, socioeconomic, and other non-conventional data will be handled.
- consider setting up a DAC, either project-specific or shared among projects, for data that can be handled in this way. The DAC may be set up along the lines of project data streams (e.g., CTD data, bottle data) and/or the more traditional single parameter DAC (i.e., the DACs used by WOCE and CLIVAR).
- consider whether to submit DIFs to GCMD as a means to provide access to project metadata.
- consider making species-specific data available through OBIS.

[2] Metadata vocabularies are controlled lists of words or phrases that are used to populate metadata fields in place of free text to ensure computer searches are not compromised by problems such as spelling variations.
[3] Operational data streams are data that are available on a regular basis from routine observing systems, such as Argo floats, sea level networks, and telemetered data buoys.
[4] Where modelling committees exist, these should be consulted in relation to model-specific aspects of data policy.

- create a mechanism to interact regularly with representatives of related project Data Management Committees to develop common approaches and procedures to share data.

Project SSCs and Data Management Committees should work together to

- specify how project models and data will be made available both to scientists with leading-edge technology and with unreliable access to even basic access methods. The project should also present plans for training developing country scientists in techniques for data access and use.
- develop plans to bring together data providers and data managers, considering how “project data management” principles could be applied to each project.

References

Anderson, D. M., P. M. Gilbert and J. M. Bulkholder (2002). Harmful algal blooms and eutrophication: nutrient sources, composition, and consequences. *Estuaries* **25**: 704-726.

Archer, D., A. Winguth, D. Lea and N. Mahowald (2000). What caused the glacial/interglacial atmospheric pCO_2 cycles? *Reviews of Geophysics* **38**: 159-189.

Armstrong, R. A., C. Lee, J. I. Hedges, S. Honjo and S. G. Wakeham (2002). A new, mechanistic model for organic carbon fluxes in the ocean: based on the quantitative association of POC with mineral ballast. *Deep-Sea Research II* **49**: 219-236.

Azam, F. and R. A. Long (2001). Sea snow microcosms. *Nature* **414**: 495-498.

Baden, S. P. and D. M. Neil (2003). Manganese accumulation by the antennule of the Norway lobster Nephrops norvegicus (L.) as a biomarker of hypoxic events. *Marine Environmental Research* **55**: 59-71.

Banse, K. (1995). Zooplankton: pivotal role in the control of ocean production. *ICES Journal of Marine Science* **52**: 265-277.

Bates, N. R., A. C. Pequignet, R. J. Johnson and N. Gruber (2002). Changes in the oceanic sink of CO_2 in Subtropical Mode Water of the North Atlantic Ocean. *Nature* **420**: 489-492.

Batten, S. D., A. W. Walne, M. Edwards and S. B. Groom (2002). Phytoplankton biomass from continuous plankton recorder data: An assessment of the phytoplankton colour index. *Journal of Plankton Research* **25**: 697-702.

Beaugrand, G., P. C. Reid, F. Ibanez, J. A. Lindley and M. Edwards (2002). Reorganization of North Atlantic marine copepod biodiversity and climate. *Science* **296**: 1692-1694.

Beaumont, K. L., G. V. Nash and A. T. Davidson (2002). Ultrastructure, morphology and flux of microzooplankton fecal pellets in an east Antarctic fjord. *Marine Ecology Progress Series* **245**: 133-148.

Bell, J., J. Betts and E. Boyle (2002). MITESS: A moored in situ trace element serial sampler for deep-sea moorings. *Deep-Sea Research II* **49**: 2103 - 2118.

Berelson, W., J. , K. McManus, K. Coale, D. Johnson, T. Burdige, D. Kilgore, F. Colodner, R. Chavez, R. Kudela and B. J. (2003). A time series of benthic flux measurements from Monterey Bay, CA. *Journal of Continental Shelf Research* **23**: 457 - 482.

Bishop, J., R. Davis, and J. Sherman (2002). Robotic observations of dust storm enhancement of carbon biomass in the North Pacific. *Science* **298**: 817-821.

Bopp, L., P. Monfra, O. Aumont, J.-L. Dufresne, H. Le Treut, G. Madec, L. Terray and J. C. Orr (2001). Potential impact of climate change on marine export production. *Global Biogeochemical Cycles* **15**: 81-99.

Bopp, L., C. Le Quéré, M. Heimann, A. C. Manning and P. Monfray (2002). Climate-induced oceanic oxygen fluxes: Implications for the contemporary carbon budget. *Global Biogeochemical Cycles* **16**: 1029-2001 GB001445.

Boucher, N. P. and B. B. Prezelin (1996). An in situ biological weighting function for UV inhibition of phytoplankton carbon fixation in the Southern Ocean. *Marine Ecology Progress Series* **144**: 223-236.

Bousquet, P., P. Peylin, P. Ciais, C. Le Quéré, P. Friedlingstein, and P. P. Tans (2000). Regional changes in carbon dioxide fluxes of land and oceans since 1980. *Science* **290**: 1342-1346.

Boyd, P. W. and S. C. Doney, Eds. (2003). The impact of climate change and feedback processes on the ocean carbon cycle. *Ocean Biogeochemistry: The Role of the Ocean Carbon Cycle in Global Change, The IGBP Series*. New York, Springer Verlag, 157-193. p.

Brander, K. M. (1995). The effect of temperature on growth of Atlantic cod (*Gadus morhua* L.). *ICES Journal of Marine Science* **52**: 1-10.

Bratbak, G., F. Thingstad and M. Heldal (1994). Viruses and the microbial loop. *Microbial Ecology* **28**: 209-221.

Breitburg, D. (2002). Effects of hypoxia, and the balance between hypoxia and enrichment, on coastal fishes and fisheries. *Estuaries* **25**: 767-781.

Bruland, K. W., E. L. Rue and G. J. Smith (2001). *Iron and macronutrients in California coastal upwelling regimes: Implications for diatom blooms.* 1661-1674. p.

Bucklin, A. and P. H. Wiebe (1998). Low mitochondrial diversity and small effective population sizes of the copepods, *Calanus finmarchicus* and *Nannocalanus minor*, possible impact of climatic variation during recent glaciation. *Journal of Heredity* **89**: 383-392.

Burkhardt, S., I. Zondervan, and U. Riebesell (1999). Effect of CO_2 concentration on C:N:P ratio in marine phytoplankton: A species comparison. *Limnology and Oceanography* **44**: 683-690.

Burnett, W. and J. Chanton (2003). "Submarine Groundwater Discharge: Its Measurement, Modeling, and Globalization". *Special Issue of Biogeochemistry* **66**: 3-202.

Butler, A. (1998). Acquisition and utilization of transition metal ions by marine organsims. *Science* **281**: 207-210.

Capone, D. G. (2000). The marine nitrogen cycle. *Marine Microbial Ecology.* 455-493. D. Kirchman, Ed. New York, J. Wiley & Sons.

Chai, F., M. Jiang, R. T. Barber, R. C. Dugdale and Y. Chao (2003). Interdecadal variation of the transition zone chlorophyll front, A physical-biological model simulation between 1960 and 1990. *Journal of Oceanography* **59**: 461-475.

Charlson, R. J., J. E. M. Lovelock, O. Andreae, and S. G. Warren (1987). Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate. *Nature* **326**: 655-661.

Chavez, F. P., J. Ryan, S. E. Lluch-Cota, and C. Ñiquen (2003). From anchovies to sardines and back: Multidecadal change in the Pacific Ocean. *Science* **299**: 217 - 221.

Chen, C.-T. A., K. K. Liu and R. MacDonald (2003). Continental margin exchanges. *Ocean Biogeochemistry,*. 53-97. M. J. R. Fasham, Ed. Berlin, Springer verlag.

Codispoti, L. A. and J. P. Christensen (1985). Nitrification, denitrification and nitrous oxide cycling in the eastern tropical South Pacific Ocean. *Marine Chemistry* **16**: 277-300.

Codispoti, L. A., J. A. Brandes, J. P. Christensen, A. H. Devol, S. W. A. Naqvi, H. W. Paerl, and T. Yoshinari (2001). The oceanic fixed nitrogen and nitrous oxide budgets: Moving targets as we enter the Anthropocene? *Scientia Marina* **65**: 85 - 105.

Cooper, R. U., L. M. Clough, M. A. Farwell and T. L. West (2002). Hypoxia-induced metabolic and antioxidant enzymatic activities in the estuarine fish *Leiostomus xanthurus*. *Journal of Experimental Marine Biological Ecology* **279**: 1-20.

Cowen, J. P., S. J. Giovannoni, F. Kenig, H. P. Johnson, D. Butterfield, M. S. Rappe, M. Hutnak, and P. Lam (2003). Fluids from aging ocean crust that support microbial life. *Science* **299**: 120 - 123.

Cury, P., A. Bakun, R. J. Crawford, A. Jarre, R. A. Quinones, L. J. Shannon and H. M. Verheye (2000). Small pelagics in upwelling systems: Patterns of interaction and structural changes in "wasp - waist" ecosystems. *ICES Journal of Marine Science* **57**: 603 - 618.

Danard, M., A. Munro and T. Murty (2003). Storm surge hazard in Canada. *Natural Hazards* **28**: 407-431.

Dayton, P. K. (1985). Ecology of kelp communities. *Annual Reviews of Ecology and Systematics* **16**: 215 - 245.

Debernard, J., O. Saetra and L. P. Roed (2002). Future wind, wave and storm surge climate in the North Atlantic. *Climate Research* **23**: 39-49.

DeMaster, D. J. (2002). The accumulation and cycling of biogenic silica in the Southern Ocean: Revisiting the marine silica budget. *Deep-Sea Research II* **49**: 3155 - 3167.

Denman, K. (1973). A time-dependent model of the upper ocean. *Journal of Physical Oceanography* **3**: 173-184.

Diaz, R. J. and R. Rosenburg (1995). Marine benthic hypoxia: A review of its ecological effects and the behavioural responses on benthic macrofauna. *Oceanography Marine Biology Annual Review* **33**: 245-303.

Dickey, T. D. (2001). The role of new technology in advancing ocean biogeochemical research. *Oceanography* **14**: 108-120.

DIVERSITAS (2002). Science Plan. Paris, France.

Dore, J. E., B. N. Popp, D. M. Karl, and F. J. Sansone (1998). A large source of atmospheric nitrous oxide from subtropical North Pacific surface waters. *Nature* **396**: 63-66.

Dugdale, R. C. and F. P. Wilkerson (1998). Silicate regulation of new production in the equatorial Pacific upwelling. *Nature* **391**: 270-273.

Edwards, M., G. Beaugrand, P. C. Reid, A. A. Rowden and M. B. Jones (2002). Ocean climate anomalies and the ecology of the North Sea. *Marine Ecology Progress Series* **239**: 1-10.

Engel, A. (2002). Direct relationship between CO_2 uptake and transparent exopolymer particles production in natural phytoplankton. *Journal of Plankton Research* **24**: 49-53.

Fasham, M. J. R., J. L. Sarmiento, R. D. Slater, H. W. Ducklow, and R. A. Williams (1993). A seasonal three-dimensional ecosystem model of nitrogen cycling in the North Atlantic euphotic zone: A comparison of the model results with observations from Bermuda Station "S" and OWS "India". *Global Biogeochemical Cycles* **7**: 379-416.

Fasham, M. J. R., B. M. Baliño and M. C. Bowles, Eds. (2001). A new version of ocean biogeochemistry after a decade of the Joint Global Ocean Flux Study (JGOFS) 4-31. p.

Feely, R. A., J. Boutin, C. E. Cosca, Y. Dandonneau, J. Etcheto, H.Y. Inoue, M. Ishii, C. Le Quéré, D. J. Mackey, M. McPhaden, N. Metzl, A. Poisson, and R. Wanninkhof (2002). Seasonal and interannual variability of CO_2 in the equatorial Pacific. *Deep-Sea Research II* **49**: 2443-2469.

Fiksen, Ø., A. C. W. Utne, D. L. Aksnes, K. Eiane, J. V. Helvik and S. Sundby (1998). Modelling the influence of light, turbulence and ontogeny on ingestion rates in larval cod and herring. *Fisheries Oceanography* **7**: 355-363.

Gallego, A., J. Mardaljevic, M. R. Heath, D. Hainbucher and D. Slagstad (1999). A model of the spring migration into the North Sea by Calanus finmarchicus overwintering off the Scottish continental shelf. *Fisheries Oceanographyh supplement* **1**: 107 - 125.

Geider, R. J. and J. La Roche (2002). Redfield revisited: Variability of C:N:P in marine microalgae and its biochemical basis. *European Journal of Phycology* **37**: 1-17.

GLOBEC (1999). GLOBEC Implementation Plan. Stockholm, IGBP Report 47.

Goddard, L. and N. E. Graham (1999). Importance of Indian Ocean for simulating rainfall anomalies over eastern and southern Africa. *Journal of Geophysical Research* **104**: 19099-190116.

Goreau, T. J., W. A. Kaplan, S. C. Wofsy, M. B. McElroy, F. W. Valois and S. W. Watson (1980). Production of NO_2- and N_2O by nitrifying bacteria at reduced concentrations of oxygen. *Applied and Environmental Microbiology* **40**: 526-532.

Grad, G., C. E. Williamson and D. M. Karapelou (2001). Zooplankton survival and reproduction responses to damaging UV radiation: A test of reciprocity and photoenzymatic repair. *Limnology and Oceanography* **46**: 584-591.

Granéli, E. and C. Haraldsson (1993). Can increased leaching of trace-metals from acidified areas influence phytoplankton growth in coastal waters. *Ambio* **22**: 308-311.

Granger, J. and B. B. Ward (2003). Accumulation of nitrogen oxides in copper-limited cultures of denitrifying bacteria. *Limnology and Oceanography* **48**: 313-318.

Grant, W. S. and B. W. Bowen (1998). Shallow population histories in deep evolutionary lineages of marine fishes: Insights from sardines and anchovies and lessons for conservation. *Journal of Heredity* **89**: 415-426.

Greve, W., Lange, U., Reiners, F. & Nast, J., Ed. (2001). Predicting the Seasonality of North Sea Zooplankton. *In Burning issues of North Sea ecology, Proceedings of the 14th international Senckenberg Conference North Sea 2000.* Senckenbergiana marit., Frankfurt am Main. 263-268. p.

Gruber, N., J. L. Sarmiento and T. F. Stocker (1996). An improved method for detecting anthropogenic CO_2 in the oceans. *Global Biogeochemical Cycles* **10**: 809-837.

Gruber, N. and J. L. Sarmiento (2002). Biogeochemical/Physical Interactions in Elemental Cycles. *THE SEA: Biological-Physical Interactions in the Oceans*. 337-399. A. R. Robinson, J. J. McCarthy and B. J. Rothschild, Eds., John Wiley and Sons.

Hare, S. R. and N. J. Mantua (2000). Empirical evidences for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography* **47**: 103-145.

Hearn, C. J. and B. J. Robinson (2001). Inter-annual variability of bottom hypoxia in shallow Mediterranean estuaries. *Estuarine and Costal Shelf Science* **52**: 643-657.

Hebert, P. D. N., A. Cywinska, S. L. Ball and J. R. deWaard (2003). Biological identifications through DNA barcodes. *Proceedings of the Royal Society of London B* **270**: 313-322.

Hedges, J. I. and R. G. Keil (1995). Sedimentary organic matter preservation: An assessment and speculative synthesis. *Marine Chemistry* **49**: 81 - 115.

Hein, M. and K. Sand-Jensen (1997). CO_2 increases oceanic primary production. *Nature* **388**: 526-527.

Helbling, E. W., A. G. J. Buma, M. K. De Boer and V. E. Villafane (2001). In situ impact of solar ultraviolet radiation on photosynthesis and DNA in temperate marine phytoplankton. *Marine Ecology Progress Series* **211**: 43-49.

Hendrey, G. R., Ed. (1992). FACE: Free-Air CO_2 Enrichment for Plant Research in the Field. Boca Raton, Florida., CRC Press,p.

Hinga, K. R. (2002). Effect of pH on coastal marine phytoplankton. *Marine Ecology Progress Series* **238**: 281-300.

Holfort, J., K. M. Johnson, B. Schneider, G. Siedler and D. W. R. Wallace (1998). Meridional transport of dissolved inorganic carbon in the South Atlantic Ocean. *Global Biogeochemical Cycles* **14**: 479-499.

Holland, H. D. (1984)*. The Chemical Evolution of the Atmosphere and Oceans.* Princeton, Princeton University Press 582. p.

Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (2001). Climate Change 2001: The Scientific Basis - Contribution of Working Group I to the Third Assessment Report of IPCC., Intergovernmental Panel on Climate Change**:** 944.

Huse, I. (1994). Feeding at different illumination levels in larvae of three marine teleost species: Cod, *Gadus morhua* L., plaice, *Pleuronectes platessa* L., and turbot, *Scophthalmus maximus* L. *Aquaculture Fisheries Management* **25**: 687-695.

IGBP/SCOR (2002). *Framework for Future Research on Biological and Chemical Aspects of Global Change in the Ocean:* An IGBP/SCOR collaboration.

Iglesias-Rodriguez, M. D., C. W. Brown, S. C. Doney, J. A. Kleypas, D. Kolber, Z. Kolber, P. K. Hayes and P. G. Falkowski (2002a). Representing key phytoplankton functional groups in ocean carbon cycle models: Coccolithophorids. *Global Biogeochemical Cycles* **16**: 1100.

Iglesias-Rodriguez, M. D., A. G. Saez, R. Groben, K. J. Edwards, J. Batley, L. K. Medlin and P. K. Hayes (2002b). Polymorphic microsatellite loci in global populations of the marine coccolithophorid *Emiliania huxleyi*. *Molecular Ecology Notes* **2**: 495-497.

IHDP (1999). Global Environmental Change and Human Security: Science Plan., Steve Lonergan et al. (eds.) IHDP Report Series No 11.

Indermühle, A., T. F. Stocker, F. Joos, H. Fischer, H. J. Smith, M. Wahlen, B. Deck, D. Mastroianni, J. Tschumi, T. Blunier, R. Meyer and B. Stauffer (1999). Holocene carbon-cycle dynamics on CO_2 trapped in ice at Taylor Dome, Antarctica. *Nature* **398**: 121-126.

Jahnke, R. A. (1996). The global ocean flux of particulate organic carbon: Areal distribution and magnitude. *Global Biogeochemical Cycles* **10**: 71 - 88.

Jahnke, R. A., J. R. Nelson, R. L. Marinelli and J. E. Eckman (2000). Benthic flux of biogenic elements on the southeastern U. S. continental shelf: Influence of pore water advective transport and benthic microalgae. *Continental Shelf Research* **20**: 109-127.

Jones, P. D., T. J. Osborn, K. R. Briffa, C. K. Folland, E. B. Horton, L. V. Alexander, D. E. Parker and N. A. Rayner (2001). Adjusting for sampling density in grid box land and ocean surface temperature time series. *Journal of Geophysical Research* **106**: 3371-3380.

Joos, F., G.-K. Plattner, T. F. Stocker, A. Körtzinger and D. W. R. Wallace (2003). Trends in marine dissolved oxygen: implications for ocean circulation changes and the carbon budget. *EOS - Transactions of the Americain Geophysical Union* **84**: 197-201.

Justic, D., N.N. Rabalais, and R.E. Turner. (1997). Impacts of climate change on net productivity of coastal waters: implications for carbon budget and hypoxia. *Climate Research* **8**: 225-237.

Kalnay, E., M. Kanamitsu, R. Kistler, W. Collins, D. Deaven, L. Gandin, M. Iredell, S. Saha, G. White, J. Woollen, Y. Zhu, M. Chelliah, W. Ebisuzaki, W. Higgins, J. Janowiak, K. C. Mo, C. Ropelewski, J. Wang, A. Leetmaa, R. Reynolds, R. Jenne and D. Joseph (1996). NCEP/NCAR 40 year reanalyses project. *Bulletin of the American Meteorological Society* **77**: 437-471.

Kannen, A., W. Windhorst and Colijn. F (2003). The use of indicators in the EUROCAT project. *Book of Abstracts. European Conference of Coastal Zone Research: an ELOISE Approach.*, Jointly organised by the European Commission-DG Research, the Norwegian Institute for Air Research, and the Gdansk University of Technology, 24-27 March 2003, page.

Karl, D. (1999). A sea of change: Biogeochemical variability in the North Pacific subtropical gyre. *Ecosystems* **2**: 181 - 214.

Karl, D., A. Michaels, B. Bergman, D. Capone, E. Carpenter, R. Letelier, F. Lipschultz, H. Paerl, D. Sigman and L. Stal (2002). Dinitrogen fixation in the world's oceans. *Biogeochemistry* **57-58**: 47 - 98.

Karl, D. M., R. R. Bidigare and R. M. Letelier (2001a). Long-term changes in plankton community structure and productivity in the North Pacific Subtropical Gyre: The domain shift hypothesis. *Deep-Sea Research II* **48**: 1449 - 1470.

Karl, D. M., K. M. Bjökman, J. E. Dore, L. Fujieki, D. V. Hebel, T. Houlihan, R. M. Letelier and L. M. Tupas (2001b). Ecological nitrogen-to-phosphorus stoichiometry at Station ALOHA. *Deep-Sea Research II* **48**: 1529-1566.

Karl, D. M. (2002). Nutrient dynamics in the deep blue sea. *Trends in Microbiology* **10**: 410-418.

Karl, D. M., N. R. Bates, S. Emerson, P. J. Harrison, C. Jeandel, K. K. Liu, J.-C. Marty, A. F. Michaels, J. C. Miquel, S. Neuer, Y. Nojiri and C. S. Wong (2003). Temporal studies of biogeo-chemical processes in the world's oceans during the JGOFS era, Ocean Biogeochemistry. *The Role of the Ocean Carbon Cycle in Global Change, International Geosphere-Biosphere Programme Book Series* M. J. R. Fasham, Ed., Springer-Verlag.

Keeling, C. D., T. P. Whorf, M. Wahlen and J. Vanderplicht (1995). Interannual extremes in the rate of rise of atmospheric carbon-dioxide since 1980. *Nature* **375**: 666-670.

Keeling, R. F. and H. Garcia (2002). The change in oceanic O_2 inventory associated with recent global warming. *Proceedings of the National Academy of Science USA* **99**: 7848-7853.

Keller, K., R. D. Slater and N. R. Bates (2002). Possible biological or physical explanation for decadal scale trends in North Pacific nutrient concentrations and oxygen utilization. *Deep-Sea Research II* **49**: 345-362.

Kester, D. R. (1986). Equilibrium models in seawater: applications and limitations. *The importance of chemical 'speciation' in environmental processes*. 337-363. M. Bernhard, F. E. Brinckman and P. J. Sadler, Eds. Berlin, Springer Verlag.

Klaas, C. and D. E. Archer (2002). Association of sinking organic matter with various types of mineral ballast in the deep sea: Implications for the rain ratio. *Global Biogeochemical Cycles* **16**: 1116.

Kleypas, J. A., R. W. Buddemeier, D. Archer, J.-P. Gattuso, C. Langdon and B. N. Opdyke (1999). Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. *Science* **284**: 118-120.

Klyashtorin, L. B. (1998). Long-term climate change and main commercial fish production in the Atlantic and Pacific. *Fisheries Research* **37**: 115-125.

Knutti, R. and T. F. Stocker (2002). Limited predictability of the future thermohaline circulation close to an instability threshold. *Journal of Climate* **15**: 179-186.

Körtzinger, A., W. Koeve, P. Kähler and L. Mintrop (2001). C:N ratios in the mixed layer during the productive season in the Northeast Atlantic Ocean. *Deep-Sea Research I* **48**: 661-688.

Köster, F. W., H. H. Hinrichsen, M. A. St. John, D. Schnack, B. MacKenzie and M. Plikshs (2001). Developing Baltic cod recruitment models II: Incorporation of environmental variability and species interaction. *Canadian Journal of Fisheries and Aquatic Science* **58**: 1534-1556.

Kustka, A., S. Sañudo-Wilhelmy, E. J. Carpenter, D. G. Capone and J. A. Raven (2003). A revised estimate of the iron use efficiency of nitrogen fixation, with special reference to the marine cyanobacterium *Trichodesmium* spp. (Cyanophyta). *Journal of Phycology* **39**: 12-25.

Labeyrie, L. (2002). *Paleoclimate, Global Change and the Future*. *IGBP Book Series* K. Alverson, R. S. Bradley and T. Pederson, Eds., Springer Verlag.

Langdon, C., T. Takahashi, C. Sweeney, D. Chipman, J. Goddard, F. Marubini, H. Aceves, H. Barnett and M. J. Atkinson (2000). Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef. *Global Biogeochemical Cycles* **14**: 639-654.

Langdon, C., W. S. Broecker, D. E. Hammond, E. Glenn, K. Fitzsimmons, S. G. Nelson, T.-H. Peng, I. Hajdas and G. Bonani (2003). Effect of elevated CO_2 on the community metabolism of an experimental coral reef. *Global Biogeochemical Cycles* **17**.

Le Quéré, C., J. C. Orr, P. Monfray, O. Aumont and G. Madec (2000). Interannual variability of the onceanic sink of CO_2 from 1979 through 1997. *Global Biogeochemical Cycles* **14**: 1247-1265.

Levitus, S., J. I. Antonov, T. P. Boyer and C. Stephens (2000). Warming of the world ocean. *Science* **287**: 2225-2229.

Levitus, S., J. I. Antonov, J. Wang, T. L. Delworth, K. W. Dixon and A. J. Broccoli (2001). Anthropogenic Warming of Earth's Climate System. *Science* **292**: 267-270.

Lewis, M., M. Carr, G. Feldmann, W. Essias and C. McClain (1990). Influence of penetrating solar radiation on the heat budget of the equatorial Pacific Ocean. *Nature* **347**: 543-545.

Loisel, H., J. M. Nicolas, P. Y. Deschamps and R. Frouin (2002). Seasonal and inter-annual variability of the particulate matter in the global ocean. *Geophysical Research letters* **29**: 2996.

Longhurst, A. (1995). Seasonal cycles of pelagic production and consumption. *Progress In Oceanography* **36**: 77-167.

Loreau, M. and I. Oliveri (1999). DIVERSITAS: an international programme on biodiversity science. *Trends in Ecology and Evolution* **14**: 5.

Luther, G. W., B. Sundby, B. L. Lewis, P. J. Brendel and N. Silverberg (1997). Interactions of manganese with the iron cycle: Alternative pathways to dinitrogen. *Geochimica et Cosmochimica Acta* **61**: 4043-4052.

Macy, W. K., S. J. Sutherland and E. G. Durbin (1998). Effects of zooplankton size and concentration and light intensity on the feeding behavior of Atlantic mackerel *Scomber scombrus*. *Marine Ecology Progress Series* **172**: 89-100.

Mann, E. L., N. Ahlgren, J. W. Moffett and S. W. Chisholm (2001). Copper toxicity and cyanobacteria ecology in the Sargasso Sea. *Limnology and Oceanography* **47**: 976 - 988.

Marshall, C. T. (1999). Total lipid energy as a proxy for total egg production by fish stocks. *Nature* **402**: 288-290.

Marzeion, A. Timmermann, R. Murtugudde and F.-F. Jin (2003). Bio-physical feedbacks in the tropical Pacific. Sub judice. *Journal of Climate*.

McGowan, J. A., S. J. Bograd, R. J. Lynn and A. J. Miller (2003). The biological response to the 1977 regime shift in the California Current. *Deep-Sea Research II* **50**: 2567-2582.

Michaels, A. and M. Silver (1988). Primary production, sinking fluxes and the microbial food web. *Deep-Sea Research I* **35**: 473-490.

Middelburg, J. J., K. Soetaert, P. M. J. Herman and C. H. R. Heip (1996). Denitrification in marine sediments : a model study. *Global Biogeochemical Cycles* **10**: 661-673.

Miller, A. J., M. A. Alexander, G. J. Boer, F. Chai, K. Denman, D. J. Erickson III, R. Frouin, A. J. Gabric, E. A. Laws, M. R. Lewis, Z. Liu, R. Murtugudde, S. Nakamoto, D. J. Neilson, J. R. Norris, J. C. Ohlmann, R. I. Perry, N. Schneider, K. M. Shell and A. Timmermann (2003). Potential feedbacks between the Pacific Ocean ecosystems and interdecadal climate variations. *Bulletin Americain Meterology Society* **84**: 617-633.

Moffett, J. W. (1995). Temporal and spatial variability of strong copper complexing ligands in the Sargasso Sea. *Deep-Sea Research I* **42**: 1273 - 1295.

Moffett, J. W. and L. E. Brand (1996). The production of strong, extracellular Cu chelators by marine cyanobacteria in response to Cu stress. *Limnology and Oceanography* **41**: 288 - 293.

Molenaar, F. J. and A. M. Breeman (1997). Latitudinal trends in the growth and reproductive seasonality of *Delesseria sanguinea, Membranoptera alata*, and *Phycodrys rubens* (Rhodophyta). *Journal of Phycology* **33**: 330-343.

Moore, T. C., W. H. J. Hundson, N. Kip, J. D. Hays, W. L. Prell, P. Thompson and G. Boden (1981). The Biological record of the ice-age ocean. *Palaeoceanography, Palaeoclimatology, Palaeoecology* **35**: 357-370.

Morel, F. F. M., J. R. Reinfelder, S. B. Roberts, C. P. Chamberlain, J. G. Lee and D. Yee (1994). Zinc and carbon co-limitation of marine phytoplankton. *Nature* **369**: 740-742.

Morel, F. M. M. and N. M. Price (2003). The biogeochemical cycles of trace metals in the oceans. *Science* **300**: 944-947.

Morrison, J. M., L. A. Codispoti, S. Gaurin, B. Jones, V. Manghanani and Z. Zheng (1998). Seasonal variation of hydrographic and nutrient fields during the US

JGOFS Arabian Sea Process Study. *Deep-Sea Research II: Topical Studies in Oceanography* **45**: 2053-2101.

Morrison, J. M., L. A. Codispoti, S. L. Smith, K. Wishner, C. Flagg, W. D. Gardner, S. Gaurin, S. W. A. Naqvi, V. Manghnani, L. Prosperie and J. S. Gundersen (1999). The oxygen minimum zone in the Arabian Sea during 1995. *Deep-Sea Research II: Topical Studies in Oceanography* **46**: 1903-1931.

Muggli, D. L. and P. J. Harrison (1997). Effects of iron on two oceanic phytoplankters grown in natural NE subarctic Pacific seawater with no artificial chelators present. *Journal of Experimental Marine Biology and Ecology* **212**: 225-237.

Murtugudde, R., J. Beauchamp, C. R. McClain, M. Lewis and A. J. Busalacchi (2002). Effects of penetrative radiation on the upper tropical ocean circulation. *Journal of Climate* **15**: 470-486.

Myers, R. A. and B. Worms (2003). Rapid worldwide depletion of predatory fish communities. *Nature* **423**: 280 - 283.

Nakamoto, S., S. Prasanna Kumar, J. M. Oberhuber, J. Ishizaka, K. Muneyama and R. Frouin (2001). Response of the equatorial Pacific to chlorophyll pigment in a mixed layer isopycnal ocean general circulation model. *Geophysical Research Letters* **28**: 2021-2024.

Nakken, O. and A. Raknes (1987). The distribution and growth of Northeast Arctic cod in relation to bottom temperatures in the Barents Sea 1978-1984. *Fisheries Research* **5**: 243-252.

Naqvi, S. W. A., D. A. Jayakumar, P. V. Narvekar, H. Naik, V. V. S. S. Sarma, W. D'Souza, T. Joseph and M. D. George (2000). Increased marine production of N_2O due to intensifying anoxia on the Indian continental shelf. *Nature* **408**: 346-349.

Naqvi, S. W. A., V. V. S. S. Sarma and D. A. Jayakumar (2002). Carbon cycling in the northern Arabian Sea during the northeast monsoon: Significance of salps. *Marine Ecology Progress Series* **226**: 35-44.

Nielsen, E. E., M. M. Hansen, C. Schmidt, D. Meldrup and P. Grønkjær (2001). Population of origin of Atlantic cod. *Nature* **413**: 272.

Nozaki, Y. (1997). Vertical profiles of elements in the North Pacific Ocean. *EOS, Transactions of the Americain Geophysical Union* **78**: 221.

Ohaman, M. D. and S. N. Wood (1995). The inevitability of mortality. *ICES Journal of Marine Science* **52**: 517-522.

Ono, T., K. Tadokoro, T. Midorikawa, J. Nishioka and T. Saino (2002). Multi-decadal decrease of net community production in western subarctic North Pacific. *Geophysical Research Letters* **29**.

Pagani, M., M. A. Arthur and K. H. Freeman (1999). Miocene evolution of atmospheric carbon dioxide. *Paleoceanography* **14**: 273-292.

Paine, R. T. (1994). Marine Rocky Shores and Community Ecology: an Experimentalist's Perspective. *Excellence in Ecology. Book 4*. 152. O. Kinne, Ed. Germany, International Ecology Institute, Oldendorf/Luhe.

Parmesan, C. and G. Yohe (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**: 37-42.

Patten, B. C., S. E. Jørgensen and S. I. Auerbach, Eds. (1995). Complex Ecology: The Part-whole Relation in Ecosystems. Englewood Cliffs, Prentice-Hall 388. p.

Pauly, D. (1987). Theory and practice of overfishing: A southeast Asian experience (Gulf of Thailand), RAPA Report 1987/10.

Pauly, D., V. Christensen, J. Dalsgaard, R. Froese and F. Torres (1998). Fishing down marine food webs. *Science* **279**: 860-863.

Pavia, E. G. and A. Badan (1998). ENSO modulates rainfall in the Mediterranean Californias. *Geophysical Research Letters* **25**: 3855-3858.

Pearson, P. N. and M. R. Palmer (1999). Middle Eocene seawater pH and atmospheric carbon dioxide concentrations. *Science* **284**: 1824-1826.

Perry, I. and R. Ommer (2003). Scale issues in marine ecosystems and human interactions. *Fisheries Oceanography* **12**: 513-522.

Petit, J. R., J. Jouzel, D. Raynaud, N. I. Barkov, J. M. Barnola, I. Basile, M. Bender, J. Chappellaz, M. Davis, G. Delaygue, M. Delmotte, V. M. Kotlyakov, M. Legrand, V. Y. Lipenkov, C. Lorius, L. Pepin, C. Ritz, E. Saltzman and M. Stievenard (1999). Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429-436.

Plattner, G.-K., F. Joos, T. F. Stocker and O. Marchal (2001). Feedback mechanisms and sensitivities of the ocean carbon uptake under global warming. *Tellus B* **53**: 564-592.

Prospero, J. M. (1999). Long-range transport of mineral dust in the global atmosphere: Impact of African dust on the environment of the southeastern United States. *Proceedings of the National Academy of Sciences* **96**: 3396-3403.

Rabalais, N. and S. Nixon (2002). Nutrient over-enrichment in coastal waters: Global patterns of cause and effect. *Estuaries* **25**: 639-900.

Rabalais, N. N. and R. E. Turner (2001). "Coastal Hypoxia: Consequences for Living Resources and Ecosystems". Coastal and Estuarine Studies, American Geophysical Union, Washington, D.C. **58**.

Rahmstorf, S. (2002). Ocean circulation and climate during the past 120,000 years. *Nature* **419**: 207-214.

Raven, J. A. and W. J. Lucas (1985). Energy costs of carbon acquisition. *Inorganic carbon uptake by aquatic photosynthetic organisms*. 305-324. W. J. Lucas and J. A. Berry, Eds. Rockville, MD, American Society of Plant Physiologists.

Raven, J. A., B. Wollenweber and L. L. Handley (1992). A comparison of ammonium and nitrate as nitrogen sources for photolithotrophs. *New Phytology* **121**: 19-32.

Redfield, A. C. (1934). On the proportions of organic derivatives in seawater and their relation to the composition of plankton. *James Johnstone Memorial Volume*. 176-192. R. Daniel, Ed. Liverpool, University Press of Liverpool.

Riebesell, U., D. A. Wolf-Gladrow and V. Smetacek (1993). Carbon dioxide limitation of marine phytoplankton growth rates. *Nature* **361**: 249-251.

Riebesell, U., I. Zondervan, B. Rost, P. D. Tortell, R. E. Zeebe and F. M. M. Morel (2000). Reduced calcification of marine plankton in response to increased atmospheric CO_2. *Nature* **407**: 364-367.

Ross, S. W., D. A. Dalton, S. Kramer and B. L. Christensen (2001). Physiological (antioxidant) responses of estuarine fishes to variability in dissolved oxygen. *Comparitive Biogeochemistry and Physiology* **130C**: 289-303.

Rost, B., U. Riebesell, S. Burkhardt and D. Sultemeyer (2003). Carbon acquisition of bloom-forming marine phytoplankton. *Limnology and Oceanography* **48**: 55-67.

Rothschild, B. J. and T. R. Osborn (1988). Small-scale turbulence and plankton contact rates. *Journal of Plankton Research* **10**: 465-474.

Sabine, C. and M. Hood (2003). Ocean Carbon scientists organise to achieve better coordination, cooperation. *EOS, Transactions of the Americain Geophysical Union* **84**: 218.

Sabine, C. L., R. A. Feely, R. M. Key, J. L. Bullister, F. J. Millero, K. Lee, T.-H. Peng, B. Tilbrook, T. Ono and C. S. Wong (2002). Distribution of anthropogenic CO_2 in the Pacific Ocean. *Global Biogeochemical Cycles* **16**: 1083.

Sabine, C. L., M. Heimann, P. Artaxo, D. Bakker, C.-T. A. Chen, C. B. Field, N. Gruber, C. LeQuéré, R. G. Prinn, J. E. Richey, P. Romero-Lanko, J. Sathaye and R. Valentini (2003). Current status and past trends of the global carbon cycle. *The Global Carbon Cycle: Integrating Humans, Climate and the Natural World* C. Field and M. Raupach, Eds. Washington, DC, Island Press.

Saiz, E. and T. Kiørboe (1995). Suspension and predatory feeding of the copepod *Acartia tonsa* in turbulent environments. *Marine Ecology Progress Series* **122**: 147-158.

Sarmiento, J. L., R. D. Slater, M. J. R. Fasham, H. W. Ducklow, J. R. Toggweiler and G. T. Evans (1993). A seasonal three-dimensional ecosystem model of nitrogen cycling in the North Atlantic euphotic zone,. *Global Biogeochemical Cycles* **7**: 417-450.

Sarmiento, J. L., T. M. C. Hughes, R. J. Stouffer and S. Manabe (1998). Simulated response of the ocean carbon cycle to anthropogenic climate warming. *Nature* **393**: 245-249.

Sarmiento, J. L. and S. C. Wofsy (1999). A US Carbon Cycle Science Plan. Washington, D.C, US Global Change Research Program**:** 69 pp.

Sarmiento, J. L., P. Monfray, E. Maier-Remier, O. Aumont, R. Murnane and J. C. Orr (2000). Sea-air CO_2 fluxes and carbon transport: a comparison of three ocean general circulation models. *Global Biogeochemical Cycles* **14**: 1267-1281.

Sarmiento, J. L., and J. R. Toggweiler, (1984). A new model for the role of oceans in determining atmospheric pCO_2. *Nature* **308**: 621-624.

Sathyendranath, S., A. D. Gouveia, S. R. Shetye, P. Ravindran and T. Platt (1991). Biological control of surface temperature in the Arabian Sea. *Nature* **349**: 54-56.

Sathyendranath, S., Ed (2000). Remote Sensing of Ocean Colour in Coastal, and Other Optically-Complex, Waters. Halifax, Nova Scotia, Canada, International Ocean Colour Coordinating Group.

Schlitzer, R. (2000). Electronic atlas of WOCE hydrographic and tracer data now available. *EOS, Transactions of the American Geophysical Union* **81**: 45.

Schneider, E. K. and Z. Zhu (1998). Sensitivity of the simulated annual cycle of sea surface temperature in the equatorial Pacific to sunlight penetration. *Journal of Climate* **11**: 1932-1950.

Schwartzlose, R. A., J. Alheit, A. Bakun, T. R. Baumgartner, R. Cloete, R. J. M. Crawford, W. J. Fletcher, Y. Green-Ruiz, E. Hagen, T. Kawasaki, D. Lluch-Belda, S. E. Lluch-Cota, MacCall AD, Y. Matsuura, M. O. Nevarez-Martinez, R. H. Parrish, C. Roy, R. Serra, K. V. Shust, M. N. Ward and J. Z. Zuzunaga (1999). Worldwide large-scale fluctuations of sardine and anchovy populations. *South African Journal of Marine Science* **21**: 289-347.

Seitzinger, S. P., C. Kroeze, A. F. Bouwman, N. Caraco, F. Dentener and R. V. Styles (2002). Global patterns of dissolved inorganic and particulate nitrogen inputs to coastal systems: Recent conditions and future projections. *Estuaries* **25**: 640-655.

Shell, K. M., R. Frouin, S. Nakamoto, and R. C. J. Somerville, (2003). Atmospheric response to solar radiation absorbed by phytoplankton. *Journal of Geophysical Research* **108**: 4445.

Shick, J. M., M. P. Lesser and P. L. Jokiel (1996). Effects of ultraviolet radiation on corals and other coral reef organisms. *Global Change Biology* **2**: 527-545.

Siegel, D. A., S. Maritorena, N. B. Nelson, D. A. Hansell and M. Lorenzi-Kayzer (2002). Global distribution and dynamics of colored dissolved and detrital organic materials. *Journal of Geophysical Research* **107**: 3228.

Simpson, J. J. and T. D. Dickey (1981a). The relationship between downward irradiance and their dynamical significance. *Journal of Physical Oceanography* **11**: 309-323.

Simpson, J. J. and T. D. Dickey (1981b). Alternative parameterization of downward irradiance and their dynamical significance. *Journal of Physical Oceanography* **11**: 876-882.

Snyder, M. A., L. C. Sloan, N. S. Diffenbaugh and J. L. Bell (2003). Future climate change and upwelling in the California Current. *Geophysical Research Letters* **30**.

Solow, A. R. (1994). Detecting change in the composition of a multispecies community. (Georges Bank). *Biometrics* **505**: 556-56.

Southward, A. J., S. J. Hawkins and M. T. Burrows (1995). Seventy years observations of changes in distribution and abundance of zooplankton and intertidal organisms in the western English Channel in relation to rising sea temperature. *Journal of Thermal Biology* **1-2**: 127-155.

Speekmann, C. L., S. M. Bollens and S. R. Avent (2000). The effect of ultraviolet radiation on the vertical distribution and mortality of estuarine zooplankton. *Journal of Plankton Research* **22**: 2325-2350.

Spencer, P. D. and J. S. Collie (1997). Effect of nonlinear predation rates on rebuilding the Georges Bank Haddock (*Melanogrammus aeglefinus*) stock. *Canadian Journal of Fisheries and Aquatic Science* **54**: 2920-2929.

Spero, H. J., J. Bijma, D. W. Lea and B. E. Bemis (1997). Effect of seawater carbonate concentration of foraminiferal carbon and oxygen isotopes. *Nature* **390**: 497-500.

Steffen, W., A. Sanderson, P. Tyson, J. Jäger, P. Matson, I. B. Moore, F. Oldfield, K. Richardson, H.-J. Schellnhuber, B. L. Turner II and R. Wasson (2004). *Global Change and the Earth System: A Planet Under Pressure.* Berlin, Heidelburg, New York, Springer-Verlag p.

Steinberg, D. K., C. A. Carlson, N. R. Bates, S. A. Goldthwait, L. P. Madin and A. F. Michaels (2000). Zooplankton vertical migration and the active transport of dissolved organic and inorganic carbon in the Sargasso Sea. *Deep-Sea Research I* **47**: 137-158.

Sterner, R. W. and J. J. Elser (2002). *Ecological Stoichiometry: the Biology of Elements from Molecules to the Biosphere*. New Jersey, Princeton University Press 440. p.

Stocker, T. F. (1999). Climate changes: from the past to the future - a review. *International Journal of Earth Science* **88**: 365-374.

Stoecker, D. K., A. Li, D. Wayne Coats, D. E. Gustafson and M. K. Nannen (1997). Mixotrophy in the dinoflagellate *Prorocentrum minimum*. *Marine Ecology Progress Series* **152**: 1-12.

Stott, L., C. Poulsen, S. Lund and R. Thunell (2002). Super ENSO and global climate oscillations at millennial time scales. *Science* **297**: 222-226.

Subramaniam, A., Christopher W. Brown, Raleigh R. Hood, Edward J. Carpenter and Douglas J. Capone (2002). Detecting *Trichodesmium* blooms in SeaWiFS imagery. *Deep-Sea Research II* **49**: 107-121.

Sundby, S. (2000). Recruitment of Atlantic cod stocks in relation to temperature and advection of copepod populations. *Sarsia* **85**: 277-298.

Svensen, C., J. C. Nejstgaard, J. K. Egge and P. Wassmann (2002). Pulsing versus constant supply of nutrients (N, P, and Si): effect on phytoplankton, mesozooplankton, and vertical flux of organic matter. *Scientia Marina* **66**: 189 - 203.

Takeda, S. (1998). Influence of iron availability on nutrient consumption ratio of diatoms in oceanic waters. *Nature* **393**: 774-777.

Thompson, P. M. and J. C. Ollason (2001). Lagged effects of ocean climate change on fulmar population dynamics. *Nature* **413**: 417-420.

Timmermann, A. and F. Jin (2002). Phytoplankton influences on tropical climate,. *Geophysical Research Letters* **29**: 2104.

Tsuda, A., S. Takeda, H. Saito, J. Nishioka, Y. Nojiri, I. Kudo, H. Kiyosawa, A. Shiomoto, K. Imai, T. Ono, A. Shimamoto, D. Tsumune, T. Yoshomura, T. Aono, A. Hinuma, M. Kinugasa, K. Suzuki, Y. Sohrin, Y. Noiri, H. Tani, Y. Deguchi, N. Tsurushima, H. Ogawa, K. Fukami, K. Kuma and T. Saino (2003). A mesoscale iron enrichment in the western subarctic Pacific induces large centric diatom bloom. *Science* **300**: 958-961.

Tsunogai, S., S. Watanabe, T. Nakamura, T. Ono and T. Sato (1999). Is there a "continental shelf pump" for the adsorption of atmospheric CO_2. *Tellus Series. B* **51**: 701 - 712.

Turk, D., M. J. McPhaden, A. J. Busalacchi and M. R. Lewis (2001). Remotely sensed biological production in the Equatorial Pacific. *Science* **293**: 471-474.

Turner, D. R. and K. A. Hunter, Eds. (2001). *The Biogeochemistry of Iron in Seawater. IUPAC Series on Analytical and Physical Chemistry of Environmental Systems.* New York., John Wiley & Sons, Ltd.p.

Turner, R. E. (2002). Elemental ratios and aquatic food webs. *Estuaries* **25**: 694-703.

Turner, R.-K., S. Georgiou, I. Gren, F. Wulff, S. Barrett, T. Söderqvist, I. J. Bateman, C. Folke, S. Langaas, T. Zylicz, K. Mäler and A. Markowsk (1999). Managing nutrient fluxes and pollution in the Baltic: an interdisciplinary simulation study. *Ecological Economics* **30**: 333-352.

Van Weering, T. C. E., H. C. de Stigter, W. Balzer, E. H. G. Epping, G. Graf, I. R. Hall, W. Helder, A. Khripounoff, L. Lohse, I. N. McCave, L. Thomsen and A. Vangriesheim (2001). Benthic dynamics and carbon fluxes on the NW European continental margin. *Deep-Sea Research II* **48**: 3191 - 3222.

Wakeham, S. G., C. Lee, J. I. Hedges, P. J. Hernes and M. L. Peterson (1997). Molecular indicators of diagenetic status in marine organic matter. *Geochimica et Cosmochimica Acta* **61**: 5363-5369.

Wallace, D. W. R. (2001). Storage and transport of excess CO_2 in the oceans: The JGOFS/WOCE Global CO_2 Survey. *Ocean Circulation and Climate*. 489-521. J. Church, G. Siedler and J. Gould, Eds. London, Academic Press.

Weeks, S. J., B. Currie and A. Bakun (2002). Satellite imaging: Massive emissions of toxic gas in the Atlantic. *Nature* **415**: 493-494.

Wolf-Gladrow, D. A., U. Riebesell, S. Burkhardt and J. Bijma (1999). Direct effects of CO_2 concentration on growth and isotopic compositions of marine plankton. *Tellus B* **51**: 461-476.

Wollast, R. and L. Chou (2001a). Ocean Margin EXchange in the Northern Gulf of Biscay: OMEX I. An Introduction. *Deep-Sea Research II* **48**: 2971 - 2978.

Wollast, R. and L. Chou (2001b). The carbon cycle at the ocean margin in the northern Gulf of Biscay. *Deep-Sea Research II* **48**: 3265 - 3293.

Wong, C. S. and R. J. Matear (1999). Sporadic silicate limitation of phytoplankton productivity in the subarctic NE Pacific. *Deep-Sea Research II* **46**: 2539-2555.

Yool, A. and M. J. R. Fasham (2001). An examination of the "continental shelf pump" in the open ocean general circulation model. *Global Biogeochemical Cycles* **15**: 831 - 844.

Zondervan, I., R. E. Zeebe, B. Rost and U. Riebesell (2001). Decreasing marine biogenic calcification: A negative feedback on rising atmospheric pCO_2. *Global Biogeochemical Cycles* **15**: 507-516.