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IGBP REPORT 40

GLOBEC REPORT 9

Global Ocean Ecosystem Dynamics (GLOBEC)
Science Plan

The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP) of the International Council of Scientific Unions (ICSU)
Stockholm, Sweden

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Global Ocean Ecosystem Dynamics (GLOBEC) Science Plan

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Stockholm, Sweden

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Science Plan

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Preface

Human population and associated industrial activities continue to increase rapidly, and have reached levels that put the environment under stress in many areas of the world. In addition natural fluctuations of the Earth's physical and biological systems, often occur in time frames that are not readily evident to man. Such fluctuations cause additional stress on the environment, and can result in changes that impact society in terms of diminished availability of clean water, unspoiled land and natural vegetation, minerals, fish stocks, and clean air. Human societies are making a rapidly increasing number of policy and management decisions that attempt to allow both for natural fluctuations and to limit or modify human impact. Such decisions are often ineffective, as a result of economic, political and social constraints, and inadequate understanding of the interactions between human activities and natural responses. Improved understanding of such issues is important in its own right, and will contribute to ameliorating economic, political and social constraints. Developing improved understanding of environmental change is within the realm of the natural sciences and is being addressed by the International Geosphere-Biosphere Programme (IGBP) and other programmes concerned with describing and understanding the Earth System.

An integrated and coherent understanding of natural forcing and its interactions with human populations requires improved understanding of global ocean ecosystem dynamics, the focus of the Global Ocean Ecosystem Dynamics (GLOBEC) IGBP Programme Element. A key issue is the ability to differentiate anthropogenic from naturally occurring effects in marine ecosystems. Three major gaps in our current knowledge are:

- Dynamics of zooplankton populations both relative to phytoplankton and to their major predators
- Influence of physical forcing on these population dynamics, particularly at the mesoscale
- Estimation of biological and physical parameters associated with the dynamics of zooplankton relative to phytoplankton.

Two examples can be used to illustrate the pressing need to improve our understanding of the ocean ecosystem. As the first, a dramatic multidecadal decline in plankton biomass has been demonstrated in the North Sea and in the eastern North Atlantic by extensive continuous plankton recorder (CPR) sampling over a 44 year time period (Figure 1). Various explanations have been offered for this decline. Refining these explanations is a major challenge for the field of ocean ecosystem dynamics. Such changes are also of interest from a biogeochemical viewpoint because they may relate to changes in the surface fluxes of CO_2. In this context the North Atlantic is one of several sites constituting a well-documented natural laboratory. Such natural laboratories can provide the bases for inferences that can then be extended to the entire global ocean system.

As a second example, and one more visible to the general public, the *New York Times* (3 August 1993, p. C4) reported that "Scientists, industry experts and government officials agreed at a United Nations (UN) Conference that overfishing and the destruction of the habitat have caused alarming drops in marine populations". This statement reflects a widespread concern with the current state of global fisheries. Both GLOBEC and the other Programme Elements of the IGBP are directed towards basic science, but they are also intended to be policy relevant, with the objective of providing the best possible scientific information to the policy and management communities. The UN statement highlights, our current lack of knowledge concerning the marine ecosystem dynamics that contribute to the health of these fisheries.

Natural variability, occurring over a variety of time scales, dominates the health of complex marine ecosystems, regardless of fishing or other environmental pressure. We are only now beginning to compile quantitative documentation of such variability, and consequently our knowledge concerning its causes remains at the level of hypotheses. Understanding of the role of variability in the functioning of marine ecosystems is essential if we are to effectively manage global marine living resources such as fisheries during this period of tremendously increased human impact, and concurrent dependence, on these resources.

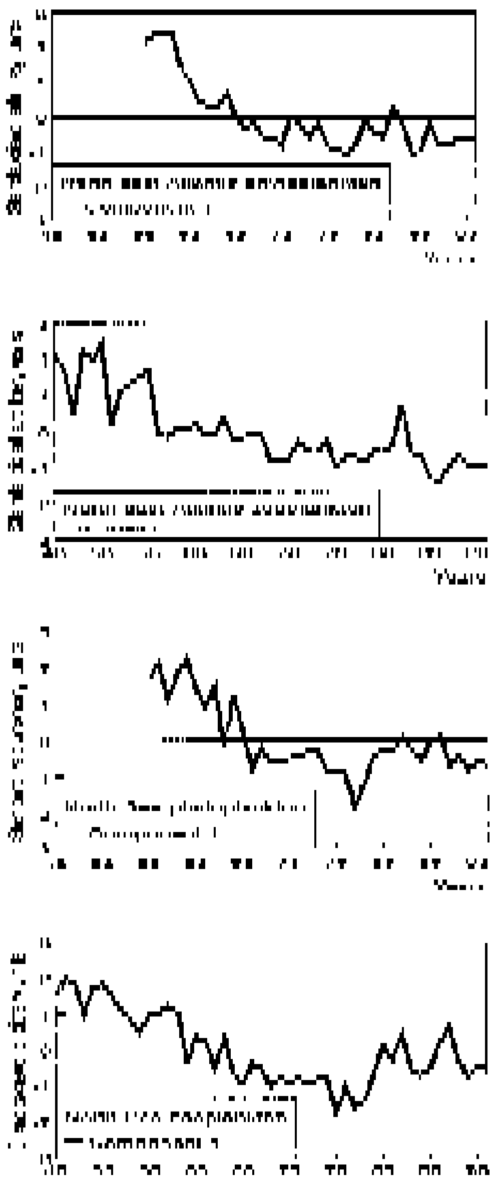
GLOBEC was established by the Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission (IOC) in late 1991, following the recommendations of a joint workshop earlier that year. These identified a need for a coordinated scientific attempt to address the above and other related questions pertaining to higher marine trophic levels. The workshop noted the need "to understand how changes in the global environment will affect the abundance, diversity and production of animal populations comprising a major component of ocean ecosystems". It also recognized the importance of zooplankton in "shaping ecosystem structure...because grazing by zooplankton is thought to influence or regulate primary production and...variations in zooplankton dynamics may affect biomass of many fish and shellfish stocks." This regulatory control function by zooplankton in marine systems is more common in the ocean than are similar controls in terrestrial systems. In the long term, zooplankton exercise a regulatory control over marine systems by the balance between nutrient input from deep water and downward transfer through the larger herbivores. GLOBEC is co-sponsored by SCOR and IOC. The International Council for the Exploration of the Sea (ICES) and the North Pacific Marine Science Organization (PICES) contribute specific regional programme components.

GLOBEC will exploit the use of appropriate models to address key questions related to the global ocean ecosystem. The research strategy includes a strong focus on physical and biological observations made over an appropriate range of spatial and temporal scales, development of multidisciplinary dynamic models, and assimilation of data into these models. It concentrates in particular on zooplankton population dynamics and responses to physical forcing. In so doing, it bridges the gap between phytoplankton studies and predator-related research that more closely pertains to fish stock recruitment and exploitation of living marine resources. Hence GLOBEC is expected to yield a much-improved understanding of the world ocean ecosystem and its response to physical variability resulting both from natural cycles and from global changes in the physical, chemical and biological components of the total earth system.

This document defines GLOBEC science, emphasising both its basic significance and its relevance to IGBP goals and other Programme Elements. GLOBEC now represents a major oceanographic effort directed at an ecosystem approach to global change, and will, of necessity, need to co-ordinate its efforts and integrate and synthesize its results with those of the other Programme Elements of the IGBP. The most effective way this will be achieved is through the Scientific Committee of IGBP (SC-IGBP) in the further development of GLOBEC implementation so that it complements the rest of the programme. Significant scientific benefits accrue through formal IGBP sponsorship of GLOBEC. GLOBEC results on ocean ecosystems will contribute, for example, to IGBP programmes on biogeochemical cycling and on other areas of earth-system science. GLOBEC's planned programme to study the ocean ecosystem, its physics and population dynamics, through a field and modelling programme complements both the other IGBP ocean projects, the Joint Ocean Flux Study (JGOFS) and Land Ocean Interactions in the Coastal Zone (LOICZ). Finally, GLOBEC will benefit from and contribute to the integrative view of the global biosphere being developed within IGBP.

Figure 1

Long-term trends in zooplankton and phytoplankton abundance in the north-east Atlantic and North Sea recorded by the Continuous Plankton Recorder (CPR) survey (Sir Alister Hardy Foundation for Ocean Science).



The Scientific Rationale for GLOBEC

The GLOBEC Goal

The oceans constitute such a large portion of the Earth's surface that the planet has been described as the Water Planet, and it could be argued that its most extensive ecosystem is marine. The ocean is inextricably involved in the physical, chemical and biological processes that regulate the total earth system. It is impossible to describe and understand this system without first understanding the ocean, the special characteristics of the environment that it provides for life, the changes that it is undergoing, and the manner in which these changes interact with the total global ecosystem.

A tremendous effort is currently being expended in studying both marine and terrestrial ecosystems. In the marine sphere, much of the effort is being devoted to JGOFS, which focuses on the lower trophic levels of the marine ecosystem. GLOBEC proposes, through a combination of field observations and modelling, to concentrate on the middle and upper trophic levels. In so doing, it will fill a significant gap in our understanding of the global ecosystem, one that is not being addressed on a global scale by other programmes.

The upper trophic levels of the marine ecosystem are the most obvious to society. Numerous examples, many of them highly publicized in the media over the past decade, can be cited to illustrate ecosystem responses to major transients in physical forcing. In the North Pacific, large increases in winter chlorophyll, macrozooplankton and nekton (swimming organisms such as fish) abundance were observed over broad geographical areas in the 1970's and 1980's. These increases, which included major fish stocks such as salmonids and the far eastern sardine, coincided with changes in the strength of wind fields over the North Pacific. Major declines in phytoplankton standing stock were observed in the Northeast Atlantic from 1950 to 1970, coincident with changes in the westerly winds over the British Isles. When the anchovetta stock off Peru, once so large that it represented about 15% of the annual global fishery, collapsed in 1972, there was a concurrent collapse of the local zooplankton population that coincided with a major El Niño event.

In another example, less visible to society, zooplankton biomass in the California Current region of the North Pacific decreased during a warm water period in the 1970s, coincident with increases in the overall North Pacific zooplankton biomass (Figure 2). The zooplankton decrease was associated with a reduction in organic nutrients resulting from reduced coastal upwelling. These changes raise the question whether the zooplankton increases in the North Pacific are coupled with the decreases in California Current zooplankton or whether their dynamics are independent of one another.

Such changes are among the more dramatic associations, on basin and sub-basin scales, of variations in oceanic biota. By strong implication, physical forcing and variations in the energy flow through the pelagic trophic levels of the upper ocean are also involved. There are, most certainly, a broad variety of other correlations and physical factors involved, but these are as yet not understood.

Better documentation of, and quantitative understanding of, the causal relationships between physical forcing and biological variability are required. The scientific understanding of these relationships obtained in GLOBEC will provide the basis for related policies in response to global change. The need is likely to become critical as anthropogenic pressures on marine ecosystems increase, particularly if the predicted changes associated with global warming materialize. For example, as one scenario, if storm activity were to increase as a result of climate change, upper ocean turbulence would be expected to increase and mixed layers would deepen, with possible effects on predator-prey-interactions in the plankton and implications for marine living resources. GLOBEC must consider such scenarios.

Figure 2

Fourty-four-year time series (1951-1994) of average zooplankton volume and water temperature, together with their anomalies from the California Current (CalCOFI surveys). Number in boxes are the mean and standard deviation used to calculate the anomalies. A warm-water period began in the late 1970s accompanied by a period of decreasing zooplankton volume (Roemmich and McGowan 1995). From P. Smith, 1995 (GLOBEC Report No. 8, 1995).

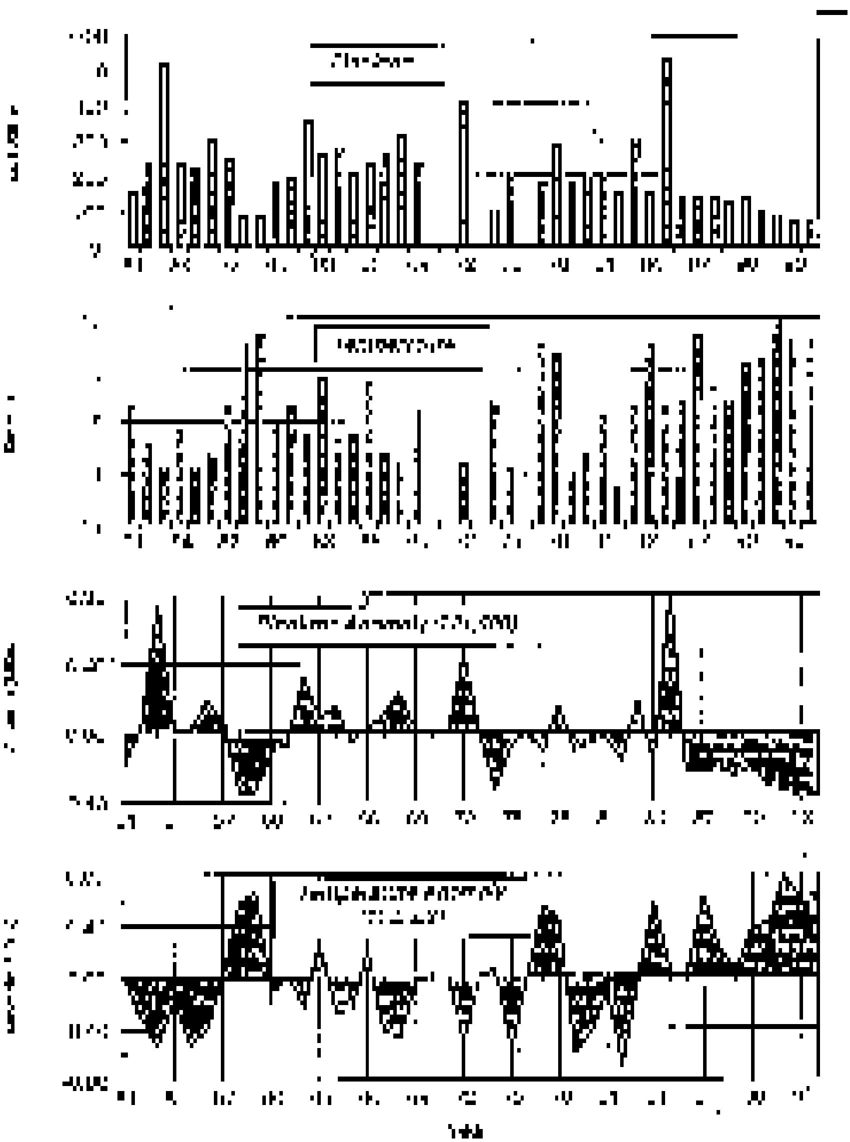
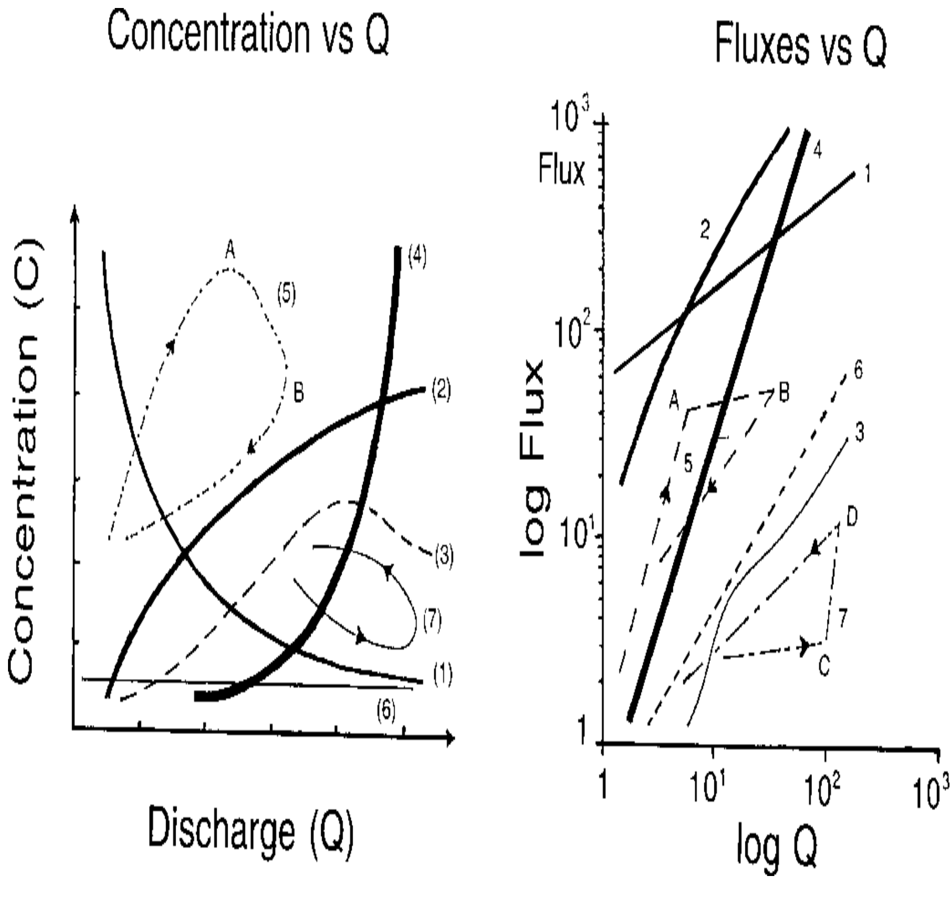


Figure 3

The linkage between zooplankton and fisheries through interactions in the plankton is a primary interest of GLOBEC.



The GLOBEC Approach

The Globec Goal

To advance our understanding of the structure and functioning of the global ocean ecosystem, its major subsystems, and its response to physical forcing so that a capability can be developed to forecast the responses of the marine ecosystem to global change.

GLOBEC uses models to analyse ecosystem interactions rather than the environment-independent population dynamics approach, classically employed as the basis for fisheries studies. It is becoming increasingly apparent that understanding of *interactions* involving lower trophic levels, and physical and chemical conditions is critical. Measurements of bulk phytoplankton production and estimation of age structures for individual fish species (for example) are inadequate to answer current questions concerning fisheries dynamics. Such measurements are even more inadequate for addressing the issue of the impacts of long term environmental change on various aspects of marine production including fish. GLOBEC recognizes the need for new understanding by investigating the structure of marine ecosystems and the dynamics of critical populations. It considers how these structures will change with variable physical forcing and how these changes will in turn influence energy flow, the marine food web, and species abundance and diversity.

GLOBEC focuses on herbivores and primary carnivores (Figure 3) - those trophic levels where primary production is processed to provide energy and nutrients for longer-lived species, which constitute the world's fisheries. The organisms in these groups include a great diversity of species and exhibit many adaptive strategies. For a specific purpose, such as studies of carbon cycling, treatment of this group as a single subset of variables may be possible. However, given the great number of different pathways by which energy and nutrients may be transferred to higher trophic levels and then fed back into nutrients, GLOBEC will require a more complex approach. Study of the entire global ocean is not feasible so selected sites must be chosen with sufficient care that they can serve as proxies for major ocean zones. One of the challenges for GLOBEC is to discover where generalizations may be made and where, conversely, attention to detail is essential. In order to meet this challenge, GLOBEC must focus on specific processes and appropriate sites. These sites will be selected to best test and improve upon the generalizations that relate structure to dynamics. They must, at the same time, represent important subsystems of the global ocean ecosystem.

The emphasis within GLOBEC on zooplankton dynamics complements the JGOFS focus on primary production (Figure 4). Further, GLOBEC studies of the structure and dynamics of critical populations are essential to illuminate the consequences of large-scale physical or biochemical changes in the ocean. There is a similar intersection between the interests of LOICZ and GLOBEC. The coastal seas, which comprise 10% of the total sea surface area, account for 90% of the world fishery catch and are by far the most biologically productive. The impacts of anthropogenic change, global as well as local, are most apparent in the coastal zone. Therefore, food web dynamics within the coastal zone are emphasized in GLOBEC, and this component of GLOBEC will complement and interact with LOICZ.

Space and Time Scale Considerations

Animals living in the ocean are affected by physical processes ranging from centimetre scales of turbulence through kilometre mesoscales, where eddy motions dominate, up to the ocean basin scales of the major current systems (Figure 5). All of these scales are ecologically interesting and scientifically important. However, the focus of the GLOBEC programme must be narrowed to those space scales on which the physical processes have the most impact on biological variability. It is at these critical scales that the answers sought by GLOBEC will be found.

GLOBEC aims to understand the forces driving changes in marine ecosystems on decadal to century time scales. Signals at these scales appear in fluctuations of many of the major world fisheries. The shorter, decadal fluctuations have physical counterparts in changes in circulation and hydrographic properties of ocean basins such as the North Pacific. Processes at space and time scales of years and thousands of kilometres link local or regional patterns and processes in the global ocean system, and thus provide a focus for the planning of field and modelling activities in GLOBEC.

Despite the large scales of the fluctuations noted above, the processes that drive the interactions between, for example, fish and copepods are generally at smaller scales. In particular, these interactions occur at the dynamically energetic oceanic mesoscales, which have dimensions of kilometres to tens of kilometres. The coupling of small scales, mesoscales and macroscales is a central problem for GLOBEC and is comparable to the integration of landscape and regional processes on land. To achieve this it will be necessary to absorb via parameterization the smaller scale processes into the larger scales.

Terrestrial vs. Marine Systems

On land, the dominant interaction at global scales is between plant communities and the atmosphere. The physical and chemical state of the atmosphere, its temperature, water and CO_2 content define the conditions for terrestrial biological activity. Soil conditions, which depend also to a large extent on atmospheric conditions, play a major role as well. The presence of terrestrial vegetation influences atmospheric physical and chemical properties and the soil conditions. Terrestrial systems change naturally on time scales of centuries, although anthropogenic influences can greatly shorten these scales. As an illustration, current land use practice has led to the nearly total destruction of the native plant ecosystem in the US Great Plains region. Declines in mammalian predators have also been attributed to land-use practices. Reduction in the extent of grazing lands has led to decreases in numbers of ungulates, and the destruction of bamboo stands has endangered the panda. The abundance, distribution and diversity of species, as well as the productivity and survival of important tree species and agricultural crops, are of special concern. This focus upon vegetation in terrestrial systems is reflected in the IGBP Programme Elements on Global Change in Terrestrial Ecosystems (GCTE) and Land-Use and Land-Cover Change (LUCC).

Marine production is dependent, at the most basic level, upon ocean mixing and circulation that control primary productivity by influencing phytoplankton exposure to nutrients and light. These physical processes are determined, in turn, by climatic factors such as variability in storm wind frequency, cloudiness and rainfall which exert dominant physical influence over the biologically active upper ocean layers. Time scales of change in marine systems can be very short, of the order of a few years, as illustrated by the crash of the Peruvian anchovetta fishery. The effects of global change on marine ecosystems are generally perceived by society only when these effects become evident at the upper end of the trophic system. Such effects include alterations in the abundance, distribution and diversity of fish and marine mammals.

Trees and perennial grasses are the longest lived components of terrestrial food webs. Ocean plants (phytoplankton) are, conversely, among the shortest lived components of their respective food webs. Marine plants reproduce far more rapidly, however, than terrestrial plants. For phytoplankton, the generation time is on the order of a few days. Aside from marine mammals and reptiles, fish are among the longer lived marine organisms. However their individual life cycles are generally less than a decade, or one to two orders of magnitude less than those typical of terrestrial systems. This overall difference in life cycle time scales makes marine systems more responsive than terrestrial ones to changes at decadal scales.

One consequence of these differences in life cycle time scales is reflected in carbon stocks. About 600 Pg C (where 1 Pg = 1 x 10^9 metric tons) are contained in terrestrial vegetation, and net terrestrial primary production results in an exchange of about 50 Pg C per year. The standing stock of carbon in oceanic phytoplankton is only 3-5% of that in terrestrial plants, however, carbon cycling in marine systems is 60-80% of the terrestrial value.

Despite these differences, marine and terrestrial systems all exhibit close linkages between energy flow, chemical cycling and food web structure. Major perturbations in the energetics or biochemistry generally lead, in either system, to dramatic changes in species composition. Variations in abundance at higher trophic levels typically reflect changes in physical or chemical processes that are mediated, in many instances, through the lower trophic levels. Hence, knowledge of the responses of dominant species at several levels in the trophic structure offers insights into subtle changes in the physical/chemical system. Correspondingly, for understanding population dynamics of dominant species, knowledge of the ecosystem energy and nutrient budgets is essential.

Figure 4

A flow diagram illustrating the complementary nature of the three IGBP marine Programme Elements; GLOBEC, JGOFS and LOICZ.

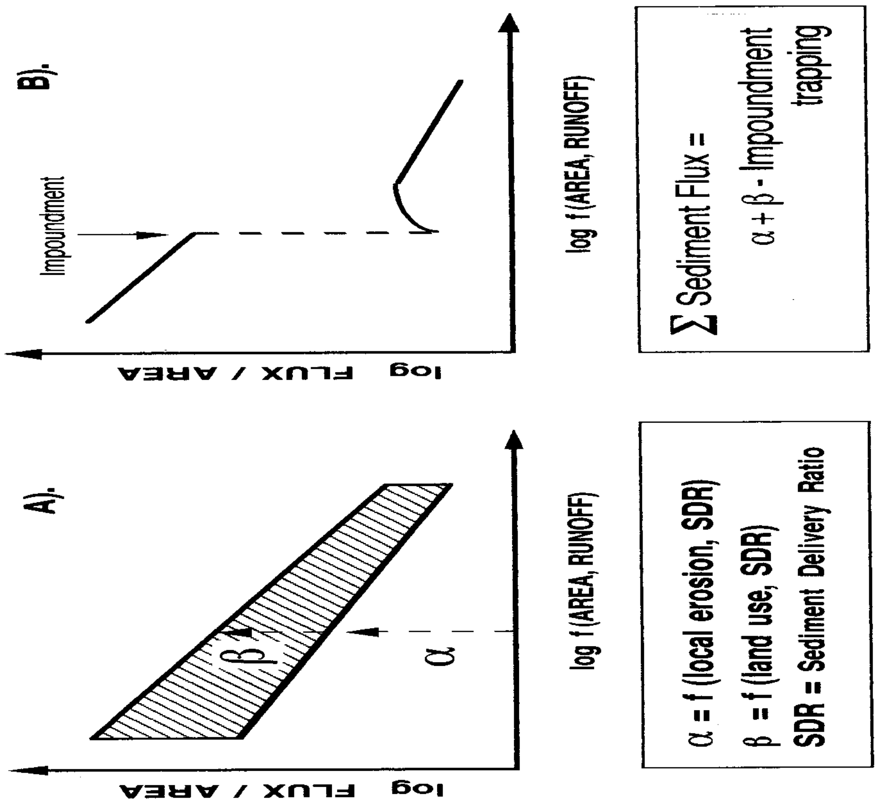
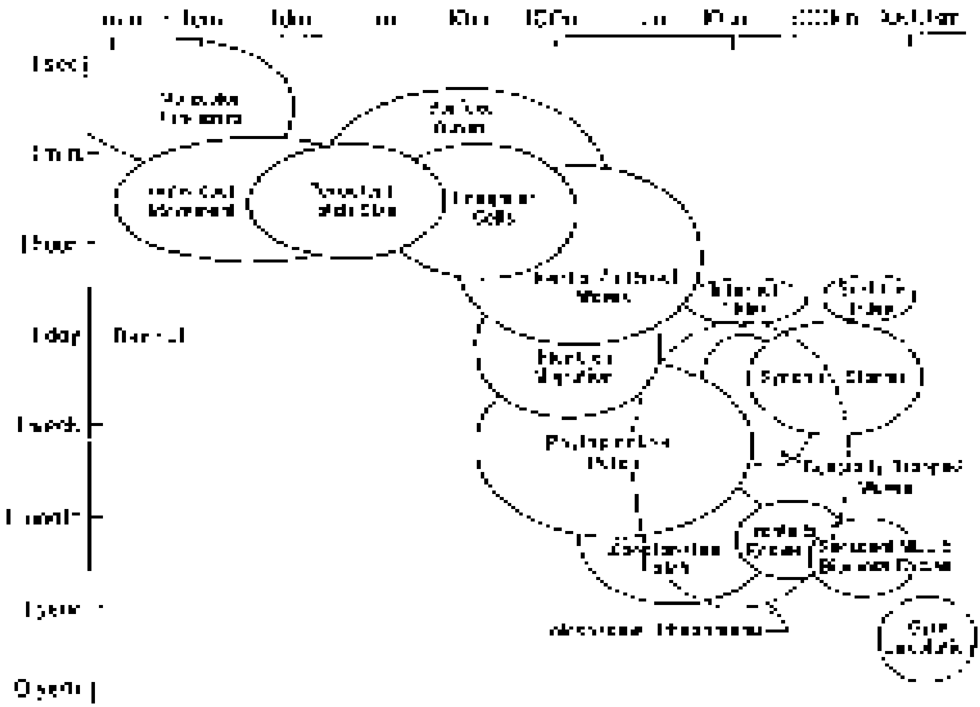


Figure 5

A schematic diagram illustrating the relevant time and space scales of several physical and biological processes of importance to GLOBEC (after Dickey, 1991) (GLOBEC Report No. 3, 1993).



Globec Objectives

Consideration of the points previously mentioned in this Science Plan lead directly to the development of the four primary GLOBEC objectives, which are stated and explained here.

Objective 1
To better understand how multiscale physical environmental processes force large-scale changes in marine ecosystems.

Physical conditions over a broad range of scales in the sea, both vertical and horizontal, influence marine ecosystem processes. At the very smallest scales, those where turbulent dissipation occurs, water motions, over distances of a few cm and over a few seconds time, are known to influence predator-prey interactions among planktonic organisms. Moving to the mesoscale, encompassing distances of kilometres to tens of kilometres, the possible physical influences on biological processes become more extensive. Strong currents associated with mesoscale features, such as coastal or shelf break currents, can transport planktonic organisms over great distances. Organisms may become trapped in mesoscale eddies and isolated from their original environment and their customary food supply. Water motion (upwelling or downwelling) associated with jets or eddies can lead to significant variations in physical and chemical characteristics of the water and in turn lead to changes in prey availability. Finally, large-scale changes in circulation or in physical or chemical water characteristics can alter the basic environmental conditions for organisms, leading, in extreme cases, to mortality and changes in species composition.

Interactions between organisms and their physical environment are neither well-documented nor understood in a qualitative sense. As an example, patchiness in space and time has long been known to be characteristic of marine populations. While it is suspected that such patchiness is related to oceanic mesoscale features, biological processes, and physical-biological interactions, observations adequate to determine causes are lacking. The same is true for observations of the very small scale interactions. Knowledge of these processes, both from an observational and a modelling viewpoint, is essential if the GLOBEC goal is to be achieved.

Objective 2

To determine the relationships between structure and dynamics in a variety of oceanic systems which typify significant components of the global ocean ecosystem, with emphasis on trophodynamic pathways, their variability and the role of nutrition quality in the food web.

Carbon flux pathways through marine ecosystems provide a valuable framework for estimating productivity at different trophic levels. However, it is extremely difficult to quantify the flows of carbon in food web networks. A much more sensitive indicator or predictor of change is alteration in species composition. An example can be taken from fisheries. For many of the dramatic changes in fish communities, there has been no associated evidence of changes in overall trophic energy flow. The past focus of fisheries studies has been on changes in individual stocks rather than on the competitive or predatory interactions among these stocks. Yet, these interactions must determine the ability of marine systems to experience major changes in species structure without any obvious changes in the energy flow through them. This is a significant difference between marine and terrestrial systems undergoing changes at these time scales.

The general or "global" problem is to describe the relationships between food web structure and trophic dynamics for ecosystems that represent the major marine environments that are representative of upwelling, coastal, oligotrophic ocean, and polar seas.

Objective 3

To determine the impacts of global change on stock dynamics using coupled physical, biological and chemical models linked to appropriate observation systems and to develop the capability to predict future impacts.

Models are an essential component of GLOBEC, and the strategy for their development is central to the Core Programme. Four features must be incorporated into this strategy. First, critical variations need to be identified. Second, models must focus on appropriate time and space scales. Third, interactions among scales must be addressed. Finally, consistency between data and model results must be tested.

GLOBEC modelling employs selection of the oceanic mesoscale as its fundamental scale, or starting point, with sufficient extension to provide information on interactions with larger and smaller scales. The modelling effort must resolve ecosystem dynamics and effects of physical forcing on these dynamics at the mesoscale. This will require incorporation of information from other scales.

Three themes contribute to the foundation of the mesoscale modelling programme;

- The role of mesoscale physics in modulating ecosystem processes;
- The dynamics of populations of copepods and other metazoan plankton; and
- Linking the dynamics of copepods and other metazoan plankton with fishery dynamics.

The linkages among physical conditions, marine food web structures and ecosystem or population dynamics provide a unifying theme for GLOBEC. An example of the coupling between physics, structure and population dynamics is provided by microbial loops, processes that are now recognized as important factors in ocean ecosystem dynamics. Microbial loops influence nutrient supply but are in themselves dependent upon vertical density stratification, which also influences the nutrient supply. The interactions are complex. Variations in the physical system will be reflected by changes in the trophic structures, hence, ultimately in fishery dynamics. From another viewpoint, this structure highlights the importance of metazoan plankton as key links between processes involved in nutrient recycling and the population dynamics of higher trophic levels (Figure 6).

Changes in the physical and biological properties of very large scale marine ecosystems, such as those having ocean basin scale, are so extensive, and impact such a large portion of the world ocean, that they themselves can be considered as global changes. Moreover, by virtue of their geographic extent, they have the potential to influence other components of the earth system. Shifts in ecosystem composition at higher trophic levels can cause changes in the phytoplankton assemblage or standing stocks, and vice versa. These changes can in turn affect the transport of gases across the sea surface because photosynthetic efficiencies and physiologies of phytoplankton species vary. Such shifts and the associated potential feedbacks are of particular interest to JGOFS and the International Global Atmospheric Chemistry Project (IGAC). A change in phytoplankton composition can also affect CO_2 exchange through mineralization processes and bring about the release of other gases, such as dimethyl sulphide to the atmosphere with implications for atmospheric acidity and particle formation.

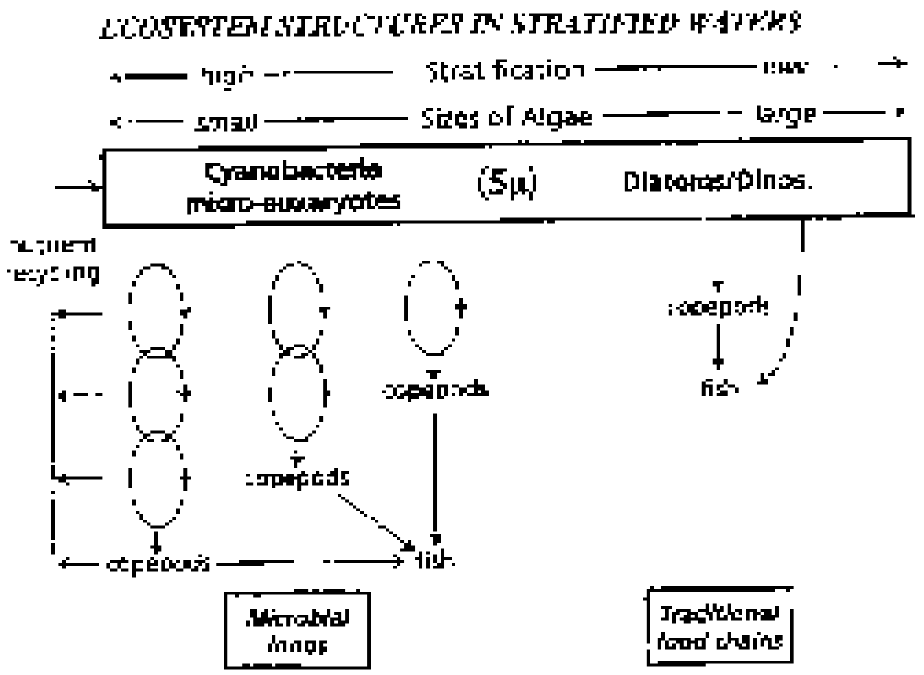
Objective 4

To determine how changing marine ecosystems will affect the global earth system by identifying and quantifying feedback mechanisms.

Other, direct effects of marine ecosystem changes include the impact that changes in commercial stocks have on coastal human populations. GLOBEC research on the response of small pelagic fish populations to climate change in the coastal zone will be of particular interest to LOICZ. GLOBEC can identify a number of the significant processes and will cooperate with other IGBP projects in pursuing an answer to the question of how changing marine ecosystems will influence the overall earth system.

Figure 6

The classical food chain (diatoms; copepods; fish) is important during upwelling events and spring blooms. But smaller organisms (bacteria; heterotropic flagellates; ciliates etc.) are an increasing significant component in stratified waters, both for food web structure and nutrient conservation in the upper layers. The copepods are then predominantly carnivorous but retain their role as “gatekeepers” for fluxes to deeper waters and higher tropic levels (after Azam *et al.,* 1983; Cushing, 1982).



Research Strategy

Overall Approach

The approach taken by GLOBEC is driven by the extreme complexity of the problems being addressed. The number of relevant variables is very large, as the models must include a broad range of physical, chemical and biological processes. To focus its efforts, GLOBEC will identify the most critical variables. Many of the key processes and interactions are not yet well understood. Many parameters, such as mixing rates and *in situ* zooplankton grazing rates, remain to be determined. Dynamical and statistical models with both analytical and numerical character are required. New field data are needed to suitably parameterize and verify these models. GLOBEC will be a highly integrated programme that utilizes coordinated field and modelling efforts to attain its goals.

Modelling within GLOBEC will address multiscale oceanic physical and biological processes and will focus on mesoscale phenomena on spatial scales from kilometres to tens of kilometres. This scale, which is determined through dynamic physical processes and can be rigorously defined in terms of physical parameters, applies to most well defined current, eddy and frontal features. Such features, which are among the most energetic in the ocean, strongly influence many biological processes through physical mechanisms such as advection, upwelling, downwelling and mixing. For example, in the vicinity of the Norwegian shelf, important planktonic species overwinter in deep water and are advected onto the shelf in spring. However, changes in the shelf currents responsible can alter the shelf-wide zooplankton population and thereby influence the recruitment of fish stocks such as herring and cod. Mesoscale oceanic features, in the form of shelf and slope current systems, are typically associated with the continental boundaries that are also the regions of highest biological productivity and most intensive fishing activity in the global ocean. Understanding the processes that control productivity in the coastal and shelf regions will demand a thorough grasp of mesoscale processes.

Turbulent motions, which occur on far smaller space and time scales than the mesoscale, are of critical importance for considering predator-prey interactions in the plankton. Turbulence influences productivity in a number of ways. At the smallest spatial and time scales, turbulent movements can influence predator-prey encounter rates and feeding efficiency. Turbulence also strongly influences chemical diffusion patterns and organized flow structures that organisms may respond to, with physico-chemical control over migration patterns being a possible example. Finally, plankton may undergo behavioural adaptations for swimming at various levels of turbulent intensity. *In situ* data on these very small scale interactions are, at present, insufficient for formulation of any but the most preliminary hypotheses.

At the other end of the space and time spectrum, basin-scale physical processes such as boundary currents respond to global atmospheric forcing. The mesoscale processes that are the primary focus for GLOBEC typically occur in the oceanic boundary regions, and derive their energy from the large-scale circulation. Likewise, the small-scale turbulent processes that directly influence feeding behaviour and predator-prey interactions derive their energy from the large-scale motions through the turbulent cascade of energy from large scales down to progressively smaller scales. Effective investigation of the relations among ecosystem processes occurring at very small scales requires that the large scales, where energy initially enters the system, also be addressed by GLOBEC.

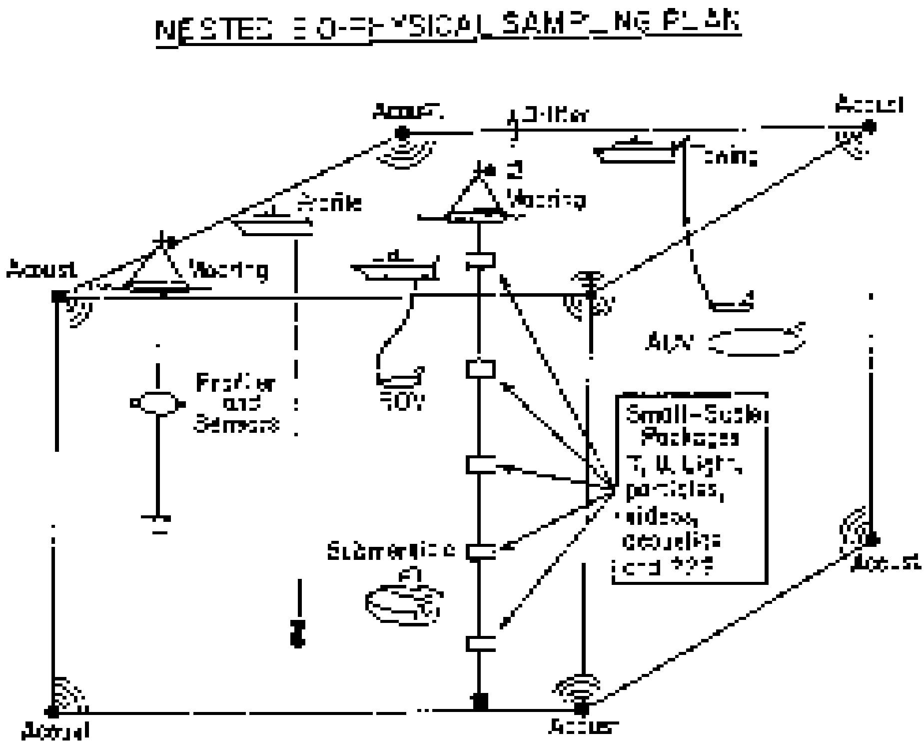
Most physical/biological models are developed to describe entire populations over time and space scales larger than the mesoscale. Measurements are often made, however, at the scale of individuals and are useful only for use in formulating models focused on individuals. This extreme range of scales, coupled with realistic resource constraints, requires that GLOBEC utilize two model development concepts that are of the utmost importance; nesting and parameterization. Smaller-scale process models are nested within larger scale, coarser resolution models, and information about the longer time scale processes is transferred between the models. Coupling between these models can take place in any number of dimensions and can encompass a range of space and time scales. Such nesting and coupling are already being done with atmospheric and oceanic circulation models and significant advances have been made. The second model development concept, parameterization, requires that certain processes within the modelled system be represented as numerical values rather than being modelled explicitly. As an example, mixing processes that occur on small scales are typically parameterized in large scale circulation models.

In order to model the processes of interest to GLOBEC realistically, coupled models that are capable of assimilating physical, chemical and biological variables are required. To maintain a basis in the real ocean, these models must derive their boundary conditions and parameterizations from field data. Further, results derived from model output need to be compared with field results to verify that the model output truly represents oceanic conditions. GLOBEC will therefore utilize coupled modelling and physical/biological observational systems (Figure 7). Assimilation of data into the models provides a mechanism whereby model parameters can be adjusted to a known distribution, the model can be updated at intervals, and the accuracy of simulated distributions can be improved. Conversely, model results can be used as a framework for the design and modification of observation programmes in the field.

GLOBEC will utilize nested and parameterized models, coupled with coordinated field data collection, in order to determine the ecosystem interactions of interest and to simulate the influence of global change on these interactions.

Figure 7

A conceptual illustration of a nested physical-biological sampling configuration designed to sample several of the processes indicated in Figure 5 (after Dickey, 1991) (GLOBEC Report No. 3, 1993).



Research Foci

The four GLOBEC objectives presented above lead to a specific set of research foci which, subject to some development during the course of the programme, describe the scientific approach. These programme foci are as follows:

Focus 1 Retrospective Analyses in the Context of Large-Scale Climatic Changes

Objective To build a foundation for future global ecosystem models through re-examination of historical data bases, synthesis and integration including the following activities:

- Identify existing data sources that contribute to GLOBEC model development (*e.g.*, fish scales, plankton records, fish abundance, oceanographic and meteorological records); potential links with the Past Global Change (PAGES) Pro gramme Element.

- Synthesize quantitative understanding of the interactions between small-, meso- and large-scale physical and ecosystem processes.

Focus 2 Process Studies

Objective To conduct process studies organized around the themes of: (1) research and modelling of ecosystems and trophodynamics, (2) identification and understanding of mesoscale physical-biological interactions, and (3) research on forced responses in ecosystems, with emphases on the following activities:

- Zooplankton feeding strategies, for example, the role of copepods as omnivores and interactions with microzooplankton requires better understanding; in particular the nutritional aspects of omnivory.

- Understanding and quantifying the role of microzooplankton in food webs. Micro-zooplankton may be major grazers of phytoplankton while large zooplankton are major grazers of the microzooplankton. The micro-zooplankton assemblage includes the larval stages of many larger zooplankton.

- Zooplankton-fish interactions: the abundance of zooplankton is thought to affect fish recruitment critically because their early developmental stages are important food for larval fish. Simultaneously, planktivorous feeding by adult and juvenile fish stocks will influence planktonic production.

- Finescale stratification, turbulent flow and their significance for zooplankton populations, particularly the extent to which turbulence modifies predator-prey encounter rates.

- Estimation of mortality, growth and reproduction rates, particularly in relation to food availability and composition of the diet.

Focus 3 Predictive and Modelling Capabilities

Objective To develop predictive and modelling capabilities with interdisciplinary, coupled modelling-observational systems including the following activities:

- Develop multiscale biological-physical dynamical models taking account of:
  - spatial and temporal nesting,
  - formulation and adequate parameterization of biological processes,
  - structured and unstructured individual-based and population models, and
  - consistency and correspondence between data and models.

- Develop new procedures for acquiring and assimilating data into dynamical models (Figure 8) that are adapted to specific experimental sites such as upwelling, coastal or polar systems via observation system simulation experiments.

- Incorporate modelling and data assimilation procedures into Advanced Modelling and Observation Systems (AMOS); recently developed methods in volving advance interdisciplinary models and measurement systems and the novel application of data assimilation techniques.

- Develop innovative ways of archiving, storing and analysing existing and new data; with IGBP-DIS (Data and Information Systems).

- Integrate dynamical models of autotroph-heterotroph interactions in the plankton in a physical setting.

- Synthesize understanding of how mesoscale physics modulates the interactions among small- and large-scale ecosystem processes.

Focus 4 Feedbacks from Changes in Marine Ecosystem Structure

Objective To cooperate with other ocean, atmosphere, terrestrial and social global change research programmes to estimate feedbacks from changes in marine ecosystem structure to the global earth system with emphasis on the following activities:

- Select appropriate topics for interaction, for example, carbon fluxes, in consultation with other programmes; particularly with JGOFS and LOICZ.

- Predict scenarios of altered marine ecosystem structure and their impact on important stocks, and potential feedbacks to the global system.

- Draw on the results of other international programmes involved in modelling of climate change and its impacts.

Applications

GLOBEC will advance significantly our understanding of the ocean ecosystem, including its responses to anthropogenic perturbations and to climate change. There are many potential applications for this enhanced understanding. In particular, of the problems that can benefit, the most pressing pertain to global change and its potential impact on the management of marine living resources. These problems relate to renewable food and economic resources, and have significant political and economic consequences at national and international levels. Two examples of what are likely to be among the more significant applications of GLOBEC results are presented below.

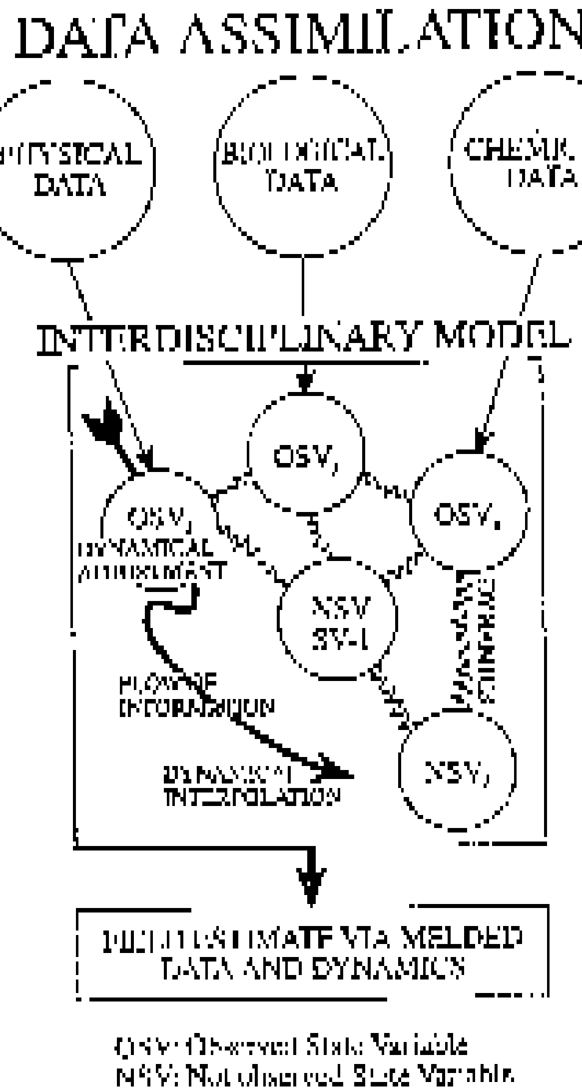
The mechanisms leading to multidecadal basin and sub-basin scale variations in upper ocean ecosystems remain uncertain. The resultant variations may be due to natural factors, to anthropogenic causes such as fishing or pollution, to dependence upon terrestrial ecosystems such as the availability of aeolian "micronutrients", or to variable factors at the ocean margins such as freshwater input. Distinguishing between anthropogenic and naturally-induced marine ecosystem changes will become an increasingly urgent scientific problem over the coming decades. Even a rudimentary attempt to separate the natural and anthropogenic causes of ecosystem variability requires a far better understanding of ecosystem functioning, integrated with knowledge of physical and biological forcing factors, than exists at the present time. GLOBEC will contribute significantly to furthering this understanding by focusing, through an integrated ecosystem modelling approach, on the mechanisms leading to variability.

A second example, particularly significant in relation to global food supply, concerns variability in fisheries recruitment. This variability is a major factor contributing to the uncertainties surrounding fisheries management. Recruitment variations on a multidecadal time scale have considerable economic implications at the national level. Unfortunately, studies of fish stock recruitment variability have generally been unsuccessful in that models providing excellent hindcast correlations generally do not provide satisfactory results when used in a forecast mode. This lack of forecasting ability results from an essential lack of knowledge of the ecosystem processes upon which recruitment variability depends. Rather than adopting the traditional approach to this problem, which has been to study the fish stocks themselves, GLOBEC will focus on those components of the ocean ecosystem that control the variability in fish stocks.

Finally, it needs to be stressed that GLOBEC will emphasize the role of physical-biological coupling and the influence of physical environmental changes on biological processes. Ideally, this emphasis will lead to development of models that would allow forecast of the biological response to a scenario of change in physical forcing. As a simple example, ocean water temperature in coastal regions is correlated with the presence of fish, so a forecast model might couple climate-based predictions of coastal temperature, ocean Global Climate Models (GCM) based predictions of water temperature variability through shelf-slope coupling mechanisms, and likely sites for productive fishing activity. Numerous other examples, both coastal and deep ocean, could be suggested. The potential practical benefits of such a system are immense.

Figure 8

Schematic of the data assimilation concept (GLOBEC Special Contribution No. 1)



Organization

Programme Organization

GLOBEC encompasses an integrated suite of research activities, with a central focal point being provided by the GLOBEC Programme Element. The Programme Element has been developed by the GLOBEC Scientific Steering Committee (SSC), whose responsibilities include planning and coordination of activities in which concerted international collaboration and oversight is required. Membership of the GLOBEC-SC rotates, and members are selected by the sponsoring bodies, IGBP, SCOR and IOC.

Examples of such internationally coordinated activities are those which no single country or small regional group of countries could effectively carry out alone. These include the GLOBEC Southern Ocean study, development of sampling and observation systems, numerical modelling and retrospective data analysis efforts and the emerging GLOBEC study of Small Pelagic Fish and Climate Change among others. Such activities are planned by international GLOBEC working groups, reporting to the SSC. A major effort has been spent on the development of the GLOBEC Programme Element; lists of important programme development meetings and workshops and the resulting publications are given in Annexes I and II.

GLOBEC will develop an integrated data and information plan, which will ensure that the results of internationally coordinated activities are readily integrated, accessed and displayed. This will be facilitated through close links with IGBP-DIS.

GLOBEC contains strong programme elements that have been conceived, and are being directed by, regional oceanographic organizations such as ICES and PICES. These multinational, regional components of GLOBEC include the ICES/GLOBEC Cod and Climate Change (CCC) study in the North Atlantic and the PICES/GLOBEC Climate Change and Carrying Capacity (CCCC) programme in the North Pacific. PICES and ICES have established committees for these programmes and there are close scientific ties to the GLOBEC SSC through individual members. Recently an ICES/GLOBEC North Atlantic regional coordination office has been established. Also in this category of regional research, there are the North Atlantic Treaty

Organization (NATO) -Turkey Black Sea study and a Baltic Sea programme in development, with other such efforts likely to arise as GLOBEC becomes firmly established.

National GLOBEC programmes already exist in a number of countries (*e.g.*, the USA, Canada, UK, France, China, and Japan) and there are currently developing programmes in others (*e.g.*, Germany, South Africa, Chile, and New Zealand). A number of existing programmes such as the Norwegian Mare Cognitum, the South African Benguela Ecology Programme, and the European Union (EU) funded Transatlantic Study of *Calanus finmarchicus* (TASC) project, have strong ties to international GLOBEC, although they were not designed specifically as national contributions to GLOBEC. Finally, as with JGOFS and other IGBP programmes, there are many individual projects that are of relevance to GLOBEC but that do not require international oversight.

Next Steps

GLOBEC is progressing towards the implementation phase. It will specify, during this progress, its long-range plan that will involve timed phasing of the core activities. This phasing is envisaged as follows. Initial emphases will be shared between construction of the coupled interdisciplinary modelling/observation programme and the implementation of global studies of critical biological and physical processes. Simultaneously, activity will increase on assembling the historical database through careful selection, for analysis, of key existing data sets. These three activities are anticipated to converge in about five years' time. The following five years would then be devoted to development of the conceptual and global ecosystem models.

During the course of this programme development GLOBEC will formulate an implementation plan based on this Science Plan. During this process, implementation workshops will provide integration among the regional and national programmes and the GLOBEC Programme Element. Initially the focus will be on implementation of steps for experimental design. In addition, the GLOBEC SSC will oversee the identification, assembly and analyses of critical new data sets relevant to GLOBEC objectives, the planning and coordination of multinational regional process studies, the development of a coordinated effort on multiscale physical/population dynamics modelling, and data assimilation studies which will emphasize the oceanic mesoscale. Additionally, the stage will be set for development of quantitative predictive scenarios and assessments related to ecosystem functioning.

Linkages with Other Programmes

There are a large number of possible linkages, both conceptual and in terms of actual programme coordination, with other international, national, regional and individual programmes. The most obvious linkages are with the other marine programmes in the IGBP; both JGOFS and LOICZ have research programmes closely related to GLOBEC. However, GLOBEC has its roots in *both* the physical and biological science communities, so it will also explore as appropriate, its linkages and potential contributions to projects, for example, in the World Climate Research Programme (WCRP).

GLOBEC is already coordinating its activities with JGOFS. GLOBEC's emphasis on zooplankton population dynamics complements the JGOFS primary focus, which is on primary production, carbon flux and the oceanic carbon budget. Both process and ecosystem approaches are necessary to formulate a complete picture of ocean ecosystem functioning. GLOBEC and JGOFS are both interested in the relationships between primary production and zooplankton, and in the role of zooplankton in processing carbon and transporting it from the upper to the deeper ocean. The two efforts are, however, distinct. JGOFS is a multidisciplinary effort that investigates the movement and interactions of carbon and other important biogenic matter in the ocean. GLOBEC is concerned with the effects of climate change on upper trophic levels via changes in ocean circulation and mixing at different scales. The difference between the two programmes is exemplified by the way in which they address the problem of zooplankton, which is of major importance to both. In JGOFS, zooplankton are important for the way in which they package and distribute carbon in the vertical, in particular how they mediate transport of material to the deep sea. In GLOBEC, zooplankton provide a biological conveyor belt that transfers carbon from the lower to the topmost trophic levels, including fish and marine mammals. In addressing the impact of changes in physical forcing on zooplankton and higher trophic level organisms, GLOBEC must take into account the intermediate effects of variations in nutrient cycling, primary production and phytoplankton/zooplankton interactions. To accomplish this, GLOBEC will make use of new JGOFS results on the influence of physical conditions on lower trophic level carbon cycling.

GLOBEC and LOICZ plan to coordinate their activities, since both will benefit considerably from formal ties. The coastal zone represents only about 10% of the surface of the globe, however, the coastal ocean accounts for roughly 18-33% of the global ocean's primary production, 85-90% of the world finfish catch, 80% of global organic matter burial, 90% of global sedimentary mineralization, 75-90% of the global sink for suspended river load and its associated elements and pollutants, more than 50% of present day carbonate deposition, and roughly 25% of global biological production. Many small coastal states have considerable economic interest in, and dependence upon, the health and productivity of their coastal zones. LOICZ is addressing issues related to external forcing on coastal zone fluxes, such as sediment and nutrient input, the relationship between coastal biogeomorphology and a varying environment, carbon fluxes in the coastal zone, and economic and social impacts on global change on the coastal zone. LOICZ is not designed to study coastal pelagic ecosystem structure, or the impact of the changes it does examine on resources such as fish stocks. GLOBEC will thus complement, not overlap with LOICZ. The LOICZ focus on the human dimensions of global change in the coastal zone could provide the social science component for GLOBEC's scientific investigations on the impact of global changes on fisheries. Both GLOBEC and LOICZ can provide scientists from such coastal states with an opportunity to participate in international programmes that are of direct interest and benefit to them. For instance two foci of the GLOBEC project on Small Pelagic Fish and Climate Change (SPACC) will relate to coastal upwelling zones and boundary currents. Coordination between GLOBEC and LOICZ will help to identify joint interests between these two programmes and ensure that efforts are not duplicated.

Finally, future oceanographic ecosystem studies now in the planning stages would benefit from coordination and integration with GLOBEC, as well as with JGOFS and LOICZ. This coordination and integration will be crucial for research on the coupling among physical, chemical and biological processes in the upper ocean, and the responses of this system to global change. The observations and modelling being undertaken in JGOFS should form the basis for subsequent field observations in such projects following the planned 1999 completion of the final JGOFS field activity. Future projects, for example the Surface Ocean Lower Atmosphere Study (SOLAS), may focus upon fluxes between the atmosphere and the ocean and continue the development of upper ocean models suitable for incorporation in a new, advanced generation of coupled ocean-atmosphere models. GLOBEC, with its emphasis on physical-biological interactions and interdisciplinary models will be a significant source of input for future projects.

GLOBEC research will certainly complement other IGBP Programme Elements, but the opportunities for interactions with these have not yet been developed. GLOBEC can, for its part, benefit substantially from IGBP Programme Elements by drawing on diverse expertise to strengthen GLOBEC's multidisciplinary approach, for example linking with GCTE and LUCC on conceptual issues of ecosystem structure and functioning. Focus 1 of GLOBEC has strong potential links with the research activities of Past Global Changes (PAGES). Similarly, Focus 4 on feedbacks may link with the Biospheric Aspects of the Hydrological Cycle (BAHC) and International Global Atmospheric Chemistry Project (IGAC). GLOBEC science will also play a full part in IGBP-Data and Information Systems (IGBP-DIS), Global Analysis, Interpretation and Modelling (GAIM) and Global Change System for Analysis, Research and Training (START).

Links to the World Climate Research Programme (WCRP), and especially to oceanographic projects such as the World Ocean Circulation Experiment (WOCE) and the Climate Variability and Prediction Research Programme (CLIVAR), will contribute significantly to the GLOBEC perspective. GLOBEC will also contribute to the design of the planned Global Ocean Observing System (GOOS) by providing information on critical parameters to be measured and on time and space scales that are best suited for predictive capabilities in such a system. GLOBEC is also concerned with continuing development of technology suitable for continuous sampling of biological and chemical parameters in the ocean, and these should also be of interest to GOOS, especially its modules on Living Marine Resources and the Health of the Ocean.

The Major Components of GLOBEC

The GLOBEC Programme Element

The GLOBEC Programme Element consists of a series of activities which are being planned and coordinated by the GLOBEC Scientific Steering Committee (SSC). Much of the foundation for this Science Plan was laid at a meeting in early 1993 of a GLOBEC Working Group on Population Dynamics and Physical Variability (see GLOBEC Report No. 2). Other working groups, reporting to the SSC, are directing the GLOBEC efforts in Numerical Modelling (see GLOBEC Report No. 6), Sampling and Observational Systems (see GLOBEC Report No. 3), and development of an initiative on Retrospective Data Analysis is currently being considered. The issues addressed by these working groups form the basis of this Science Plan.

In addition, the GLOBEC Programme Element has a major field study component. The four largest field research programmes are briefly described below. Much more detailed planning documents are available for each of them.

The first two field studies - Southern Ocean GLOBEC (SO-GLOBEC) and the study on Small Pelagic Fishes and Climate Change - are the responsibility of two GLOBEC working groups (see GLOBEC Reports Nos.5 and 8) and therefore, fall directly under the oversight of the GLOBEC SSC. In the case of the former, the extent of the Southern Ocean region, the number of countries involved and the enormous logistical difficulties encountered in any major oceanographic effort there, make full international coordination essential. The SPACC programme will involve a very large number of countries in studies in many different regions of the world ocean. Again, the GLOBEC SSC and its SPACC working group are directly responsible for the planning and implementation of SPACC.

Finally, there are two large-scale studies, each of which is confined to a single ocean basin, which are being planned by regional oceanographic organizations in very close cooperation with GLOBEC. While individuals involved in each of these studies provide scientific input to the international GLOBEC SSC, the lead responsibility for these programmes is taken by the regional organisation as its contribution to the GLOBEC programme. These programmes are the Cod and Climate programme in the North Atlantic Ocean which is co-sponsored by GLOBEC and ICES, and the North Pacific programme on CCCC of PICES and GLOBEC.

GLOBEC Southern Ocean Programme (SO-GLOBEC)

Planning for an international GLOBEC programme in the Southern Ocean began at a meeting in La Jolla, USA in May 1991. Sponsored by U.S. GLOBEC, it brought together about 40 scientists from 10 countries. The rationale for a SO-GLOBEC programme was discussed at length, with consideration of study sites and target species in the framework of general Southern Ocean ecology. In June 1993, a workshop was organized in Norfolk, USA by the international SO-GLOBEC working group. It further developed the plans for SO-GLOBEC and began to consider issues of implementation (see GLOBEC Report No. 5). At a meeting of the same working group in Bremerhaven in June 1994, a Southern Ocean Implementation Plan was developed (and has been published as GLOBEC Report No. 7). Steps towards active implementation are the current concern of the SO-GLOBEC working group.

The Antarctic marine food web is characterized by dependence on a single key species, the Antarctic krill, and by the dependence of many of the components of this food web on sea-ice during some or all of their life histories. Key species in the Antarctic food web, such as the krill, use sea-ice as a winter refuge and feeding ground. The seasonal retreat of sea ice has a major influence on the rapid phytoplankton growth in the zone influenced by ice edge melt water. This is where a major portion of the region's annual primary production occurs, especially in areas where the ice edge and ocean current boundaries overlap. This annually recurring, rich food source is easy to track and exploit for animals overwintering under or on the ice. Indeed, the krill-based food chain is an exceptionally efficient one because of the predictability of the physical environment over evolutionary time scales. Because of this seasonal predictability, Antarctic zooplankton have been able to synchronize their life-cycles to the recurring primary production.

The annual extent of sea-ice advance and retreat is subject to marked interannual variability. The annual cycles of zooplankton overwintering in open water, in contrast to those of their ice-based counterparts, are likely to be greatly influenced by annual variation in ice cover. SO-GLOBEC will investigate and compare the population dynamics of zooplankton and their various predators with these differing life cycle strategies.

These special characteristics make the Southern Ocean marine ecosystem especially vulnerable to global climate change. Predictions of the responses of the Antarctic marine food web to environmental variability and climate change first require understanding and documentation of the cycles of natural population variability.

Since the much-publicized ozone hole is at its greatest extent during the Antarctic spring, the increased exposure to UV-light of organisms living close to the surface during the peak production period is of particular importance and will be investigated.

The SO-GLOBEC programme is focused on understanding how physical forces influence population dynamics and predator-prey interactions between key species. Special efforts will be made to study the little-known overwintering strategies of zooplankton and top predators. Knowledge gained will significantly advance our understanding of Southern Ocean marine ecosystems and will enable us to monitor adequately and predict the impact of climate change.

SO-GLOBEC will include studies of:

- Regional differences in overwintering strategies of Antarctic krill in relation to the physical environment.
- Population dynamics of selected zooplankton species, both sea-ice related and pelagic species.
- Population dynamics of major krill predators, both ice-based and pelagic species.
- The effects of UV-B radiation on zooplankton dynamics.

Two major field projects have been considered, each of a minimum of six months' duration. The summer study would focus on foraging and recruitment; the winter study would focus on overwintering strategies. Field studies will take place in three areas: the Antarctic Peninsula region, the eastern Weddell Sea, and the Indian Ocean sector of the Southern Ocean (Figure 9). The research envisaged will consist of two elements: a synoptic, mesoscale time-series survey in an area of 40,000 km^2, and process studies aimed at understanding phenomena and mechanisms of crucial importance within the survey area. These two elements will alternate at 2-week intervals, providing a continuous research effort over a minimum period of 6 months. A series of standardized measurements are planned allowing for comparison of results, both within and among the three study areas. A variety of new technologies will be used for sampling and analysis drawing in particular on developments in the GLOBEC Sampling and Observation Systems Working Group. Detailed logistic and scientific plans for these studies will be made in a series of planning meetings for each study site.

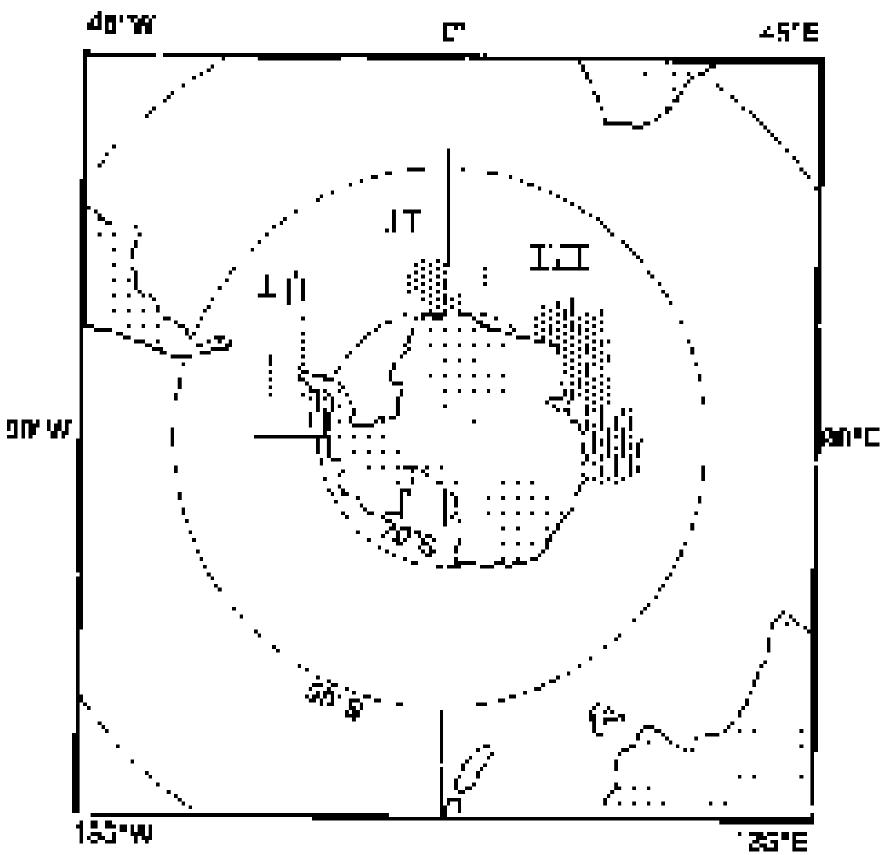
The modelling effort will be initiated prior to the advent of field programmes, in three main subject areas: the development of a conceptual model of the ecosystem, circulation models, and biological models. Regarding circulation, mixed-layer and sea-ice models are required, with emphasis on site-specific models. Existing models must be evaluated as a point of departure for SO-GLOBEC efforts. Biological models of trophic transfer and krill swarming are particularly needed. Data assimilation methods will be developed in association with the GLOBEC Numerical Modelling Working Group.

The SO-GLOBEC data policy emphasizes timely submission of data, source recognition and open availability. Catalogues of historical data are needed, particularly the data sets from significant research programmes that were not part of any coordinated international activity.

The wealth of information now becoming available on the physics and biology of the Southern Ocean pelagic system has set the stage for a new understanding of its ecosystems. Recent developments in observation and sampling technology, coupled with significant advances in computing and modelling capabilities provide the necessary tools to accomplish the goals of the SO-GLOBEC programme.

Figure 9

Study regions for SO-GLOBEC field studies: I) Antarctic Peninsular region; II) Eastern Weddell Sea; III) Indian Ocean sector (GLOBEC Report No. 7).



Small Pelagic Fishes and Climate Change (SPACC)

Fishery records extending back hundreds of years, paleoecological records for thousands of years, and genetic assessments over evolutionary time all indicate great variations in the productivity of small pelagic fish populations (sardines, anchovies, scads, herrings, mackerels, sprat, menhadens, and others). Because such populations are relatively transient in the evolutionary sense, they may be particularly sensitive to climate variability.

The goal of the SPACC programme is to understand and ultimately predict climate-induced changes in the fish production of marine ecosystems. In addition to having broad economic importance, this goal is especially pertinent today because of the accumulation of greenhouse gases that will force changes in ocean climate over the next hundred years. Small pelagic fishes are an ideal subject for the study of climate variability and ocean forcing because they are globally distributed (Figure 10), constitute over a third of the global marine fish catch (Figure 11), and respond rapidly to changes in ocean forcing because of their brief lives and short, plankton-based food chains. These populations also exhibit great swings in abundance (Figure 12), climatic teleconnections between populations, and have rich retrospective data resources.

The SPACC programme is being planned as a major component of the GLOBEC field research programme with the aim of being able to identify those physical forces that control growth of small pelagic fish populations (Figure 13) and the linkages between these process and population dynamics. The long-range goal is to forecast how changes in the patterns and intensity of these forces, caused by elevated greenhouse gases and global warming, will alter the productivity of small pelagic fish populations.

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

- Process studies, in which cause-and-effect linkages between fish population dynamics and ocean climate are inferred from comparisons of standard measurements from different ecosystems, and
- Retrospective studies, in which ecosystem histories are reconstructed by means of time series, paleoecological data, and genetic data.

SPACC shares common themes with the GLOBEC programme of which it will be a major component: the study of linkages between physical forces and biological processes, an emphasis on modelling to interpret multidisciplinary observations, and a focus on zooplankton as a key link between physics and fish productivity. A unique characteristic of the SPACC programme is its use of a common set of core measurements to compare ecosystems. Cause-and-effect linkages between fish, zooplankton and ocean physics can be inferred from comparisons of the many diverse ecosystems dominated by small pelagic fishes. Five core elements for SPACC field studies have been proposed:

- daily somatic growth of larval and juvenile fishes;
- daily production of zooplankton;
- circulation and vertical structure of the water;
- a minimal ocean monitoring system (coastal stations, satellites, *etc*.); and
- numerical models to integrate these elements.

Where possible, SPACC will also use comparative retrospective studies that employ time series data and paleoecological records to examine teleconnections between systems and common patterns of change, as well as genetic studies to examine population change over longer time scales.

Small pelagic fish stocks are especially important to small coastal states where they may be the basis for a substantial portion of the local economy. Thus, SPACC provides an important opportunity to involve marine scientists in a number of developing countries in research which has direct relevance to them. To assure world-wide participation in its comparison of ecosystems, SPACC will emphasize inexpensive core measurements that can be made in most countries, while maximising the use of advanced technologies. This means that training, education, and mutual assistance will be a major programme element, and strong links will be established with START.

The basis for a SPACC Science Plan was developed at a workshop involving more than 50 scientists which took place in La Paz, Mexico in June 1994 (GLOBEC Report No.8). Two workshops have considered planning for the implementation of SPACC, one involving European and African scientists took place in Namibia in December 1995; the other, primarily for North and South Americans, was held in Mexico City in August 1996.

Figure 10

Regional populations of sardines (*Sardina* and *Sardinops* (summarized from Parish *et al.,* 1989), and major oceanic surface currents and summer sea-surface temperatures between 13° and 25° C. (GLOBEC Report No. 8, 1995).

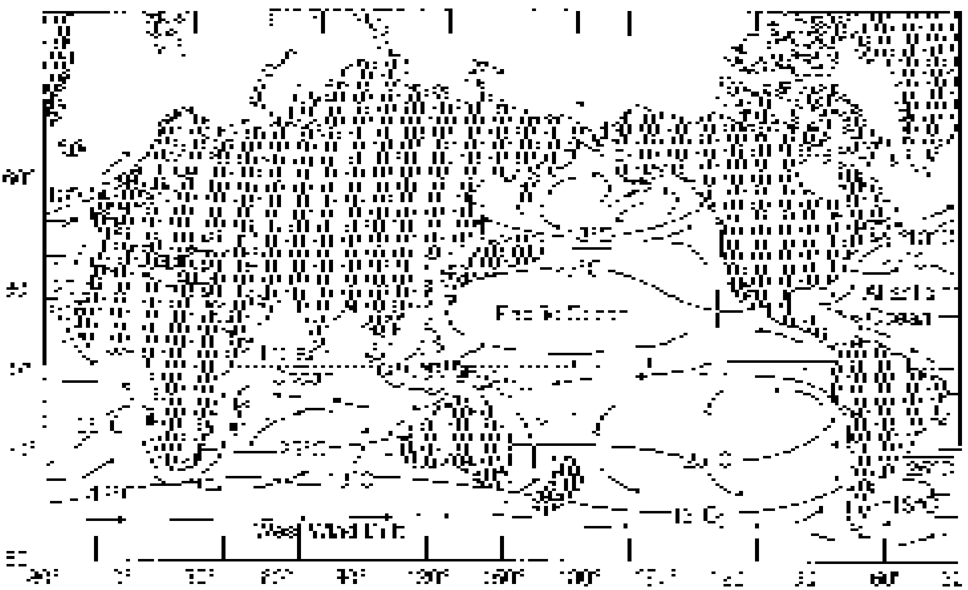
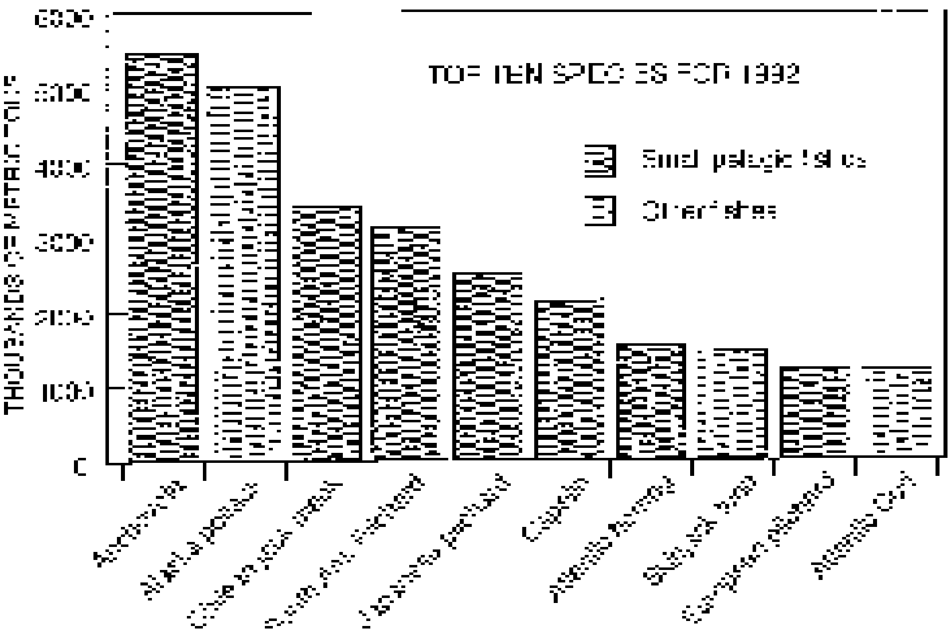


Figure 11

Top ten species in the 1992 world fish catch. Note that all but three are small pelagic fishes. Redrawn from FAO Yearbook (Anon., 1992) (GLOBEC Report No. 8, 1995).



ICES - GLOBEC Cod and Climate Change Programme (CCC or "3Cs")

The International Council for the Exploration of the Sea (ICES) and GLOBEC have joined together to develop an innovative programme to advance the understanding and prediction of variability in fish stock recruitment, both in the short term (annual forecasts) and in the long term ("climate effects"). Cod has been chosen to serve as the candidate species for this exercise because its biology is well-known and supported by ample data bases, it has a pan-Atlantic distribution, and its abundance and distribution have been shown to be sensitive to specific past examples of environmental variability. These considerations provide Cod and Climate Change (CCC) with the possibility of developing new capabilities in predicting fish recruitment from a better understanding of the interaction of physical processes and population dynamics.

The central question being investigated by the CCC programme is the effect of climate variability on cod stock fluctuations. It is simply stated, but involves many different scientific disciplines and scales of investigation. These range from the effects of small-scale turbulence on encounter rates between fish larvae and their prey, to large-scale effects of interdecadal changes in wind fields on circulation and transport of heat and young fish. In spite of the complexity of the processes by which variable physical forcing may affect cod stocks, the effects of climatic variability can be detected for several stocks. For example, periods of low temperature are observed to result in stock declines at the northern limits of cod distribution (Barents Sea, Greenland); particular hydrographic and wind conditions result in unusual transport of eggs and larvae (Iceland-Greenland) or flush out deoxygenated basins where cod spawn (Baltic). These examples combine empiricism, a growing understanding of ocean/climate variability and detailed knowledge of processes during the life history of cod (especially the early life history). They give grounds for believing that the question posed is not intractable and that it may be possible to predict at least the broad direction of changes in cod abundance under different physical regimes.

The GLOBEC approach provides a framework under which studies at different scales can be nested. A great deal of research which is relevant to CCC is already underway, even if it was not primarily designed with that in mind (*e.g.,* studies of copepod dynamics and cod recruitment). The CCC working group (GLOBEC Report No.4) has identified themes and approaches which strengthen and facilitate the programmes being carried out at national and individual levels and has proposed and initiated other studies which can be carried out more effectively at the regional or international level coordinated by ICES and GLOBEC.

The CCC approach will have key elements similar to those of other components of the GLOBEC programme: analysis of historical data bases, the use of ongoing monitoring activities (such as the Continuous Plankton Recorder survey in the North Atlantic), and advanced modelling/observation system development. The core scientific issues are:

- Cod in relation to the ecosystem - the causes of the wide variation in growth rates of all life history stages of cod in ecosystems around the Atlantic will be examined. Possible explanations include genetics, abiotic conditions, or differential ecosystem productivity.

- Effects of large-scale processes - rather than develop its own basin-scale modelling programme, the CCC programme will interact with those programmes that already exist. The programme will focus on the development and application of regional-scale, coupled biological/physical models. It will try to strengthen the liaison between regional efforts and larger scale programmes. A comparative study of the usefulness of models developed in other regions will be conducted.

- Effects of intermediate scale processes - CCC will develop intermediate scale hydrodynamic models and incorporate key biological processes into them. An analysis of commercial fishing effort distribution to infer long-term variation in spawning concentrations related to oceanographic structure will be carried out. Testing of models will be done to determine if hindcast variability in cod and haddock recruitment can be explained as the effects of variable meteorological conditions on stratification.

A number of unifying themes have been grouped roughly in relation to the scales of physical processes. Large-scale processes range from global to regional (*e.g.,* Georges Bank, the North Sea) and include long-term changes in atmosphere and ocean dynamics which affect cod stocks through changes in heat and transport. Intermediate scale processes include eddies, rings and fronts which have effects due to localized aggregation, retention and enhancement of plankton production. Small-scale processes include water column stability and turbulence which affect plankton production and prey encounter rates.

In the context of marine ecological models, the main processes to be dealt with, from the CCC point of view, are dispersal and predator-prey interactions. It is necessary to strike the right balance between the necessary simplification of processes and structure while retaining sufficient detail to address questions concerning the population dynamics of particular species.

The CCC Working Group has recommended that retrospective analysis of existing cod and climate-related data bases should begin immediately and workshops have been organized to this end. This analysis should provide relatively rapid results concerning the likely effects of climate change as well as pointing the way for future data collection and highlighting the need to develop comparable time series of information in different systems over the long-term.

Figure 12

Variation in the annual catch of sardine and anchovy in four major current systems during the twentieth century. Redrawn from Lluch-Belda *et al.,* 1989. (GLOBEC Report No. 8, 1995).

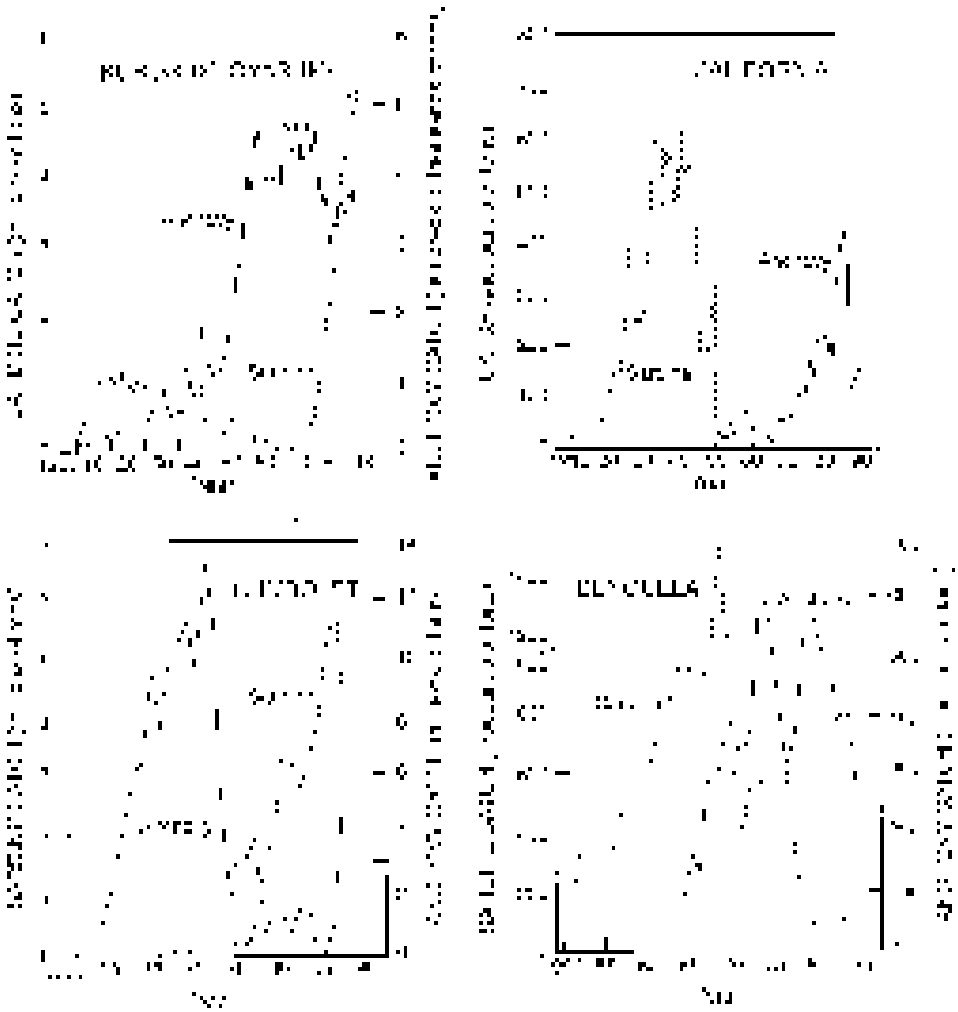
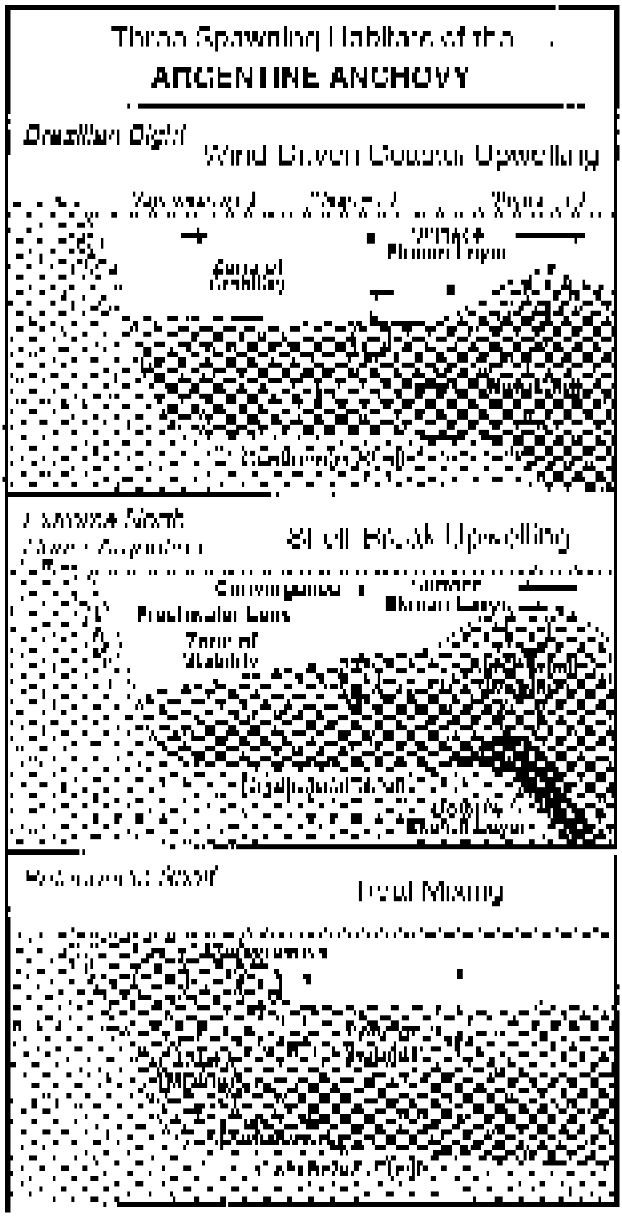


Figure 13

Schematic diagram of key physical processes, in three different spawning habitats of the Argentine anchovy (*Engraulis anchoita*), redrawn from Bakun and Parrish, 1991. Wide arrows indicate mean water transport with lengths scaled to relative magnitudes. Circular arrows indicate mixing; the size indicates the intensity of mixing. Shading indicates greater water density (GLOBEC Report No. 8, 1995).



PICES-GLOBEC Climate Change and Carrying Capacity (CCCC or "4Cs")

The North Pacific Marine Sciences Organization (PICES) and GLOBEC agreed in 1993 to organize an international science programme on Climate Change and Carrying Capacity (CCCC) in the temperate and subarctic regions of the North Pacific Ocean. A PICES-GLOBEC Workshop in 1994 developed a Science Plan for CCCC and an Implementation Plan was considered at the PICES Annual Meeting in October 1995.

Remarkable changes have been observed in the North Pacific and adjacent seas in recent decades. Concurrent changes in atmospheric pressure and ocean temperatures indicate that in 1976 and 1977 the North Pacific shifted from one climate state, or regime, to another that persisted through the 1980s. Analysis of records of North Pacific sea surface temperature and atmospheric conditions show a pattern of regime shifts lasting several years to decades. Specifically, since 1976 the Aleutian low has intensified during the winter and has shifted further east. Associated changes took place in wind stress curl, the corresponding Sverdrup transport, a warming over Alaska and cooling in the central and western North Pacific. The strengths of flows in the Alaska and California currents may fluctuate out of phase with one another. Modelling studies suggest that if global warming is occurring, its effects should be most strongly developed, and initially observed, at high latitudes.

Although the important linkages are poorly understood, there is growing evidence that biological productivity in the North Pacific responds to these decadal-scale shifts in atmospheric and oceanic conditions, by alternating between periods of high and low productivity. In coastal areas, both the far eastern and California stocks of Pacific sardine peaked in abundance in the 1930s, declined in the 1950s and 1960s, then began to increase synchronously in the 1970s. Large scale changes in pelagic fish production in the western Pacific suggest that coastal production is linked to variations in ocean climate. Paleosedimentary records indicate that such interdecadal fluctuations have been characteristic of the California Current system for the last 2000 years.

Summer biomass of zooplankton increased two-fold between the 1960s and the mid-1970s (Figure 14), as did the biomass of some higher trophic level carnivores in the eastern subarctic Pacific. There were also significant fluctuations in zooplankton biomass in the Oyashio and Kuroshio current systems off the coast of Japan. While salmon catches in the North Pacific declined steadily from historic highs in the late 1930s to a low in the mid-1970s, this was followed by a striking increase in which the combined national salmon catches in the North Pacific nearly regained the earlier historic highs.

In addition to the decadal-scale regime shifts, longer-term global climate change may result in substantial changes in the biological carrying capacity of the North Pacific. For example, coincident with the recent increases in salmon catches, the average size of adult salmon has significantly decreased in some areas of the North Pacific. There is also evidence that growth and mortality of some salmon stocks may vary with production: in some cases the growth rates appear to be inversely related to stock size. Some portion of these patterns of variation may be due to the combined current abundance of salmon and other high trophic level carnivores approaching the present carrying capacity of the subarctic North Pacific.

The term "carrying capacity" is used in the CCCC Science Plan to mean how the dominance and productivity of zooplankton and higher trophic level carnivore species respond to changes in ocean climate. The CCCC programme will develop a new theoretical and mathematical framework which extends the classical, single species concept of carrying capacity into the multi-species ecosystem domain that the CCCC programme will address.

The general scope of the CCCC Programme has a strong emphasis on coupling between atmospheric and oceanographic processes, their impact on the production of major living marine resources and how they respond to climate change on time scales of decades to centuries. It will include the following elements:

- The use of mechanistic processes to improve understanding and develop early recognition and prediction capabilities for regime changes.
- The development and use of models to guide research activities, integrate results and improve capabilities for forecasting ecosystem responses to climate change.
- The development of broader insights through the use of regional comparative studies, and
- Links to other activities within the GLOBEC international programme and to other existing and planned international programmes.

The key scientific issues to be addressed in CCCC include:

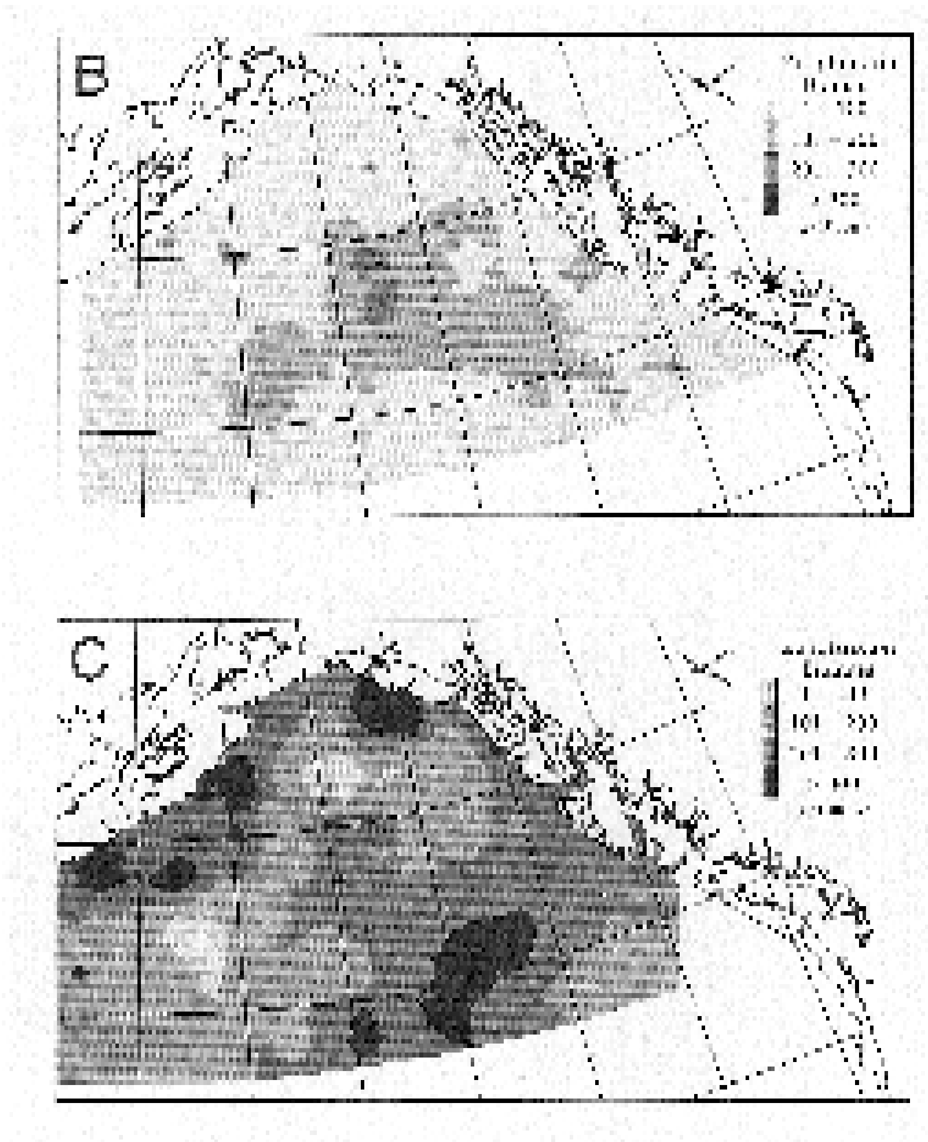
- Physical forcing: What are the characteristics of climate variability, can interdecadal patterns be identified, how and when do they arise?
- Lower trophic level response: How do primary and secondary producers respond in productivity, and in species and size composition, to climate variability in different ecosystems of the subarctic Pacific?
- Higher trophic level response: How do life history patterns, distributions, vital rates and population dynamics of the higher trophic levels respond directly and indirectly to climate variability?
- Ecosystem interactions: How is the subarctic Pacific ecosystem structured? Do higher trophic levels respond to climate variability solely as a consequence of bottom up forcing? Are there significant inter-trophic level and top down effects on lower trophic level production and on energy transfer efficiencies?

As with other components of GLOBEC, research activities within CCCC will fall into five major categories: retrospective analyses, development of numerical models, ecosystem process studies, the development of observation systems and data management.

The CCCC Science Plan was approved by PICES in late 1994 and an Implementation Plan was presented to PICES for approval at its Annual Meeting in October 1995. Certain national activities have already begun. Throughout the CCCC planning process, there have been close links with international GLOBEC activities.

Figure 14

Distribution of zooplankton biomass in the Gulf of Alaska for 1960-1962 (B) and 1980-1989 (C). From Brodeur and Ware 1992, (PICES/GLOBEC Science Plan, PICES Scientific Report No. 4, 1996).



Key References

As part of the planning for GLOBEC, a set of key references has been compiles. These are given here; however, for the sake of clarity, only a limited number have been individually cided in the preceeding text. This list provides a guide to current further reading on Global Ocean Ecosystem Dynamics.

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Acronyms and Abbreviations

AMOS	Advanced Modelling and Observation System
BAHC	Biospheric Aspects of the Hydrological Cycle (IGBP)
CACGP	Commission on Atmospheric Chemistry and Global Pollution
CCC	Cod and Climate Change (ICES/GLOBEC)
CCCC	Climate Change and Carrying Capacity (PICES/GLOBEC)
CLIVAR	Climate Variability and Prediction Research Programme (WCRP)
CPR	Continuous Plankton Recorder
ENSO	El Niño -Southern Oscillation
EU	European Union
GAIM	Global Analysis, Interpretation and Modelling (IGBP)
GCM	Global Climate Model
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GLOBEC	Global Ocean Ecosystem Dynamics (IGBP)
GOOS	Global Ocean Observing System (IOC/ICSU/WMO)
IAI	Inter-American Institute
ICES	International Council for the Exploration of the Sea
IGAC	International Global Atmospheric Chemistry Project (IGBP/CACGP)
IGBP	International Geosphere-Biosphere Programme (ICSU)
IGBP-DIS	Data and Information System (IGBP)
IHDP	International Human Dimensions Programme on Global Environmental Change
IOC	Intergovernmental Oceanographic Commission (UNESCO)
JGOFS	Joint Global Ocean Flux Study (IGBP/SCOR)
LOICZ	Land-Ocean Interactions in the Coastal Zone (IGBP)

LUCC	Land Use/Cover Change (IGBP/IHDP)
PAGES	Past Global Change (IGBP)
PICES	North Pacific Marine Sciences Organisation
SC(-IGBP)	Scientific Committee for the IGBP
SCOR	Scientific Committee on Oceanic Research
SO-GLOBEC	Southern Ocean Programme (GLOBEC)
SOLAS	Surface Ocean Lower Atmosphere Study
SPACC	Small Pelagic Fish and Climate Change (GLOBEC)
SSC	Scientific Steering Committee
START	System for Analysis, Research and Training (IGBP)
TASC	Transatlantic Study of *Calanus finmarchicus* (EU)
UN	United Nations
WCRP	World Climate Research Programme (ICSU/IOC/WMO)
WOCE	World Ocean Circulation Experiment (WCRP)

Appendix I

GLOBEC Meetings 1991-1996

IOC-SCOR Workshop on Global Ocean Ecosystem Dynamics. Solomons, MD USA. 29 April-2 May 1991.

The First International GLOBEC Planning Meeting. Ravello, Italy. 31 March-2 April 1992.

Meeting of the GLOBEC working group on Population Dynamics and Physical Variability. Cambridge, UK. 1-5 February 1993.

Meeting of the GLOBEC working group on Sampling and Observational Systems. Paris. 30 March-April 2, 1993.

Meeting of the ICES/GLOBEC working group on Cod and Climate Change. Lowestoft, UK. 7-11 June 1993.

First meeting of the GLOBEC working group on Southern Ocean Planning. Norfolk, VA USA. 15-17 June 1993.

First meeting of the GLOBEC working group on Numerical Modelling. Villefranche-sur-Mer, France. 12-14 July 1993.

ICES Symposium on Cod and Climate Change. Reykjavík, Iceland. 23-27 August 1994.

Meeting of the SCOR/IOC GLOBEC SSC. Jekyll Island, GA USA. 10-14 January 1994.

Second meeting of the GLOBEC Southern Ocean Working Group. Bremerhaven FRG. 6-8 June 1994.

First meeting of the GLOBEC working group on Small Pelagic Fish and Climate Change. La Paz, Mexico. 18-25 June 1994.

GLOBEC Strategic Planning Conference. Paris. 18-21 July 1994.

Meeting of the PICES/GLOBEC Working Group on Climate Change and Carrying Capacity. Nemuro, Japan. 15-17 October 1994.

First meeting of the SCOR/IGBP GLOBEC Core Project Planning Committee. London. 8-10 February 1995.

GLOBEC meeting on Advanced Modelling and Observation Systems. La Paz, Mexico. 20-22 March 1995.

Second meeting of the GLOBEC working group on Numerical Modelling. Nantes, France. 15-21 July 1995.

Meeting of European and African scientists on regional implementation of the study on Small Pelagic Fish and Climate Change. Namibia. 3-8 December 1995.

Meeting of North and South American scientists on regional implementation of the study on Small Fish and Climate Change. Mexico City. August 1996.

Meeting of the IGBP/SCOR/IOC GLOBEC Scientific Steering Committee, Baltimore, November 11-13, 1996.

Appendix II

GLOBEC Publications

IOC-SCOR Workshop on Global Ocean Ecosystem Dynamics. IOC Workshop Report No. 75.

Towards the Development of the GLOBEC Core Programme: A report of the First International GLOBEC Planning Meeting. GLOBEC Report No. 1. SCOR.

Population Dynamics and Physical Variability: Report of the First meeting of an International GLOBEC Working Group. GLOBEC Report No. 2. SCOR.

Sampling and Observational Systems: Report of the First Meeting of an International GLOBEC Working Group. GLOBEC Report No. 3. SCOR.

Cod and Climate Change: Report of the First Meeting of an ICES/International GLOBEC Working Group. GLOBEC Report No. 4. SCOR.

Towards the Development of an International GLOBEC Southern Ocean Programme: Report of the First Meeting of the GLOBEC Southern Ocean Working Group. GLOBEC Report No. 5. SCOR.

Numerical Modelling: Report of the First Meeting of an International GLOBEC Working Group. GLOBEC Report No. 6. SCOR.

International GLOBEC Southern Ocean Programme: Report of the Second Meeting of the GLOBEC Southern Ocean Working Group. GLOBEC Report No. 7. SCOR

Small Pelagic Fish and Climate Change Program: Report of the first planning meeting. GLOBEC Report No.8. SCOR.

Predicting and Monitoring of the Physical-Biological-Chemical Ocean. By Allan R. Robinson. GLOBEC Special Contribution No. 1. SCOR.

Report of PICES-GLOBEC Workshop. In 1994 Annual Report, North Pacific Marine Sciences Organisation.

Cod and Climate Change. Proceedings of a Symposium held in Reykjavík. ICES Marine Science Symposia, Vol 198, October 1994.

PICES-GLOBEC Science Plan. PICES Scientific Report No.4., 1996.

An Advanced Modelling/Observation System (AMOS) for Physical-Biological-Chemical Ecosystem Research and Monitoring (Concepts and Methodology). A Working Paper/Technical Report prepared by the GLOBEC Working Groups on Numerical Modelling and Sampling and Observation Systems. GLOBEC Special Contribution No. 2. (in press) SCOR.

Implementation Plan for the PICES/GLOBEC study of Climate Change and Carrying Capacity. PICES Scientific Report No.4., 1996.

List of IGBP Publications

IGBP Report Series. List with short summary

IGBP Reports are available free of charge from:
IGBP Secretariat, Royal Swedish Academy of Sciences, Box 50005, S-104 05 Stockholm, Sweden.

*Report Nos. 1-11 and reports marked * are no longer available.*

No. 12
The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP). The Initial Core Projects (1990). IGBP Secretariat, Stockholm, 330 pp.
The IGBP science plan is composed of research projects aimed at answering a number of key questions related to global change, through the establishment of Core Projects on the distinct sub-components of the Earth system, and related activities on data systems and research centres. An implementation strategy provides for its fulfilment.

No. 13
Terrestrial Biosphere Exchange with Global Atmospheric Chemistry. Terrestrial Biosphere Perspective of the IGAC Project: Companion to the Dookie Report. Report on the Recommendations from the SCOPE/IGBP Workshop on Trace-Gas Exchange in a Global Perspective. Sigtuna, Sweden, 19-23 February, 1990. Edited by P. A. Matson and D. S. Ojima (1990). IGBP Secretariat, Stockholm, 103 pp.
The Sigtuna workshop contributed to the development of a scientific action plan on terrestrial ecosystem gas exchange, complementing the International Global Atmospheric Chemistry Project (an IGBP Core Project) in areas of natural variability, boreal regions, global integration and modelling of fluxes, and trace gas fluxes in mid-latitude ecosystems.

No. 14

Coastal Ocean Fluxes and Resources. Report of a CP2 Ad Hoc Workshop, Tokyo, Japan, 19-22 September 1989. Edited by P. Holligan (1990). IGBP Secretariat, Stockholm, 53 pp.

The focus of IGBP Coordinating Panel 2 on Marine Biosphere-Atmosphere Interactions is the elucidation and prediction of the feedback loops between climate and ocean biogeochemistry under conditions of significant anthropogenic changes to the trace gas composition of the atmosphere. The workshop concentrated on global change and the coastal oceans.

No. 15

Global Change System for Analysis, Research and Training (START). Report of a Meeting at Bellagio, December 3-7, 1990. Edited by J. A. Eddy, T. F. Malone, J. J. McCarthy and T. Rosswall (1991). IGBP Secretariat, Stockholm, 40 pp. Also available in Spanish and French.

START is a plan for the development of an international network of regional research centres and sites to gather data and study global change problems in their regional contexts. These regions are identified. Issues to be addressed are: How changes in land use and industrial practices alter the water cycles, atmospheric chemistry and ecosystems dynamics; how regional changes affect global biogeochemical cycles and climate; and how global change leads to further regional change in the biospheric life support system.

No. 16

Report from the IGBP Regional Meeting for South America. São José dos Campos, SP, Brazil, 5-9 March 1990 (1991). IGBP Secretariat, Stockholm, 58 pp.

The workshop discussed, in a South American context, past global changes, the effects of climate change on terrestrial ecosystems, the role of ocean processes in global change, land transformation and global change processes, the importance of the Andes for general circulation models, and regional research centres. Recommendations promote the role of South American science in global change research.

No. 17

Plant-Water Interactions in Large-Scale Hydrological Modelling. Report of a Workshop, Vadstena, Sweden, 5-8 June 1990 (1991). IGBP Secretariat, Stockholm, 44 pp.

The workshop addressed plant-water interrelationships at landscape to continental scales: the spatial pattern at landscape level of the dynamics of water flows and waterborne fluxes of dissolved and suspended mater; plant/vegetation characteristics and properties affecting return flow to the atmosphere; methodological issues of large-scale modelling; research in humid tropical, semi-arid and temperate zones.

No. 18:1

The Recommendations of the Asian Workshop, New Delhi, India, February 11-15, 1991. Edited by R. R. Daniel (1991). IGBP Secretariat, Stockholm, 36 pp.

Recommendations of the Workshop address issues of prime concern to Asian countries, with reports and recommendations from Working Groups on IGBP Core Projects and key activities.

No. 18:2

Proceedings of the Asian Workshop, New Delhi, India, 11-15 February 1991. Edited by R. R. Daniel and B. Babuji. Madras, Committee on Science and Technology in Developing Countries (COSTED) and the Indian National Committee for the IGBP (1992). Madras, COSTED, Asia Regional Office, 152 pp.
The Proceedings include 19 papers on Earth system research and global environmental change in Asia, and national reports on global change programmes.

No. 19*

PAGES Past Global Changes Project: Proposed Implementation Plans for Research Activities. Edited by John A. Eddy (1992). IGBP Secretariat, Stockholm, 112 pp.
The Past Global Changes (PAGES) project will secure better understanding of the natural and human-induced variations of the Earth system in the past, through studies of both natural and written records. Focus is on changes within two temporal streams: global changes for the period 2000 BP, and changes through a full glacial cycle. Implementation plans address: solar and orbital forcing and response, Earth system processes, rapid and abrupt global changes, multi-proxy mapping, palaeoclimatic and palaeoenvironmental modelling, advances in technology, management of palaeodata, and improved chronologies for palaeoenvironmental research.

No. 20*

Improved Global Data for Land Applications: A Proposal for a New High Resolution Data Set, Report of the Land Cover Working Group of IGBP-DIS. Edited by John R. Townshend (1992). IGBP Secretariat, Stockholm, 75 pp.
This report outlines a proposal to produce a global data set at a spatial resolution of 1 km derived from the Advanced Very High Resolution Radiometer primarily for land applications. It defines the characteristics of the data set to meet a number of requirements of IGBP's science plan and outlines how it could be created. It presents the scientific requirements for a 1 km data set, the types and uses of AVHRR data, characteristics of a global 1 km data set, procedures, availability of current AVHRR 1 km data, and the management needs.

No. 21*

Global Change and Terrestrial Ecosystems: The Operational Plan. Edited by W. L. Steffen, B. H. Walker, J. I. Ingram and G. W. Koch (1992). IGBP Secretariat, Stockholm, 97 pp.
The objectives of GCTE are: to predict the effects of changes in climate, atmospheric composition, and land use on terrestrial ecosystems, including agricultural and production forest systems, and to determine how these effects lead to feedbacks to the atmosphere and the physical climate system. The research plan is divided into four foci: ecosystem physiology, change in ecosystem structure, global change impact on agriculture and forestry, and global change and ecological complexity. Research strategies are presented.

No. 22

Report from the START Regional Meeting for Southeast Asia. Arranged by The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP), in collaboration with Human Dimensions of Global Environmental Change (HDGEC) Programme (1992). IGBP Secretariat, Stockholm, 114 pp.
The report presents general recommendations on global change research in the region, thematic studies relating to IGBP Core Project science programmes, global change research in studies of eight countries in the area, and conclusions from working groups on the participation of the region in research under the five established IGBP Core Projects and the related HDGEC programme.

No. 23

Joint Global Ocean Flux Study: Implementation Plan. Jointly published with the Scientific Committee on Oceanic Research (SCOR) (1992). IGBP Secretariat, Stockholm, 78 pp. (JGOFS Report No. 9)
The Report describes how the aims of JGOFS are being, and will be, achieved through global synthesis, large scale surveys, process studies, time series studies, investigations of the sedimentary record and continental margin boundary fluxes, and the JGOFS data management system.

No. 24

Relating Land use and Global Land-Cover Change: A Proposal for an IGBP-HDP Core Project. A report from the IGBP/HDP Working Group on Land-Use/Land-Cover Change. Edited by B. L. Turner, R. H. Moss, and D. L. Skole (1993. IGBP Secretariat, Stockholm, 65 pp. (Human Dimensions of Global Environmental Change Programme, HDP Report No. 5)
The report presents the main findings of the joint Working Group of the IGBP and the International Social Science Council on Land-Use/Land-Cover Change; it describes the research questions defined by the group and identifies the next steps needed to address the human causes of global land-cover change and to understand its overall importance. It calls for the development of a system to classify land-cover changes according to the socioeconomic driving forces. The knowledge gained will be used to develop a global land-use and land-cover change model that can be linked to other global environmental models.

No. 25

Land-Ocean Interactions in the Coastal Zone (LOICZ) Science Plan. Edited by P.M. Holligan and H. de Boois, with the assistance of members of the LOICZ Core Project Planning Committee (1993). IGBP Secretariat, Stockholm, 50 pp.
The report describes the new IGBP Core Project, giving the scientific background and objectives, and the four research foci. These are: the effects of global change (land and freshwater use, climate) on fluxes of materials in the coastal zone; coastal biogeomorphology and sea-level rise; carbon fluxes and trace gas emissions on the coastal zone; economic and social impacts of global change on coastal systems. The LOICZ project framework includes data synthesis and modelling, and implementation plans cover research priorities and the establishment of a Core Project office in the Netherlands.

No. 26

Towards a Global Terrestrial Observing System (GTOS): Detecting and Monitoring Change in Terrestrial Ecosystems. Report of the Fontainebleau Workshop. Edited by O. W. Heal, J.-C. Menaut and W. L. Steffen (1993). Paris: MAB, 71 pp. (UNESCO Man and the Biosphere Digest 14)

The Fontainebleau Workshop, July 1992, defined a strategy to initiate a global terrestrial monitoring system for the IGBP project on Global Change and Terrestrial Ecosystems, the French Observatory for the Sahara and the Sahel, and the UNESCO Man and the Biosphere programme, in combination with other existing and planned monitoring programmes. The report reviews existing organisations and networks, and drafts an operational plan.

No. 27*

Biospheric Aspects of the Hydrological Cycle. The Operational Plan. 1993. Edited by BAHC Core Project Office, Berlin (1993). IGBP Secretariat, Stockholm, 103 pp.

A presentation of the mandate, scope, principal subjects and structure of the BAHC research plan is followed by a full description of the four BAHC Foci: 1) Development, testing and validation of 1-dimensional soil-vegetation-atmosphere transfer (SVAT) models; 2) Regional-scale studies of land-surface properties and fluxes; 3) Diversity of biosphere-hydrosphere interactions; 4) The Weather Generator Project.

No. 28

The IGBP in Action: The Work Plan 1994-1998. 1994. IGBP Secretariat, Stockholm, 151 pp.

This Report provides an overview of the global change research to be carried out under the aegis of the International Geosphere-Biosphere Programme over the next five years. It represents a follow-up to IGBP Report No. 12 (1990) that described the basic structure of the global change research programme, the scientific rationale for its component Core Projects and proposals for their development. The IGBP Core Projects and Framework Activities present their aims and work programme in an up-to-date synthesis of their science, operational and implementation plans.

No. 29

Africa and Global Change. A Report from a Meeting at Niamey, Niger, 23-27 November, 1992. (1994). IGBP Secretariat, Stockholm. (English and French under the same cover)55 pp.

A summary is given of the conference arranged by the Global Change System for Analysis, Research and Training (START) on behalf of the IGBP, the Human Dimensions of Global Environmental Change Programme (HDP), and the Joint Research Centre of the Commission of the European Communities (CEC) that describe the global change scientific research situation in Africa today.

No. 30

IGBP Global Modelling and Data Activities, 1994-1998. 1994. Strategy and Implementation Plans for Global Analysis, Interpretation and Modelling (GAIM) and the IGBP Data and Information System (IGBP-DIS). IGBP Secretariat, Stockholm, 86 pp.

This report sets out the goals and directions for GAIM and IGBP-DIS over the next five years, expanding on the recent overview of their activities within IGBP Report 28 (1994). It describes the work within IGBP-DIS directed at the assembly of global databases of land surface characteristics, and within GAIM, directed at modelling the global carbon cycle and climate-vegetation interaction.

No. 31

African Savannas and the Global Atmosphere. Research Agenda. 1994. Report of a joint IGBP/START/IGAC/GCTE/GAIM/DIS Workshop on African Savannas, Land use and Global Change: Interactions of Climate, Productivity and Emissions, 1-5 June 1993, Victoria Falls, Zimbabwe. Edited by C. Justice, B. Scholes and P. Frost. IGBP Secretariat, Stockholm, 53 pp.
The workshop focused on interactions between African savannas and the global atmosphere, specifically addressing land-atmosphere interactions, with emphasis on sources and sinks of trace gases and aerosol particles. The report discusses the ecology of African savannas, the research issues related to carbon sequestration, ongoing and proposed activities, and gives a research agenda.

No. 32

International Global Atmospheric Chemistry (IGAC) Project. The Operational Plan. 1994. IGBP Secretariat, Stockholm, 134 pp.
The goals of IGAC are to: develop a fundamental understanding of the processes that determine atmospheric composition; understand the interactions between atmospheric chemical composition and biospheric and climatic processes, and predict the impact of natural and anthropogenic forcings on the chemical composition of the atmosphere. The Operational Plan outlines the organisation of the project. The plan describes the seven Foci, their related Activities and Tasks, including for each the scientific rationale, the goals, strategies.

No. 33

Land-Ocean Interactions in the Coastal Zone. Implementation Plan. 1995. Edited by J. C. Pernetta and J. D. Milliman. IGBP Secretariat, Stockholm, 215 pp.
LOICZ is that component of the IGBP which focuses on the area of the Earth's surface where land, ocean and atmosphere meet and interact. The implementation plan describes the research , its activities and tasks, and the management and implementation requirements to achieve LOICZ 's science goals. These are, to determine at regional and global scales: the nature of these dynamic interactions, how changes in various compartments of the Earth system are affecting coastal zones and altering their role in global cycles, to assess how future changes in these areas will affect their use by people, and to provide a sound scientific basis for future integrated management of coastal areas on a sustainable basis.

No. 34

BAHC-IGAC-GCTE Science Task Team. Report of First Meeting. Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, 10-12 January, 1994. 1995. IGBP Secretariat, Stockholm, 45 pp.
The Science Task Team discussed and developed recommendations for multi-Core Project collaboration within the IGBP under three headings: process studies in terrestrial environments, integrated modelling efforts, and partnership with developing country scientists. Three interrelated themes considered under process studies are: transects and large-scale land surface experiments, fire, and wetlands. Methods for implementation and projects are identified.

No. 35
Land-Use and Land-Cover Change. Science/Research Plan. 1995. Edited by B. L. Turner II, D. Skole, S. Sanderson, G. Fischer, L. Fresco and R. Leemans. IGBP Secretariat, Stockholm, HDP Secretariat, Geneva, (IGBP Report 35/HDP Report 7) 132 pp.
The Science/Research Plan presents land-use and land-cover change and ties it to the overarching themes of global change. It briefly outlines what is currently known and what knowledge will be necessary to address the problem in the context of the broad agendas of IGBP and HDP. The three foci address by the plan are: (i) land-use dynamics, land-cover dynamics - comparative case study analysis, (ii) land-cover dynamics - direct observation and diagnostic models, and (iii) regional and global models - framework for integrative assessments.

No. 36
The IGBP Terrestrial Transects: Science Plan. 1995. Edited by G. W. Koch, R. J. Scholes, W. L. Steffen, P. M. Vitousek and B. H. Walker. IGBP Secretariat, Stockholm, 53. pp. Also available in Chinese.
The IGBP Terrestrial Transects are a set of integrated global change studies consisting of distributed observational studies and manipulative experiments coupled with modelling and synthesis activities. The transects are organised geographically, along existing gradients of underlying global change parameters, such as temperature, precipitation, and land use. The initial transects are located in four key regions, where the proposed transects contribute to the global change studies planned in each region.

No. 37
IGBP Northern Eurasia Study: Prospectus for an Integrated Global Change Research Project. 1996. Edited by W.L. Steffen and A.Z. Shvidenko. IGBP Secretariat, Stockholm, 95 pp. Also available in Russian.
This report was prepared by scientists representing BAHC, IGAC, and GCTE. It is a prospectus for an integrated hydrological, atmospheric chemical, biogeochemical and ecological global change study in the tundra/boreal region of Northern Eurasia. The unifying theme of the IGBP Northern Eurasia Study is the terrestrial carbon cycle and its controlling factors. Its most important overall objective is to determine how these will alter under the rapidly changing environmental conditions.

No. 38
Natural Disturbances and Human Land Use in Dynamic Global Vegetation Models. A report of a workshop co-convened by the GAIM, GCTE, LUCC, and IGBP-DIS Programme Elements of the IGBP. 1997. Edited by F.I. Woodward and W.L. Steffen. IGBP Secretariat, Stockholm, 49 pp.
This report summarises the findings and recommendations of an International Geosphere-Biosphere Programme (IGBP) Workshop which aimed to develop an approach to modelling landscape-scale disturbances in the context of global vegetation change.

No. 39

Modelling the Transport and Transformation of Terrestrial Materials to Freshwater and Coastal Ecosystems. A workshop report and recommendations for IGBP Inter-Programme Element Collaboration. 1997. Edited by C.J. Vörosmarty, R. Wasson and J. Richey. IGBP Secretariat, Stockholm, 84 pp.
This report is the major product of a three-day workshop entitled: "Modelling the Delivery of Terrestrial Materials to Freshwater and Coastal Ecosystems" held in Durham, NH, USA from 5-7 December 1994.

No. 40

Global Ocean Ecosystem Dynamics. Science Plan. 1997. Final editing by: R. Harris and the members of the GLOBEC Scientific Steering Committee (SSC). IGBP Secretariat, Stockholm, 83 pp.
Based on a draft plan written by the SCOR/IOC SSC for GLOBEC in 1994. That plan was itself based on a number of scientific reports generated by GLOBEC working groups and on discussions at the GLOBEC Strategic Planning Conference (Paris, July 1994). This document was presented to the Executive Committee of the Scientific Committee on Ocean Research (SC-SCOR) for approval (Cape Town, November 14-16 1995), and was approved by the SC-IGBP at their meeting in Beijing in October 1995. The members of the SCOR/IGBP CPPC were: B. J. Rothschild (Chair), R. Muench (Chief Editor), J. Field, B. Moore, J. Steele, J.-O. Strömberg, and T. Sugimoto.

Book of Abstracts

Book of Abstracts. Natural and Anthropogenic Changes: Impacts on Global Biogeochemical Cycles. Asian Change in the Context of Global Change. Beijing, 23-25 October, 1995. IGBP Secretariat, Stockholm, 107 pp
This book of abstracts is a result of materials presented at the scientific symposium held in conjunction with the Fourth Scientific Advisory Council for the IGBP (SAC) held in Beijing, 23-25 October, 1995.

IGBP Booklet*

A Study of Global Change. 1989. Edited by IGBP Secretariat, Stockholm, 9pp.

Global Change: Reducing Uncertainties

Prepared by P. Williamson, with editorial assistance from the Scientific Committee for the IGBP (June, 1992; reprint August 1993), IGBP Secretariat, Stockholm, 40 pp.

IGBP Directory

IGBP Directory. No. 1, February 1994
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