Ocean biogeochemistry and biology: a vision for the next decade of global change research

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The ocean is a vital component of the Earth System and plays an active role in global change (**Box 1**). Signs of global change in the physical, chemical and biological properties of the ocean can already be observed (see for example **Boxes 2 - 5**). IGBP and SCOR have joined forces in creating an integrated research initiative in ocean biogeochemistry and biology. The IGBP-SCOR Ocean Vision focuses on (i) understanding the role of the ocean in Earth System biogeochemistry and (ii) predicting the consequences of global change for ocean biogeochemistry and biology, as a means to investigate pathways towards sustainability.

Global change is defined in this context as global-scale changes that affect the functioning of the Earth System. It is more inclusive than climate change and also encompasses changes in biodiversity, geochemical cycles and anthropogenic impacts. The aim of this document is to provide an integrative framework for ocean research within IGBP II.

The Role of the Ocean in the Earth System

The ocean has a vast capacity for storage and exchange of heat and gases, and thus exerts a major control on climate. It harbours the most extensive and least-known biosphere and contains living and mineral resources which we have just begun to identify. Within the Earth System, the ocean is intimately linked to the atmosphere and land and cannot be considered separately when addressing questions of global change (**Box 1**). The ocean buffers physical and chemical signals received from the atmosphere and land. However, it can also amplify such signals. For example, relatively small changes in freshwater input have in the past interrupted the thermohaline circulation in the north Atlantic Ocean, causing abrupt shifts in climate conditions on decadal time scales (Dansgaard-Oeschger Cycles). Palaeorecords show that oceanic processes link the dynamics of atmospheric carbon dioxide to those of dust-borne iron fluxes to the ocean (**Box 6**). Such changes indicate close links and feedbacks between the components of the Earth System even though we may not fully understand their mechanisms.

The last decade has seen major advances in our understanding of the ocean system through efforts ranging from individual science to the major ocean research projects co-sponsored by IGBP, SCOR and other organizations. Key processes have been investigated on a global scale. Present and past biogeochemical processes and the impact of climate change on these processes have become clear. For instance the importance of trace elements - primarily iron - for ocean productivity has been highlighted both from experiments and from palaeorecords. Recently identified micro-organisms, such as the wide-spread occurrence of *Archaea* and heterotrophic photosynthetic bacteria, have changed our understanding of marine biogeochemical cycles. It is very likely that the ocean will be a source of further new and surprising discoveries in the next decade.

Despite this progress, many questions on the role of the ocean in global change remain unanswered. Regime shifts (**Box 2**) are being observed in ocean ecosystems that are related to climatic oscillations such as El Niño-Southern Oscillation (ENSO) and the North Atlantic

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Oscillation (NAO), but in most cases causes, consequences, and time scales are uncertain. To obtain a meaningful understanding of the ocean system and its varying states we must incorporate data and processes operating on short to long time scales. For instance, the CO_2 that is outgassing from the ocean at present was absorbed by the ocean many centuries, perhaps millennia, ago.

The ocean's interfaces, that is, the coastal zone, sea surface and seafloor, are sensitive boundaries through which large fluxes of energy and material are exchanged. For example, increasing fluxes of nitrogen compounds from land increasingly alter elemental cycles in the coastal ocean (**Box 3**). Exchanges between the ocean interior and the seafloor are still poorly understood, partly due to technological difficulties in making observations in these remote areas. Vast quantities of methane stored in the sediments can, at increased temperatures, be an as yet unquantifiable source to the atmosphere. Across the ocean-atmosphere interface enormous fluxes of gases occur. They affect and are affected by air chemistry and climate. Therefore we need to understand the susceptibility of critical processes occurring at the ocean interfaces to global change.

Since the development of human civilisation, some key components of the Earth System, in particular atmospheric methane and CO_2 concentrations and average global temperature, have now moved outside the range of natural variability. Marine ecosystems experience fundamental changes in their composition and structure as a result of atmospheric forcing of ocean dynamics. These non-linear changes have been identified, but are not well-understood and, at present, cannot be predicted. It is not clear how the ocean system will respond to such changes in the future. Truly remarkable advances in our understanding have been achieved through coupled models, but they still cannot adequately provide the information needed to address key ecological questions. Of particular importance to our understanding of the Earth System are feedbacks between different components of the Earth System causing either damping of processes (negative feedbacks) or enhancement of processes (positive feedbacks) and abrupt changes in system behaviour. Such examples are known from palaeorecords and emerge from models, but are difficult, if not impossible, to observe directly by our short-term measurement programmes.

Future research on global change in the ocean must focus on the triggers and buffers in Earth System dynamics and on regions most susceptible to global change. Four overarching questions have been adapted from the GAIM "Earth System Questions"[3] to guide the development of specific research questions for ocean biogeochemistry and biology:

- *What are the critical components in the ocean?*
- *What are the major feedbacks between the ocean and other Earth System components?*
- *What are the ocean regions most vulnerable to global change?*
- *What critical components of the ocean system are most sensitive to human action and have greatest impact on humans?*

The multitude of interacting components that determine the ocean system are not all critical for global change. Some components change on such long time scales that they may not be relevant for human societies. Some regions of the ocean (e.g., the North Atlantic thermohaline circulation, polar deep water formation, monsoon areas) are vulnerable to specific

[3] Sahagian, D, and the GAIM Task Force (2002) Special Issue – GAIM's Hilbertian questions. Research GAIM, 5(1):1-16.

disturbances and may trigger abrupt large-scale changes. An analysis of the critical components of the ocean system and their relevance for global change is needed. Such an analysis will lead to specific research questions such as: Will the ocean uptake of anthropogenic carbon continue at present levels for the next 100 years? What is the role of key species in the functioning of the ocean system and what are the implications of species composition changes? Can, or will, human activities change the dust flux to the ocean in such a way that ocean productivity is altered significantly?

Sustainability[4] and the Ocean

Human activities, both on land and in the ocean, are influencing the ocean at an ever-increasing rate. Already 66% of the world's population lives within 400 km of the coast[5]. Population growth and expansion of mega-cities in the coastal zone have increased pressure on ecosystems and also made human societies more vulnerable to changes in the ocean. Societies rely on the continued provision of *ecosystem goods and services* from the sea, and thus on an ablility to predict and adjust to the future behaviour of the ocean. *Ecosystem goods* (e.g., food, energy, mineral resources) *and services* (e.g., waste assimilation, climate regulation, recreation, transport) are the benefits human populations derive, directly or indirectly, from the marine ecosystem[6].

About 1 billion people depend on fish as a source of protein. Total marine capture fisheries production reached 86 Mt in 2000, the highest level ever[7]. As a result, fishery-induced restructuring of the food web is one of the biggest direct human impacts on the ocean and has led to the collapse of some economicaly valuable fish stocks. Fisheries management has tried, with more or less success, to regulate the exploitation of fish resources. However, decadal climatic oscillations, such as El Niño and others, can surpass human-induced impacts and are presently unpredictable. Longer-term directional changes are relatively unpredictable, and thus, appropriate mitigation and adaptive strategies cannot be devised. The consequences of the combination of natural variability and fishing can be dramatic (**Box 4**). Other direct human impacts on the ocean include increasing nutrient load in rivers, changing freshwater runoff, coastal pollution, destruction of marine habitats and introduction of alien species. Humans also affect the ocean via atmospheric changes: increases in atmospheric carbon dioxide have lowered surface-ocean pH (**Box 5**), and rising temperatures and reduction in sea ice are already being observed. In fact, concern is growing that human-induced changes may severely alter the marine ecosystem and affect the benefits we derive from it. Ecological expression of these changes are seen in the spreading of dead zones in the Gulf of Mexico and elsewhere and the degradation of coral reefs.

The inter-dependence of the ocean and human society points to the need to understand the interaction of the ocean with other components of the Earth System – including humans. Since the beginning of the 20th Century, humans have been a driving force of global change,

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[4] The United Nations define sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations website: http://www.un.org/esa/sustdev/sdissues/sdissues.htm).
[5] Cohen JE, Small C, Mellinger A, Gallup J, Sachs J, Vitousek PM, and Mooney HA. (1997) Estimates of coastal populations. Science, 278(5341):1211-1212.
[6] Costanza R, Andrade F, Antunes P, van den Belt M, Boersma D, Boesch DF, Catarino F, Hanna S, Limburg K, Low B, Molitor M, Pereira G, Rayner S, Santos R, Wilson J, and Young M. (1999) Ecological economics and sustainable governance of the oceans. Ecological Economics, 31:171-188.
[7] FAO (2002), The State of World Fisheries and Aquaculture 2002. Food and Agriculture Organisation of the United Nations, Rome.

influencing the Earth System disproportionately to population size and biomass due to growing technological potential and economic demand. Current knowledge is inadequate to use marine resources while at the same time sustaining the health and integrity of the ocean system. Studies integrating natural and social sciences are required to provide the knowledge necessary to maintain a healthy equilibrium between human requirements and the ocean ecosystem, and to help society to adapt to changes. Overarching questions to guide research on human use of the ocean are:

- *What states of the ocean system could occur which are not compatible with human health and survival?*
- *What are the options and caveats for geo-engineering in the ocean?*
- *What structure of institutions is required for an effective and efficient management of marine resources and for the protection of marine environments as well as marine-based human communities?*

With current technology we have the capability to undertake large-scale manipulations of marine processes to benefit some people, but with costs to others, or to the ecosystem. Such technological fixes include purposeful sequestration and burial of CO_2, new approaches in aqua-culture and exploitation of renewable ocean energy resources. The next decade will undoubtedly feature rising pressure to realize the potential of such options, as global change problems become more pronounced. Scientific knowledge is needed to help identify what is most important for human health and survival, and the options for preserving a resilient and functioning marine ecosystem. Natural and social scientists together should also address the problem of developing more efficient management structures for the marine environment.

Goals and Approaches

The primary objectives for the next decade of global change research in ocean biogeochemistry and biology are to:

- identify, observe and describe components of the ocean that cause, or respond to, global change
- understand the feedbacks from the ocean to Earth System functioning
- predict future changes in ocean biogeochemistry and biology in order to investigate pathways towards sustainability

To achieve these ambitious objectives, enhanced collaboration among physical, biogeochemical, ecological, palaeoceanographic and social scientists will be necessary. Many of the vulnerable regions of the planet are under-studied due to remoteness or a lack of research capacity. A great effort must be made to be globally inclusive in research, in particular strengthening links between developing country and developed country research.

Ocean observing systems are needed to measure key parameters over all ocean regions and over long periods of time. These must be linked to terrestrial and climate observing systems. Feedbacks within the Earth System must receive special attention and humans must be considered as both driving and responding to global change. Enhanced outreach to the public will be vital to ensure that the new knowledge can influence public attitudes, and influence policy and legislation.

Recognizing the importance of a more integrative research agenda, IGBP has recently been restructured. The projects of the second Phase of IGBP are described in **Box 7** with a focus on the development of a single ocean research project.

Where should we be at the end of the next decade of global change research in the ocean? We know now that significant changes are already taking place in the ocean. By the end of the decade we must be able to understand the fundamental processes, drivers, and time scales for these changes. With this information will we be able to develop the capability to forecast future changes to the ocean system. This knowledge is essential to better protect and care for the marine environment for the benefit of future generations. We believe that better stewardship is an achievable goal. Global change research in the ocean has to provide the knowledge to underpin wise policies for sustainable use of the oceans, including policies for impact mitigation and adaptive management.

List of Contributors

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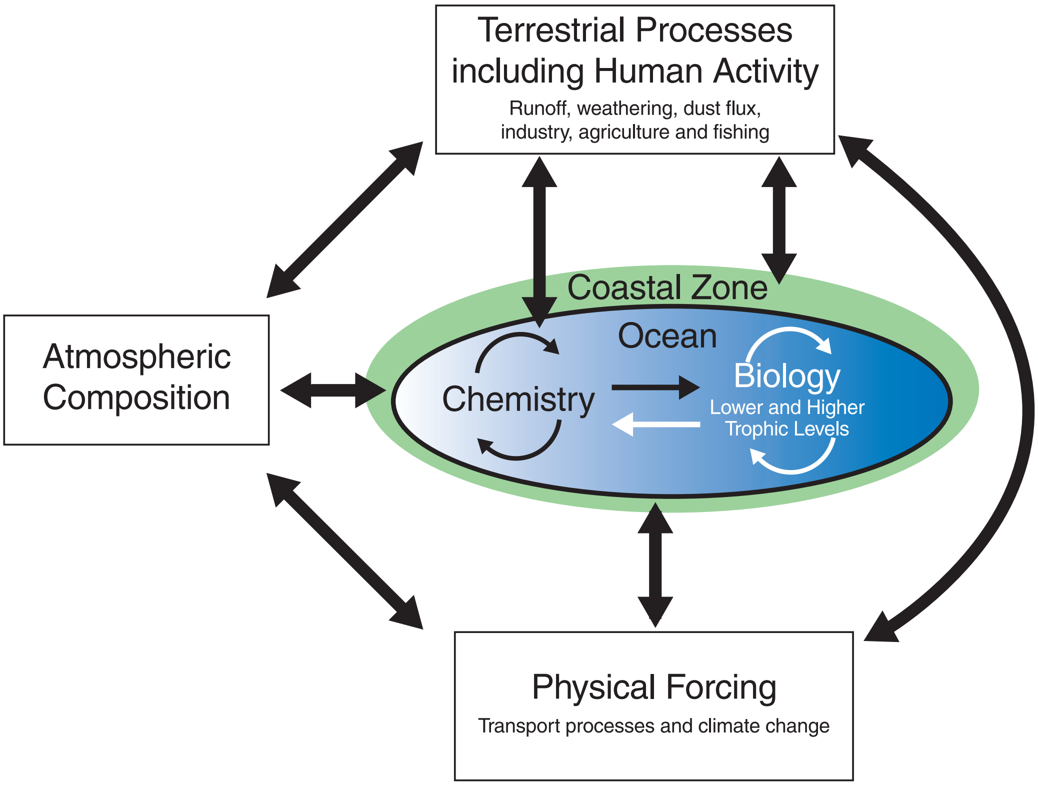
Acronyms

DIVERSITAS: an international programme of biodiversity science
GLOBEC: Global Ocean Ecosystem Dynamics
GOOS: Global Ocean Observing System
IGBP: International Geosphere-Biosphere Programme
IHDP: International Human Dimensions Programme on Global Environmental Change
IMBER: Integrated Marine Biogeochemistry and Ecosystem Research
LOICZ: Land-Ocean Interactions in the Coastal Zone
SCOR: Scientific Committee on Oceanic Research
SOLAS: Surface Ocean – Lower Atmosphere Study
WCRP: World Climate Research Programme

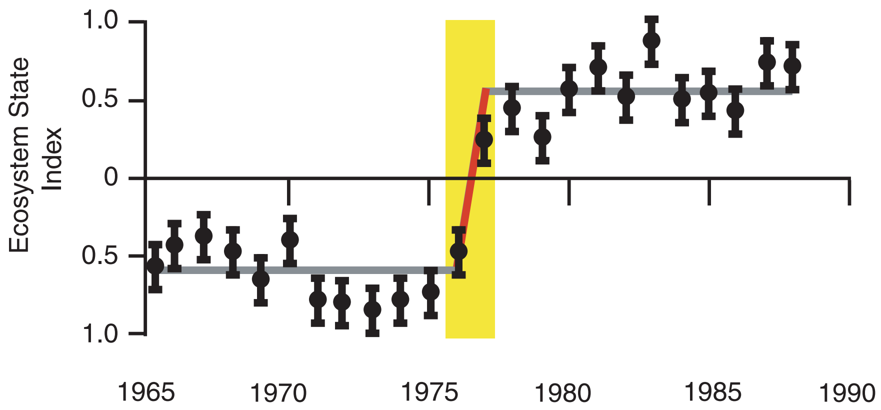
Box 1: Global Change and the Ocean in the Context of the Earth System

The physical, chemical, and biological environment of the ocean and its margins form a complex and tightly coupled system. Global changes (represented by the arrows between the boxes) indicate the connectivity of the ocean and its margins to physical forcing, atmosphere composition, and terrestrial processes including human activity. A few examples of the global changes represented by the arrows include carbon dioxide, iron, nitrogen, and dimethyl sulphide concentrations in the atmosphere and ocean, atmospheric and oceanic temperature, pollution, waste disposal, oxygen concentration, fish catches, introduction of alien species and eutrophication. Human impacts are most apparent in the coastal zone while changes in the atmosphere and the physical forcing are more likely to produce large-scale and long-term effects in the open ocean.



Box 2: Regime Shifts

In the northeast Pacific Ocean a dramatic change in the composition of bottom-dwelling communities from shrimps to fish became apparent in the 1970s (top panel: catches in Pavlof Bay, Alaska)[1]. This coincided with a climatic shift that triggered changes in the north Pacific ecosystem in 1977 (bottom panel: relative changes from 100 physical and biological variables from time series observations)[2]. These regime shifts are related to the decadal Pacific Decadal Oscillation, but the causal relationships are not yet understood. This example demonstrates the strong impact of climatic oscillations on the whole ecosystem.

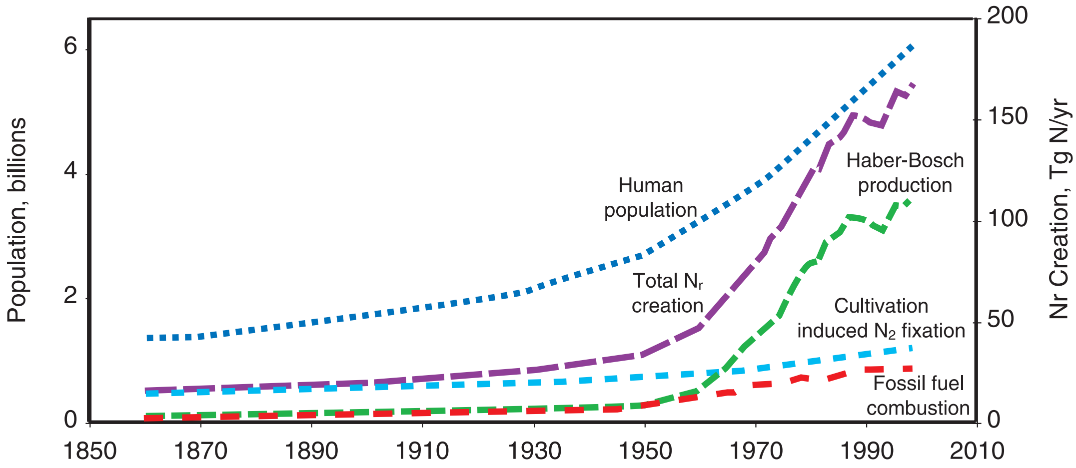


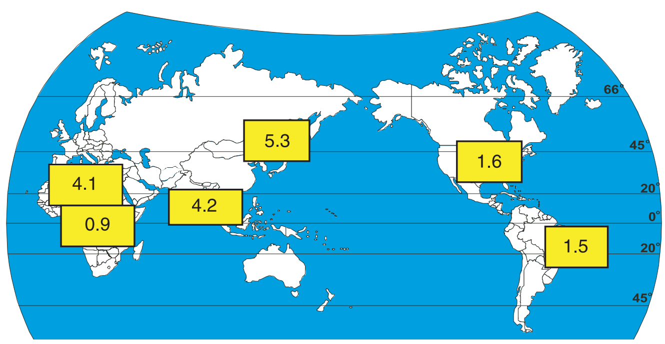
[1] Botsford, L.W., Castilla, J.C, Petersen, C.H. (1997) The management of fisheries and marine ecosystems. Nature, 277: 509-515.

[2] Hare, S.R., Mantua, N.J. (2000) Empirical evidence for north Pacific regime shifts in 1977 and 1989. Progress in Oceanography, 47:147-169.

Box 3: Export From Land to Ocean: Example Nitrogen Fluxes

Export of nitrogen compounds to the coastal zone is one of the major causes for environmental deterioration, for example, causing eutrophication-induced hypoxic zones in coastal seas. Cultivation induced and industrial (Haber-Bosch production) N_2-fixation rates have increased drastically during the past 50 y caused by enhancced food and energy production exceeding the growth rate of the human population (top panel; N_r = reactive nitrogen created from elemental N_2))[1]. This increase in fluxes is partly caused by shifts in human lifestyles to high-protein diets in many developed countries. Dissolved inorganic nitrogen export by rivers to the coastal ocean (in Tg N per year) varies globally due to climatic and societal differences (bottom panel)[2]. Global total export in 1990 was 21 Tg N per year. Models predict a doubling of this river export to 42 Tg N per year by the year 2050[3]. Causes and consequences of such massive changes in elemental fluxes have to be understood and need to be managed to avoid serious deterioration of coastal ecosystems.





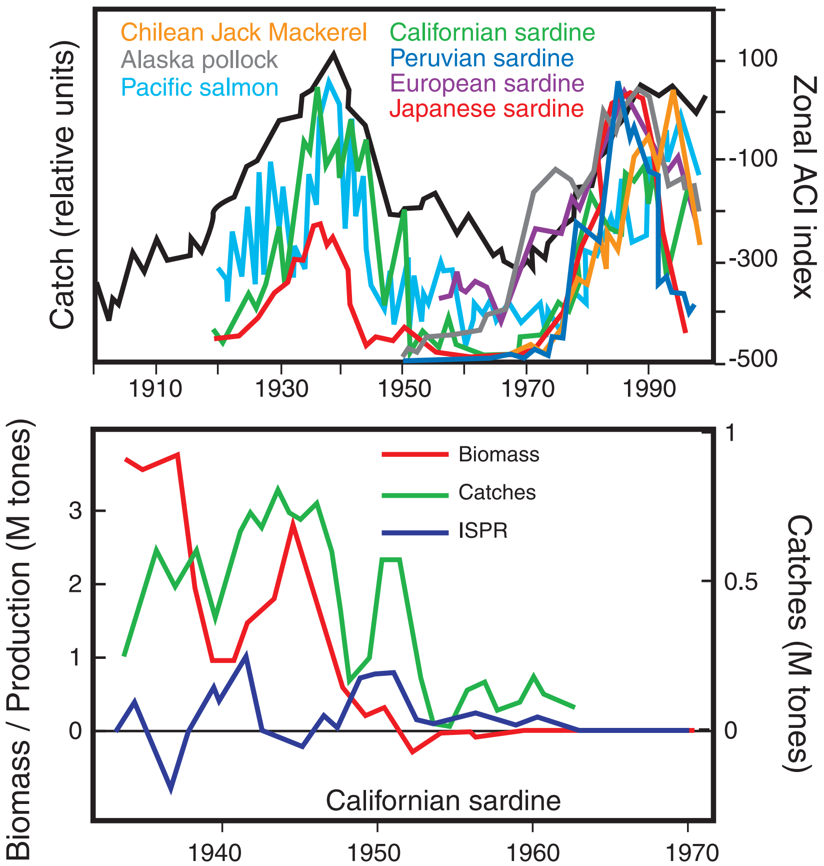
[1] Galloway, J.N., Aber, J.D., Erisman, J.W., Seitzinger, S.P., Howard, R.W., Cowling, E.B., Cosby, B.J. (2003) The nitrogen cascade. BioScience, 53: 341-356.

[2] Seitzinger, S.P., Kroeze, C. (1998) Global distribution of nitrous oxide production and N inputs in freshwater and coastal marine ecosystems. Global Biogeochemical Cycles, 12: 93-113.

[3] Kroeze, C., Seitzinger, S.P. (1998) Nitrogen inputs to rivers, estuaries and continental shelves and related nitrous oxide emissions in 1990 and 2050: a global model. Nutrient cycling in agroecosystems, 52: 195-212.

Box 4: Natural and Fisheries Impacts on Fish Stocks

Fluctuations of fish catches for twelve species (accounting for more than 50% of worldwide catches) over the last 100 years show cyclical fluctuations of about 55 years (top panel). Although the length of the series is too short for strong conclusions to be made it agrees with the 50-70 year fluctuation of sardine and anchovy biomass in the California region over the last 1600 years (data not shown)[1], as well as with the fluctuations in the Atmospheric Circulation Index (ACI). The ACI characterises the dominant direction of air mass transport in the Northern Hemisphere. It is less variable but strongly correlated with other global indices such as the Length of Day (LoD) and the anomaly in air surface temperature (dT). The implication is that fish fluctuations are modulated by global production cycles, although overexploitation over the last two decades may be overwhelming these cycles. Overfishing, when Californian sardine stocks were naturally low, led to a stock collapse in 1940s (bottom panel)[2].

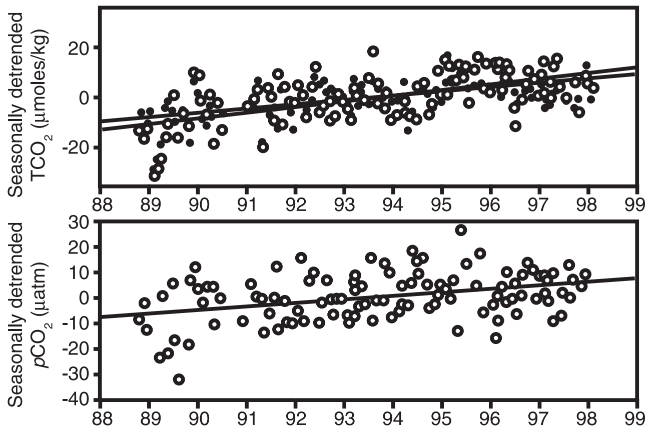


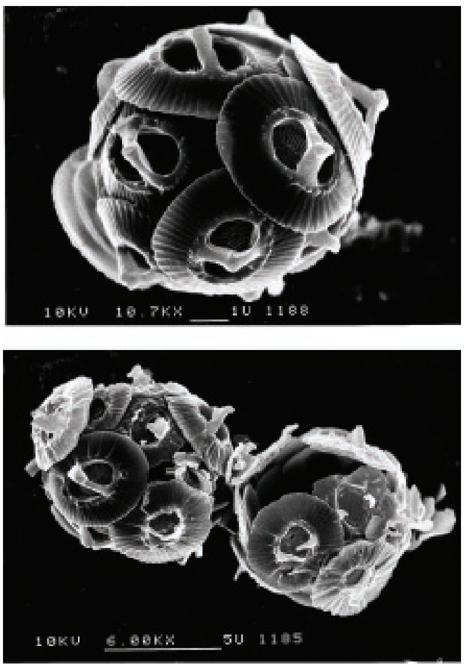
[1] Baumgartner, T., A. Soutar, V. Ferreira-Bartrina. 1992. Reconstruction of the history of Pacific sardine and northern Pacific anchovy populations over the past two millennia from sediments of the Sta Barbara Basin. CalCOFI Rep., 33: 24-40.

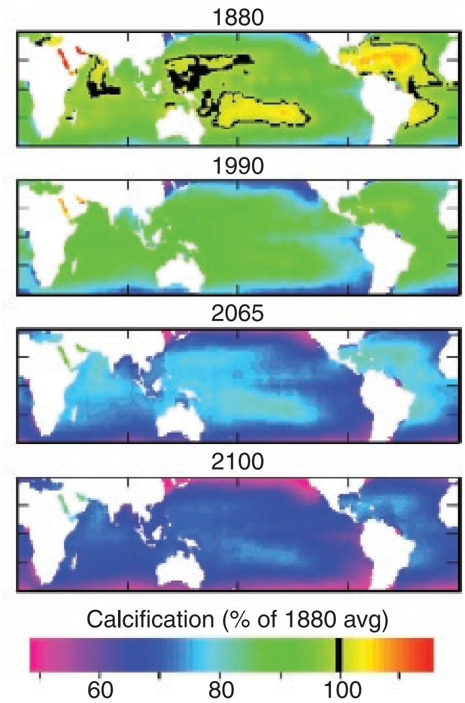
[2] Modified from Klyashtorin, L. 2001. Climate change and long-term fluctuations of commercial catches: the possibility of forecasting. FAO Fish. Tech. Pap. 410. 86 p.

Box 5: Rising CO_2 and Marine Ecosystems

Over the period of a decade, increases in surface water total CO_2 (TCO_2) and CO_2 partial pressure (pCO_2) have been observed at the Bermuda Atlantic Time-Series Station (top panel)[1]. Such change in CO_2 decreases seawater pH with detrimental effects on biological calcification, as shown here for carbonate shells of plankton algae (coccolithophorid *Geophryocasa oceanica*) exposed to CO_2 levels predicted for the year 2100 (left panel)[2]. For the future, a substantial decrease in calcification of plankton and corals is indicated by models (right panel)[3]. It is unclear how the marine foodweb, from plankton to fish, will adapt to such changes.



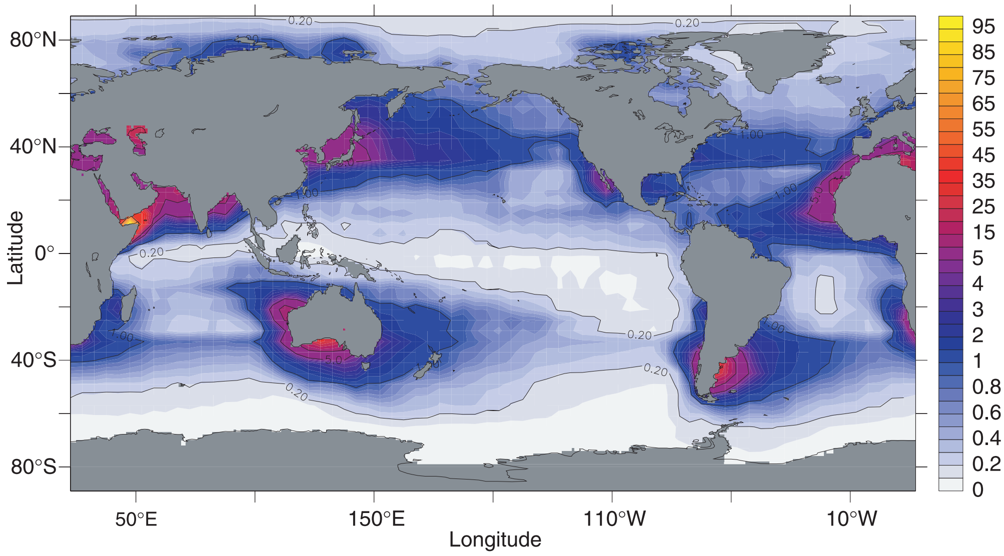


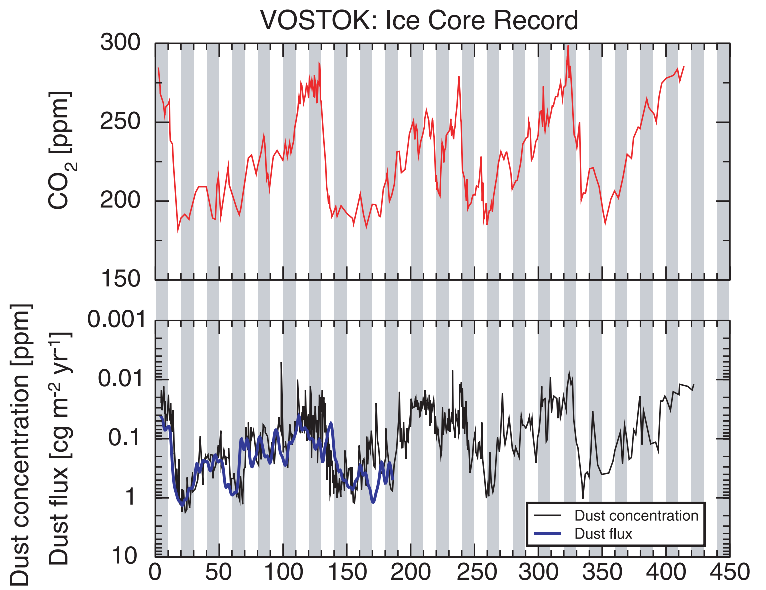


[1] Bates, 2001, Deep Sea Research II, Interannual variability of oceanic CO_2 and biogeochemical properties in the Western North Atlantic subtropical gyre48, 1507-1528
[2] photos courtesy Ulf Riebesell.
[3] Kleypas, J. A., Buddemeier, R.R., Archer, D., Gattuso, J-P., Langdon, C. & Opdyke, B. N., 1999, Geochemical consequences of increased atmospheric carbon dioxide on coral reefs. Science. 284, 118-120.

Box 6: Feedbacks in the Earth System Via Dust

Dust flux from land supplies iron to the ocean – a limiting element for algal growth in wide ocean areas. Modelled contemporary dust fluxes (top panel) highlight strong regional differences in dust flux, with some areas of the ocean receiving extremely low inputs[1]. Antarctic ice cores show an inverse relationship between atmospheric carbon dioxide and dust fluxes (bottom panel)[2]. Changes in dust-borne iron may have altered biological uptake of carbon dioxide in the ocean and may thus have contributed to a climatic feedback in the Earth System. The mechanisms of such a potential feedback are still uncertain.



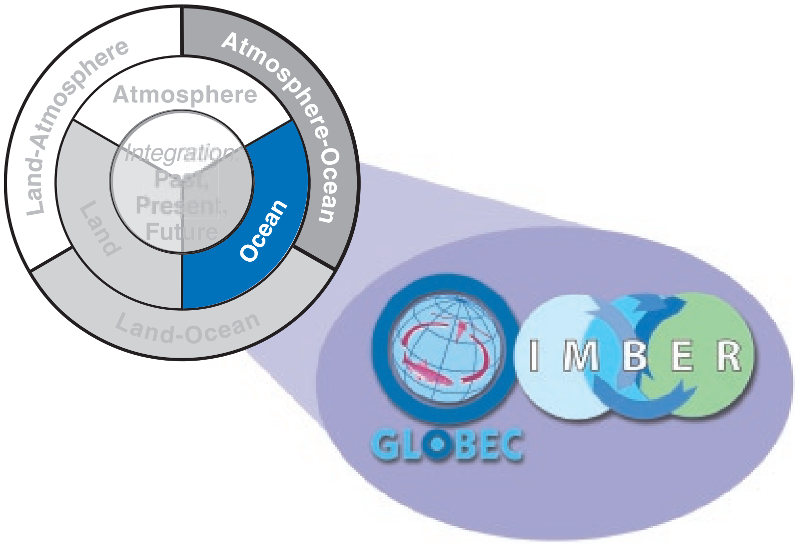


Petit et al. (1999)

[1] Tegen I, and Fung IY. (1994) Modelling mineral dust in the atmosphere - sources, transport, and optical thickness. Journal of Geophysical Research - Atmospheres, 99(D11):22897-22914. (modified by N. Gruber)

[2] Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola J-M, Basile I, Bender M, Chappellaz J, Davis M, Delaygue G, Delmotte M, Kotiyakov VM, Legrand M, Stievenard M (1999) Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. Nature, 399:429-436. (modified by N. Gruber)

Box 7: IGBP Ocean Research in an Earth System Context



IGBP research over the next decade will be built around eight projects: three oriented towards the major Earth System compartments – land, ocean, and atmosphere; three concentrating on the interfaces between compartments; and two focusing on the changing environment of the entire planet – from the past through the present to the future. The ocean project is developing within this structure, in collaboration with SCOR and other co-sponsors. The Ocean Vision provides a scientific framework to guide integrated research.

The ocean project will be implemented through a partnership of GLOBEC and IMBER that will undertake joint activities such as:

- research to address questions such as those posed in the Ocean Vision, starting with a comprehensive food web study;
- periodic scientific syntheses or overview papers;
- open science conferences;
- collaborative research and integrated data management with the IGBP interface projects that have marine components – SOLAS and LOICZ.

Partnership activities will be supervised by a coordinating committee composed primarily of representatives from the GLOBEC and IMBER Scientific Steering Committees (SSCs) and International Project Offices (IPOs), with additional representation from SOLAS and LOICZ as appropriate. The work of the partnership will be facilitated by the co-location of the GLOBEC and IMBER IPOs (pending arrangement of suitable financial support) and joint sessions of the two SSCs. The partnership will implement the IGBP ocean project until 2009, when GLOBEC will complete its work. As the partnership evolves, and as more joint activities are developed, a parallel planning process aimed at creating a single, integrated ocean project from 2009 will be undertaken by the two SSCs. To fulfil the Ocean Vision also will require collaboration with scientists from WCRP, IHDP, DIVERSITAS, GOOS and others.