A Component of the U.S. Global Change Research Program

Initial Science Plan

U.S. Global Ocean Ecosystems Dynamics

Report Number 1

February 1991

U.S. GLOBEC

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Produced by

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ABSTRACT

GLOBEC (GLOBal ocean ECosystems dynamics) is a research initiative organized by the oceanographic and fisheries communities as a component of the U.S. Global Change Research Program to address the question of how changes in global environment are expected to affect abundances, variations in abundance, and production of animals in the sea. Our approach to this problem is to develop a fundamental understanding of the mechanisms that determine both the abundances of key marine animal populations and their variances in space and time. We assume that the physical environment is a major contributor to patterns of abundance and production of marine animals, in large part because the planktonic life stages typical of most marine animals are intrinsically at the mercy of fluid motions of the medium in which they live. Consequently, we reason that a logical approach to predicting the potential impact of a globally changing environment is to understand how the physical environment, both directly and indirectly, contributes to animal abundance and its variability in marine ecosystems.

GLOBEC's approach to this problem has several definable characteristics:

- A partnership between physical and biological oceanographers will be needed to assess how population and ecosystem dynamics are linked to physical phenomena in the sea, from the large scale, such as changing inputs of freshwater modifying buoyancy-driven flows in the entire Gulf of Alaska, for example, to the smaller scales of turbulence, mixing, and transport near-shore and in fronts.

- GLOBEC's population and ecosystem dynamics approach will require evaluation and integration of the fundamental biological rates of feeding, survivorship, and reproduction. These, in turn, will depend upon passive and active movements of individuals, effects of predators, competitors, and commensals, key aspects of the physical environment, food quality and quantity, and how physics modify biological interactions.

- GLOBEC's intent is to construct general physical/biological models of ecosystems dynamics based upon "first-principle" mechanisms of processes that affect the individual organisms. By understanding mechanism we may extrapolate, generalize, and predict from site-specific results.

- Study sites for GLOBEC field programs are proposed for (1) the Northwest Atlantic, including Georges Bank, as a contribution to the international Cod and Climate Change Program, (2) the California Current ecosystem, as representative of an Eastern Boundary Current upwelling system, (3) the Antarctic, to investigate a high-latitude system, where models of climate predict some of the greatest climate changes, (4) an open ocean site in the Indian Ocean, where effects of climate-driven variation in monsoon events can be assessed, and possibly (5) an Alaska Current system, where changes in buoyancy-driven coastal flows could be evaluated.

- The mechanistic understanding of the processes that determine abundance, fluctuation in abundance, and production of marine animals must necessarily involve coupled physical-biological models, linking performance of the individual organism to local and mesoscale physical processes and linking both the biology and local and regional physics to basin-scale changes in global climate. Modeling will play a substantial role in GLOBEC.

- An optimistic prognosis for the success of GLOBEC is based in large measure on the potential for novelty and fundamental scientific breakthroughs that can come from integrating the physical and biological processes. The development of new technologies that will allow coverage of biological sampling to approach that now possible in ocean physics promises giant steps forward in appreciating the role of changing physics and global climate in modifying marine ecosystems dynamics.

PRELUDE

The primary purpose of this document is to publicize the emerging plans for GLOBEC, the coordinated study of the potential impact of global change on ocean ecosystems dynamics. The steering committee charged with planning the U.S. GLOBEC program first met in May 1989. This initial science plan represents the progress achieved over the first one-and-one-half years. During the next year, various components of this initial science plan will become more explicitly defined through the efforts of the working groups, community feedback in response to this initial science plan, interactions with representatives of appropriate funding agencies, and the interplay with international GLOBEC planning efforts.

This initial science plan is being widely circulated to individual scientists, agency personnel, and science administrators. It should be read in conjunction with the Report of the Wintergreen Workshop on Global Ocean Ecosystems Dynamics, held in 1988, and other documents published by the GLOBEC steering committee and available through the GLOBEC planning office: the Modeling Report (February 1990), the Halifax Workshop Report on Northwest Atlantic Programs (February 1991), and the Miami Workshop Report on Biotechnology (February 1991). We solicit feedback at all stages on all aspects of this planning process. Addresses for both printed and electronic mail are provided for each member of the steering committee in Appendix B of this document.

The planning efforts to date for GLOBEC have been supported by NSF jointly with ONR, NOAA, and NASA. The National Academy of Sciences provided early support and direction in developing and printing a report on recruitment of marine animals, from which the GLOBEC initiative has evolved.

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I. EXECUTIVE SUMMARY

A. Rationale

Compelling evidence exists showing that the physical environment of the earth is in flux. Considerable recent debate has raged over the question of how closely observed climate change can be related to enhanced production of greenhouse gases and other anthropogenic influences. Regardless of the relative contributions of human activities to global climate change, it is clear from paleoceanographic studies that global climate has varied tremendously even within recent geologic periods. Transitions between ice ages and warmer periods are numerous. The question is not whet-her climate change will happen but how rapidly. Along with global climate change, toxic chemicals and wastes are being introduced into the air and water in quantities sufficient to cause fundamental changes in the life support systems of the earth. Nutrient levels are becoming substantially enhanced in the waters of the globe. Several large research initiatives are now underway to assess the significance of these changes to our global climate, physics, and geochemistry. GLOBEC (GLOBal ocean ECosystems dynamics) is designed to evaluate the likely consequences of these changes in global climate and physics to the sustainability of animal production in the sea.

The approach of GLOBEC is to understand how physical processes, both directly and indirectly, influence the success of individual animals in the sea, their feeding, growth, reproduction, and survivorship. From this information can be derived the consequences of changing physical processes on animal populations and ecosystems. Models of global climate can then be used to relate global change to changes in regional ocean physics and, subsequently, changes in regional physics to shifts at the scales of events that influence the individual organism. Effects on zooplanktonic life stages will be emphasized because so many marine animals undergo at least one planktonic life stage and because the planktonic size classes are most at the mercy of the physics of their fluid environment.

GLOBEC is the vehicle to plan, promote, and coordinate this physical-biological partnership needed to assess the consequences of changing global climate on marine animal production. We envision substantial progress arising from the development and application of new technologies for sampling, from the interactive collaboration of physical oceanographers and marine biologists, and from the stimulation and opportunity that this initiative provides to investigators in the ocean sciences community.

B. Guidance From the Scientific Community

The directions taken by GLOBEC have their origins in the recommendations made at several workshops organized to discuss the most compelling scientific issues facing each of the component scientific disciplines represented within GLOBEC (see Appendix A for details). In specific, meetings of ocean scientists interested in fish populations (Fish Ecology I, II, III), zooplankton (the Lake Arrowhead Colloquium), benthic invertebrates (the Nearshore Benthic Ecology Meeting), long time-series observations (Deep-Sea Observatories Workshop), and coastal physical oceanography (the COPO planning process) have contributed guidance and stimulation to the GLOBEC planning groups. The present set of plans for GLOBEC is derived from the guidelines, recommendations, and mandates of three workshops explicitly organized to evaluate the scientific need for global ocean ecosystems studies and to provide guidance for the evolving research initiative: the National Academy of Sciences meeting on recruitment and ocean ecosystems dynamics, the Wintergreen GLOBEC workshop, and the Halifax planning meeting for a GLOBEC study in the Northwest Atlantic Ocean.

Participants in these workshops and planning meetings reached widespread consensus on several recommendations, all of which have been incorporated fundamentally into the GLOBEC science plan:

(1) Base the approach on fundamental mechanisms at the level of the individual organism that influence growth, reproduction, and mortality, thereby effecting population change and ecosystem responses;

(2) Effect a cooperative partnership between physical and biological oceanographers, dedicated to solving the problems of how changing global climate might affect ocean physics and thereby directly and indirectly alter ocean ecosystem dynamics;

(3) Develop a research program based upon interactive feedbacks between coupled physical-biological models and field observations/experiments; and

(4) Promote development and utilization of new technologies and instrumentation to redress the problem of chronic undersampling of the sea, a problem especially critical for zooplanktonic animals.

C. Progress and Plans for Major Program Elements

1. Modeling

From analyses performed by the GLOBEC working group on modeling in 1989, the steering committee decided that several initial modeling efforts would be necessary to initiate promptly prior to mounting any specific field program to help guide the field studies and to resolve certain key questions about what measurements need to be taken, at what resolution, and under what conditions. An announcement of opportunity was prepared and released by NSF (the National Science Foundation) in February 1990 to solicit proposals for these initial modeling studies:

- Conceptual studies of simplification and predictability to address how scaling, pooling, and averaging might be appropriately applied to simplify measurement needs in ocean ecosystems dynamics models and how environmental variability of a variety of sorts might influence the degree of predictability possible in ocean ecosystems dynamics;

- Prototype investigations of biological processes in idealized flows to address how flow regimes affect biological processes at the level of the individual, population, community, and ecosystem and how sensitive results are to enhancing the realism and complexity of the flow regime; and

- Preliminary site-specific models addressing the mechanistic interactions of the physics and biology and relating the ocean physics to global change through necessary intervening scales and processes.

2. Field Studies Combining Modeling/Observation

The intention of the GLOBEC steering committee is to develop an understanding of the fundamental mechanisms by which ocean physics contribute to ecosystem dynamics, especially in the planktonic environment. We hope to be able to develop formal models combining biological and physical variables that have sufficient generality to be broadly applicable, with appropriate site-specific modifications,, to planktonic systems in the sea.

This approach implies intensive study of physics and ecosystem dynamics in a small number of carefully chosen study systems, with subsequent extension to additional systems that include physical and biological processes not adequately represented in the initial study systems.

Through this process of testing, validating, and elaborating on a core set of physical/biological models, GLOBEC intends to examine the implications of global change on animal abundance and production in the major ocean basins. In each ocean basin, ocean ecosystems dynamics will be associated with those key physical changes most likely to be triggered by global change. Planning has begun and progressed to differing degrees for the following field sites:

- Northwest Atlantic - Our planning process is most advanced for this system as a consequence of the Halifax workshop in June 1990 to plan U.S.-Canadian cooperative efforts as a part of the international Cod and Climate Change (CCC) program covering the North Atlantic ocean. In 1991, we anticipate release of an NSF Announcement of Opportunity to further preparations for a pilot study of how changes in global circulation of water masses driven by global climate change are likely to influence regional physics in the vicinity of Georges Banks and how those changes in turn are expected to alter the ecosystem dynamics that dictate the abundance and production of codfish, sea scallops, and those holoplanktonic zooplankters integral to the ocean food webs. We anticipate further planning to integrate this NSF-supported activity with NOAA (National Oceanic and Atmospheric Administration) studies of fisheries dynamics and oceanography in this region.

- Eastern Pacific - Plans for GLOBEC sites in the Eastern Pacific will become more focused in 1991 through workshops to assemble interested scientists to identify the best approaches and sites to evaluate them. The steering committee has decided to proceed with planning workshops to assess the value of a GLOBEC study in the California Current ecosystem as representative of an Eastern Boundary Current system. In addition, we are interested in developing plans, possibly in conjunction with CoOP (Coastal Ocean Processes), to examine the consequences of global change in the higher latitude Alaska Current and Bering Sea Shelf ecosystems, where temperature change and precipitation change could dramatically affect these buoyancy-driven flows.

- Southern Ocean - We expect to initiate planning activities for the Antarctic region through initial workshops sponsored by federal agencies such as NOAA and NSF. Global change is expected to have its most intense effects in the higher latitudes, including changes in air temperature, ice cover, freshwater inputs, and UV radiation. These form reasonable candidate changes to investigate in a GLOBEC study of Southern Ocean ecosystem responses.

- Indian Ocean - We anticipate study of the implications of global change for the dynamics of monsoon processes in this ocean basin, with subsequent study of how the physical-biological couplings imply ecosystem responses. The Office of Naval Research (ONR) is reviewing a program to study the physical- biological couplings of the monsoon system in the Indian Ocean that we hope to involve in the GLOBEC quest to understand the likely consequences of global change on ocean physics and ecosystems dynamics.

- Other Study Systems - Although our primary interest is to uncover fundamental and general processes whereby ocean physics affect ecosystems dynamics by in-depth investigation of some small number of prototype systems, particularities and idiosyncrasies of other systems will doubtless require additional site-specific studies of further physical phenomena and their biological consequences. In specific, we expect to develop plans for study of how climate change may affect ocean circulation around tropical islands and coral reefs and the ecosystem implications of those changes. We also anticipate a need to examine how the bounded nature of the Great Lakes and peculiarities of the life histories of their freshwater biota may require changes in the ecosystem dynamics models and conclusions developed from studying ocean ecosystems.

3. Technology

The GLOBEC working group on technology prepared a review in 1989 of the most promising technological solutions to the problems of undersampling and of time-lagged sampling of zooplanktonic animals in the sea. Our ability to couple physical and biological processes into models of important dynamical events and interactions is at present grossly compromised by the limitations of biological sampling. Effective evaluation of most important coupled physical-biological processes will require quantum jumps in the speed and resolution of zooplankton sampling so as to approach the capability of synoptic sampling. Three sets of instrument systems were considered as possible solutions to this technology problem. The working group explored the merits, limitations, feasibility, and likely costs of a rapid (probably acoustics-based) zooplankton mapper, a shipboard counter by size (probably using optics) and taxon (possibly utilizing molecular genetic tags or optical information), and a field profiler (probably incorporating the Multi-frequency Acoustic Profiling System, MAPS).

A special technology session at the Halifax workshop was directed towards establishing priorities for action to promote development of desired new technologies for GLOBEC research. The recommendations included organization of a biotechnology workshop to evaluate alternative possible technologies for assessing the physiological state of planktonic animals and for identifying planktonic animals by taxon. The recommended biotechnology workshop has now been held and a GLOBEC workshop report will soon be available describing the proceedings. In addition, the technologists meeting in Halifax recommended assembly of a group of acousticians and experts on optics to make further recommendations on how to promote use of these technologies in oceanographic instrumentation necessary for GLOBEC investigations. This meeting will be conducted later in 1991. The GLOBEC steering committee also anticipates need to customize physical instrumentation, such as the Acoustic Doppler Current Profiler (ADCP), to provide the coverage and performance necessary for study of critical physical dynamics, especially those both high and low in the water column.

II. *WHAT IS GLOBEC — RATIONALE*

A. Global Change and Marine Ecosystems

Evidence continues to accumulate that the environment of our planet is changing (e.g., Mitchell, 1989). Many of the changes are thought to be the consequences of human intervention into natural processes (such as the ozone depletion over the Antarctic, increased concentrations of greenhouse gases, the enhanced acidity of rainfall downwind of industrialized areas, etc.), but paleoclimatic records reveal that the earth has experienced at least some similar changes in the past. We possess little knowledge of the spatial or temporal scales of these changes. Some occur on relatively short time scales (El Niño-Southern Oscillation Events), whereas others may be operating over very long periods of time (the incorporation of carbon into the deep sea: Broecker and Peng, 1982). Even for processes that operate at a global scale, the climatic shifts are not uniformly distributed across the face of the globe. This characteristic not only complicates detection but also demands mechanistic models to permit prediction of future change. Many scientists are now deeply involved in verifying the existence and magnitude of these shifts in the environment, as well as in modeling the likelihood of various alternative scenarios for future change. These studies of the shifts in the physical and geochemical environment of our planet are of critical importance, but equally urgent is the challenge of assessing the biological consequences and the sustainability of biological life-support systems in the face of such global change.

GLOBEC (GLOBal ocean ECosystems dynamics) is a research initiative proposed by the oceanographic and fisheries communities to address the question of how changes in global environment are expected to affect the abundance and production of animals in the sea. Our approach to this problem is to develop a fundamental understanding of the mechanisms that determine both the abundance of key marine animal populations and their variances in space and time. We assume that the physical environment is a major contributor to pattems of abundance and production of marine animals, in large part because the planktonic life stages typical of most marine animals are intrinsically at the mercy of the fluid motions of the medium in which they live. Consequently, we reason that a logical approach to predicting the potential impact of a globally changing environment is to understand how the physical environment, both directly and indirectly, contributes to animal abundance and its variability in marine ecosystems.

B. Physical-biological Coupling and Impacts of Global Change

While all animals in the sea are affected to some degree by the dynamics of the waters around them, it seems likely that planktonic animals are the most tightly coupled to the physics of the fluid medium. Since the majority of marine animals spend at least a portion of their life in the plankton, we intend to focus most of our attention on zooplanktonic organisms, both the holoplankton and the meroplankton. The holoplankton, such as numerous copepods and other macro- and microzooplankters, completes its entire life cycle in the plankton. Many marine benthic invertebrates have larval stages that are meroplankters, spending from hours to several weeks in the plankton. Most nektonic animals, the large swimming forms such as fish and squid, also have at least one planktonic life stage during which they too are at the mercy of the fluid motions of the sea. Accordingly, success of recruitment into the adult population for marine animals does not depend on biological processes alone. The transport of organisms into regions that may be either favorable or inhospitable to them plays a major role in dictating the success of recruitment and thus the abundance of marine animals. Moreover, the characteristics of a region that determine its suitability for any given organism depend not only on the availability of food and the abundance of predators but also upon the dynamic physical features of the local environment that influence the success of recruitment, the efficiency of feeding, and the susceptibility to predation.

The potential impact of global change on animal populations in the sea can be approached by addressing how these physical processes of significance to the success of planktonic organisms are themselves likely to shift with changes in global climate. Scientists cannot predict with complete certainty what the impact of global change will be on the various parameters that characterize the oceans and the atmosphere. Nevertheless, reasonable scenarios predict global warming from the "greenhouse effect", altered precipitation pattems, and sea level rise (e.g., Mitchell, 1989). We provide three examples to illustrate, how these global changes could have profound impacts on the physical features and processes of the sea that help dictate the abundance, distribution, and production of marine planktonic animals.

The coastal region of the Gulf of Alaska, for example, could be the site of a large physical and biological response to global change. The high latitudes seem more sensitive than the low latitudes to many parameters of global change (Mitchell, 1989). As precipitation pattems change and as global warming triggers rapid melting of previously persistent ice fields and retreat of glaciers, the volume of freshwater that enters the Gulf of Alaska is likely to be affected substantially. We already know that the input of freshwater from the entire coastline of the gulf is a critical component of the driving forces for the Alaska Coastal Current. Under a different precipitation regime with different pattems and degrees of icemelt, the magnitude and even the direction of this current could shift dramatically. Effects of such a shift on populations of various fish species could be large. For example, transport of eggs and larvae of the Alaskan pollock could be affected. Walsh and McRoy (1986) modeled effects of advective transport on this species in the adjacent Bering Sea, testing the hypothesis that years of reduced temperature (such as a climatic shift) delay the development of copepod nauplii that represent the primary food source for pollock larvae. They concluded that the observed pattern of interannual variability in year-class strength was consistent with the larval starvation hypothesis, and not with the effects of advection. It would be interesting to examine this same hypothesis in the region affected by the Alaska Coastal Current, where freshwater inputs and resultant currents can be substantially higher (Royer, 1982). Implications of such a study would extend far beyond the Gulf of Alaska. For example, coastal currents driven by the buoyancy derived from freshwater inputs can be found off the coast of Norway. Mean currents in the Middle Atlantic Bight may be forced by freshwater injections from the St. Lawrence River estuary. The Mississippi River likewise has a measurable effect on the nearshore circulation of the entire Gulf of Mexico west of the Mississippi Delta, especially in spring.

Another important set of examples of how global change may influence the biology of the sea involves oceanic fronts. Fronts exist where sharp boundaries are present between two neighboring water masses with different properties (e.g., differing temperatures, salinities, chlorophyll concentrations, speeds). Fronts are ubiquitous in the ocean, especially in the coastal zones. One can identify at least five common types of fronts: shelf/slope (or shelf break) fronts, upwelling fronts, tidal mixing (or shallow sea) fronts, estuarine fronts, and advective fronts (see Joyce, 1983 for a thorough set of classifications). Biological activity is well known to be concentrated in frontal regions for a variety of reasons (e.g., Le Fevre, 1986). The locations of several of these frontal types as well as the behavior and dynamics of the fronts, such as downwelling and mixing, may be expected to shift with changing global climate because most fronts can be strongly affected by winds. For example, the position of upwelling fronts will be under the control of coastal wind pattems, which are thought to be subject to climatic variation (Bakun, 1990). Indeed, paleoceanographic evidence indicates that coastal upwelling associated with the Asian monsoon was more intense about 9000 B.P. during the maximum in Northern Hemisphere solar insulation (Mitchell, 1989). It seems reasonable to hypothesize that associated upwelling fronts may have changed their locations in addition to their upwelling regimes. In addition, the positions of estuarine fronts will be under the control of freshwater input to the estuary and consequently subject to variation with shifting precipitation regimes. The ecological importance of the position of any given front in the life history of organisms is not generally known, but we know that this role is significant in certain well-studied cases (Tyler and Seliger, 1978).

Our final example involves the impact of changing sea level. A growing consensus of scientists agrees that sea level is now rising at a rate of 1-3 mm per year and that this rate is likely to increase (Thomas, 1987). Extrapolated over the coming 50-100 years, this rise in sea level promises to have profound impacts on nearshore habitats. The width of the inner shelf environment (the inner shelf is the strip of ocean where the bottom significantly affects flow, or formally where the surface mixed layer approaches the bottom boundary layer) may be expected to increase greatly, especially over gently sloping bottoms. It is likely that the mean surface gravity wave energy reaching the shore may decrease when distributed over a wider shelf. Since transport in the wave zone, both transverse to and along shore, is controlled by surface waves, the transport of planktonic forms including larvae and juveniles of many organisms may be substantially modified. The role of onshore transport in affecting the success of recruitment of many benthic invertebrates is now undergoing intense scrutiny (e.g., Roughgarden et al., 1988). Most of our present understanding of the ecology of intertidal populations and communities is based on an appreciation of the importance of such processes as competition and predation that occur after the time of larval settlement (Connell, 1961; Paine, 1966). Important current research is evaluating the significance of recruitment limitation in this system and the role of larval transport in affecting the supply of recruits to shore. Changing rates of transport due to rising sea level could have profound implications to the resolution of this issue.

The common thread in these three scenarios is that changing global climate affects the physical phenomena in the sea, from the large scale, such as changing inputs of freshwater modifying buoyancy-driven flows in the entire Gulf of Alaska, to the small scale of turbulence, mixing, and transport nearshore and in fronts. Furthermore, because so many marine animals have planktonic life stages, we expect that the changing physics will have profound effects on individual organisms, and by changing their demographic parameters on populations, and by changing populations on the communities and ecosystems of the sea. This sequence, in fact, represents the strategy by which GLOBEC intends to approach the problem of predicting the impacts of global change on animal abundance, distribution, and production in the sea.

C. Components of GLOBEC's Approach - Based on Understanding of Mechanisms that Influence Individual Organisms

1. GLOBEC intends to vastly increase our understanding of the fundamental mechanistic processes that dictate:

    - the abundance of marine animals,
    - the fluctuations in their abundance, and
    - the secondary production of ocean ecosystems in the context of a changing global climate.

Our philosophical approach to predicting the possible impacts of global change on animal abundance, variation in abundance, and production in the oceans is to develop a basic understanding of how physical and biological processes at the level of the individual organism determine population change. From this fundamental understanding, we intend to assess the potential impact of global change by linking global change to change in those physical processes that affect the individual organisms and populations of organisms.

2. GLOBEC'S "first-principles" population dynamics approach to population ecology requires evaluation of fundamental biological processes:

- feeding and growth,
- survivorship, and
- reproduction and fecundity.

The rates of feeding and growth, survivorship, and reproduction and fecundity may depend upon:

- population density,
- passive and active movements of individuals,
- effects of predators, competitors, and commensals,
- key aspects of the physical environment, and
- how physics modify biological interactions.

We maintain that the process by which change in the physical environment influences abundance and production of animals in the sea is through modification of the success of individual organisms, which then alters parameters of population growth and thereby triggers ecosystem change. Consequently, appreciation of the role of changing physics in the ecosystems dynamics of the oceans requires a "first-principles" approach at the level of the individual organism. Such studies lie at the cutting edge of population ecology in that they demand evaluation not only of the direct effects of key physical variables, features, and processes on individual performance but also of the indirect effects of how changing physics modify the important biological interactions. For example, enhanced turbulence may alter the feeding rate of a zooplankter, positively by renewing food supplies that might otherwise become depleted in its local vicinity and by increasing encounter rates between the zooplankter and its prey, or negatively by interfering with effective deployment of its feeding appendages.

3. Only by understanding mechanism can we extrapolate, generalize, and predict from site-specific results.

The standard means of justifying extrapolation of a set of results to systems outside of specific study sites is to replicate studies in each of several strata, where stratification is done along each of the variables deemed most likely to influence the outcome of whatever is being measured. Replication in this fashion is probably impossible for studies of marine ecosystems because of the high costs involved and because of the intrinsic variation in biological systems that renders true replication difficult to achieve. The alternative to this sort of inductive approach to generalization is to focus on mechanistic processes and to practice deduction as a means of extending the results to additional systems. This represents one of our major motivations in choosing a reductionist, process-oriented approach to the problem of predicting the influences of global change on marine ecosystems.

4. The understanding of the processes that determine abundance, fluctuation in abundance, and production of marine animals must necessarily involve coupled physical-biological models, linking performance of the individual organism to local physical processes and linking both the biology and local physics to basin-scale changes in global climate.

We expect modeling to play a significant role in GLOBEC studies at several levels. The explicit incorporation of physical variables and processes into biological population models holds promise for great originality and progress. Appropriately constructed models of both physical and biological processes should guide the choice of field experiments and observations, while results of those field exercises should feed back interactively into the models. We envision use of nested models to bring the implications of global change down to the scale of events that influence the individual organism. Regional models may be nested within global models, such as general circulation model's (GCMs), and within region several submodels may reduce processes to the levels at which biological impacts occur.

5. Our optimistic prognosis for the success of GLOBEC is based in large measure on the potential for novelty and fundamental scientific breakthroughs that will come from integrating the physical and biological processes. The development of new technologies that will allow the coverage of biological sampling to approach that now possible in ocean physics promises giant steps forward.

The oceans are notoriously undersampled. GLOBEC plans to help fill this void by developing and utilizing new technologies to sample synoptically certain targeted ocean physics and biology. Physical instrumentation such as the Acoustic Doppler Current Profiler (ADCP) can be much more widely applied to describe water movements of significance to marine plankton. Biological sampling needs to be automated by catalyzing the evolution of new instrumentation for assessing the abundance and distribution of planktonic animals. GLOBEC plans to evaluate the potential for application of acoustics, optics, biotechnology, and other tools to provide these measurements. A major thrust of GLOBEC will then be the development of the most promising of these potential technological solutions to the need to automate biological sampling.

D. Physical Processes of Most Significance to GLOBEC

Understanding the coupling of physical and biological processes is the core GLOBEC activity. This general topic has been reviewed for coastal ecosystems by Denman and Powell (1984) and Powell (1989), and its contribution to the phenomenon of patchiness and spatial heterogeneity has been discussed by Mackas et al. (1985). Though virtually all physical processes make some contribution to the abundance and distribution of animals, we explore here a representative subset of the many physical phenomena in the sea that can have substantial ecological impact. We focus on effects at several spatial and temporal scales: turbulence at the small-scale; front and cross-shelf exchanges at intermediate scales; and basin-scale circulations at the large scale. Though the impacts of variability at one scale can be felt at another (e.g., energetic frontal motions might lead to energetic vertical motions, turbulence, and mixing), it seems to be a good first-order approximation to consider effects at these different scales separately (Denman and Powell, 1984). Equivalently, the coupling between scales is weak, but not negligible.

1. Turbulence

The scales of turbulent motion in the ocean are comparable to the scales at which plankton operate and interact. Interactions are affected by the turbulence. The Kolmogorov scales can be estimated from the local rate of turbulent energy dissipation, ε, and the kinematic viscosity, ν. The time scale is $\tau_k=(\nu/\varepsilon)^{1/2}$, the velocity scale is $v_k=(\upsilon\varepsilon)^{1/4}$, and the spatial scale is $l_k=(\nu^3/\varepsilon)^{1/4}$. Although the kinematic viscosity is nearly constant for seawater, roughly $10^{-2}cm^2s^{-1}$, the dissipation rates vary by several orders of magnitude. A typical range of the dissipation rate in the ocean is between 10^{-6} and 10^{-2} in cm^2s^{-3}. Therefore the Kolmogorov scales are the following:

ε	10^{-6} cm^2s^{-3}	10^{-2} cm^2 s^{-3}
τ_k	100 s	1 s
v_k	0.01 cm s^{-1}	0.1 cm s^{-1}
l_k	1 cm	0.1 cm

The peak of the dissipation spectrum occurs at a wavelength about 30 times larger than the Kolmogorov length scale, at this dimension viscosity changes the turbulent relative motion to a uniform straining motion. The actual stirring speeds associated with the energy containing eddies of the turbulent motion are much larger than the Kolmogorov velocity scale. The turbulence velocity, v*, associated with an energy containing eddy of size l*, is $(\varepsilon l^*)^{2/3}$. In the upper ocean energy containing eddies can be on the order of 10 m or more (depending on the depth of the mixed layer). The velocity scale v* can be on the order of several cm/sec.

Because turbulent flow is constrained by both the continuity and the Navier-Stokes equations, it is not a completely random flow field and does not simply disperse particles in space. There are organized structures in the flow field (Hussain, 1986). These large structures affect particles, for example, dense particles are collected in regions of high strain rate or low vorticity (Maxey, 1987; Squires and Eaton, 1990). This mechanism may be an important process for marine aggregates, as well as the interaction between prey and predator.

Historically two effects of physical processes on biological populations have been considered important (Hjort, 1914): advection (transport to more or less desirable locations) and in situ environmental parameters (temperature, salinity, light, nutrients). Another factor contributing to the variability in population levels is relative motion which leads to variability in contact, a necessary precursor to ingestion. This relative motion can arise from differential sinking, Brownian motion, swimming, or shearing motion in the water.

At smaller spatial scales (microns to centimeters), where many planktonic creatures exist, the shear comes from turbulence. Even if the scales are so small that turbulent velocity fluctuations are damped out by viscosity, the shear still exists (Hinze, 1975). Hence there is an effect of turbulence on planktonic contact rates. It is important to consider the distribution of the turbulence in space, its coincidence with biological populations, and the non-linear interactions due to behavior.

A recent study, Rothschild and Osborn (1988), shows that turbulence enhances the encounter probability as the intensity of turbulence increases. An analytical approach to their prediction is not tractable. A turbulent velocity field has a spatial and temporal coherence as well as satisfying the continuity equation. The relative motion of parcels of water depends on their separation. Thus the description of the coherent structure of turbulence demands a much more complex stochastic model than a simple random walk.

We intuitively expect that the organisms must have become adapted to their immediate environment, including the kinematic effects of turbulence upon planktonic trophodynamics. Strickler and his colleagues (Costello et al., 1990; Marras et al., 1990) have experimentally investigated the effect of turbulence on planktonic trophodynamics. The prey is mostly *Gymnodinium* spp. so the swimming ability of prey is much smaller than that of predator. However, in order to record the video images of prey contact, the plankter was tethered and the motility of the plankton was suppressed. 'Thus, the experimental results can not be compared to oceanic environment or calculations. However, the results show a substantially increased feeding rate associated with the onset of turbulence, and a surprising continuation of the foraging response after the cessation of turbulence. Indeed the whole process shows hysteresis, which implies a non-linear response to turbulent shears.

Purcell (1977) and Zaret (1980) discuss the physical environment of planktonic organisms. In general the organisms live in highly viscous conditions at low Reynolds number. The population, however, is subject to turbulent diffusion and stirring (Yamazaki and Osborn, 1988). Accumulating evidence shows that planktonic food webs are strongly related to turbulent mixing (McGowan and Hayward, 1978; Sonntag and Parsons, 1979; Gallegos and Platt, 1982; Rothschild and Osborn, 1988; Costello et al., 1990; Haury et al., 1990; Marras et al., 1990). Denman and Powell (1984) note that the relation of physical process and planktonic ecosystem should be studied by matching both biological and physical scales. By this account not only measurements of a planktonic ecosystem but also modeling should be performed at planktonic scales.

Much of the work on planktonic trophic interactions infers that contact rates and hence ingestion rates depend only on the relative density of predator and prey (Steele, 1974; Steele and Frost, 1977; Frost, 1980). Variations in the velocity field and behavior modify the contact and ingestion rates, independent of the plankton density. Taking account of the turbulent environment provides the opportunity to begin to study the fundamental relations between turbulence-generating events (e.g., wind induced mixing), trophic interactions, and population dynamics.

2. Fronts

Fronts are ubiquitous throughout the world oceans; a brief introductory reference to their impacts can be found in the Rationale section of this report. In addition, at smaller spatial scales the physical forces governing these discontinuities are little understood. Indeed, "The scales smaller than those resolved in a typical ocean model (e.g., 30 km) are perhaps the most poorly understood in physical oceanography" (GLOBEC Wintergreen Report, 1988). This poor understanding presents an extraordinary opportunity to significantly advance both a critical area in ocean physics as well as a crucial problem in biological oceanography. Moreover, motion over these scales provides the "pipeline" which couples mesoscale and large-scale circulation pattems to the nearshore processes that are important to the settlement of organisms in benthic habitats.

In somewhat more general terms scalars, like salinity and temperature, as well as the components of the velocity field, show distinct inhomogeneities on a wide variety of spatial scales. Convergences, divergences, fronts, and regions of high gradient are common signatures of these features. Spatial scales may range from 10's of centimeters to 10's of kilometers. Some of these important features (e.g., fronts) may be longer in one horizontal dimension (perhaps 100's of kilometers) than the other. There are often surface manifestations, like slicks or foam lines, and their influence may extend many hundreds of meters below the surface. They are characteristically regions of high horizontal and/or vertical current speeds. These features may be semi-permanent, but more commonly are transient over periods that vary from minutes to months (or longer) - all of which are time scales that may coincide with important time scales of population change in the marine habitat. Often these features are sites of high concentrations of organisms, both planktonic and nektonic. Measurements of velocities made outside these zones may grossly underestimate the potential transport that can be effected by such physical phenomena.

Transport in frontal regions may have critical biological impacts given the typically high concentration of organisms within these zones. Dispersal of larval stages may be largely accomplished within these features. Onshore transport and ultimate success of recruitment may be determined for some species by such transport. Predator-prey interactions and competition for resources may also be intense within these features. In short, the critical, in situ, population processes, as well as the dominant physical transport, may be substantially amplified in these zones.

The existence of such discontinuities may have profound implications for modeling. Few population models take into account spatially heterogeneous populations. Mackas and Boyd (1979) and Weber et al. (1986) showed that the spatial spectrum of zooplankton fluctuations differs substantially from that of phytoplankton, as measured by fluorescence, or physical features, like temperature. There is much greater variance at small scales in the zooplankton spectra. We do not know the source of this small scale variance; perhaps the existence of swarming, even schooling, behavior is implicated. We do not know what triggers these extreme aggregations -- concentration differences of six orders of magnitude may be found within distances of 10's of meters. Models which include such aggregations, coupled to small scale regions of high physical transport, must lead to very different results from those efforts that average over larger spatial regions, or neglect spatial variation altogether.

3. Cross-shelf Transport

Better understanding of the cross-shelf transport of mass, momentum, and energy is the goal of CoOP, Coastal Ocean Processes, an interdisciplinary program that focuses on physical transport processes and their biological, chemical, and geological impacts. Ibis is not the place to discuss the complexities of (and the exciting prospects for new insights from) the detailed physics of cross-shelf exchanges. A brief summary, however, of working group reports on buoyancy-driven exchanges, air-sea exchanges, inner-shelf exchanges, and benthic-interior exchanges can be found in Appendix A.l.d.

It is sobering to acknowledge that most of the information gathered in the last twenty years on the physics of the coastal ocean says little about the crucial cross-shelf processes for two reasons: first, because alongshore speeds are, in general, much larger than cross-shelf speeds, overwhelming any cross-shelf signal; and second, because the larger alongshore spatial scales allowed considerable progress to be made in understanding alongshore phenomena, fostering neglect of the complementary problem of cross-shelf exchange.

Cross-shelf transport processes may have potentially large impacts on marine populations. For example, buoyancy-driven currents, like the Alaska Coastal Current, might have substantial impacts on the transport of fish eggs and larvae of species like the Alaskan pollock. One might also anticipate dominant buoyancy-driven effects where large rivers, like the Mississippi or the Columbia, enter the coastal ocean. Similarly, transports in the inner shelf region may have especially profound effects on benthic populations (for a definition of inner-shelf see Appendix A.l.d. of this report). In these nearshore environments, surface processes (i.e., wind), tides, and large-scale current shears have demonstrable impact on the movement of sediment (Nittrouer et al., 1988). These processes also impress large forces on benthic dwelling organisms, shaping the morphology of individuals (Koehl, 1984), and affecting in a substantial fashion the transport of energy and material to the organisms (e.g., Koehl and Alberte, 1988). Moreover, transport of larval stages of intertidal invertebrates is increasingly seen as a crucial process in determining the success of recruitment into adult populations. Roughgarden et al. (1988) have studied fluctuations in barnacle populations along the coast of central California. They observed a large recruitment peak in their populations following the onshore movement of an upwelling front. They concluded that these transport events dominate the year-to-year variability of these, and potentially other, invertebrate populations in central California.

Much early work on the physics of the coastal ocean was directed to the study of coastal upwelling, a cross-shelf transport process, because of its ecological importance. We submit that the same rationale applies for studying basic coastal physical exchange processes. Knowledge of these physical processes will allow us to better understand their importance to populations of marine animals that inhabit coastal environments.

4. Large Scale Ocean Circulation

The large scale gyres in the world's ocean circulation are the equivalent to terrestrial features such as prairies and forests that make up biogeographic provinces on land. While the biogeographic ranges of various species in the oceans are not wholly confined to individual gyres, in general the distributions of organisms are highly correlated with circulation pattems. Ibis affinity between the ocean circulation and the range of animals and plants has both a causal link through advection and diffusion of organisms as well as non-causal ties to factors that are either patterned by the circulation or, in the case of atmospheric forcing, are responsible for it. To further understand the connection between ocean circulation and the distribution of organisms in the marine environment it is expedient to first consider the broad scale distribution of ocean currents.

The ocean gyres can be subdivided into polar (Arctic, Weddell), subpolar (North Atlantic, Alaska Gyres), subtropical (all oceans between 10-40°N and S with the exception of the northern Indian Ocean), and equatorial. To round out the current systems one must add the Antarctic Circumpolar Current which flows around the entire globe in the zone between Antarctica and approximately 45°S. These currents make up what is commonly known as the wind-driven circulation. Superimposed upon these circulations tied to the wind stress distribution are flows forced by differential heat and fresh water fluxes; the thermohaline circulation. This density driven circulation is manifested by regions of deep convection or broader zones where fluid leaves the surface (density outcrops). The sinking fluid is replaced by upwelling on a broad scale. Some of the upwelling is more concentrated in wind-driven divergences along most eastern boundaries and along much of the equator. A combination of the wind and thermohaline driven circulations sets up the basic biogeographic regions in the ocean.

To ocean biology horizontal wind-driven circulation is the primary agent of dispersal of planktonic organisms while thermohaline circulation is responsible for the basic structure of the vertical stratification. The stratification is also closely related to the distribution of nutrients through the role that the thermohaline circulation plays in setting up the stratification and in biogeochemical cycling. Therefore, the thermohaline circulation plays a fundamental role in setting up biogeographic pattems through the distribution of nutrients, control of gas fluxes, and by maintaining gradients in temperature, salinity, and density. The biological control of these pattems includes changes in food chains in response to variations in nutrient supply, species interactions involving predation or competition, and the problem of reproduction and recruitment. The connection to the physical environment can be relatively straightforward such as the relationship between stratification and phytoplankton as described by Sverdrup (1953) or quite complicated involving behavioral cues and active swimming such as in fish or whale migration (Olson and Podesta, 1986). In both of these examples, the ocean circulation plays a central role in the establishment of a species distribution. The nature of the interaction of the organisms with the physical environment, however, is very different in the two cases.

Climate variability in large scale ocean circulation has been documented for various portions of the globe. Related changes have also occurred in marine populations in association with some features in the global circulation. Perhaps the best studied is the El Niño-Southern Oscillation (Philander, 1990) where changes in both circulation, water masses, and biota have been traced from the equatorial Pacific northward along the coast and into the Alaska Gyre. Similar fluctuations in the atmosphere/ocean with slightly longer time periods occur in the North Atlantic sector (Bjerknes, 1962; Rogers and van Loon, 1979). Here also there are strong fluctuations in biological communities including fish stocks (Koslow, 1984; Koslow et al., 1987).

III. MAJOR ELEMENTS OF THE PROGRAM

The objective of GLOBEC is to understand ocean ecosystems dynamics and how they are influenced by physical processes so that the predictability of population fluctuations in a changing global climate can be ascertained. This objective is far reaching and complex. Because of this, its attainment requires integration of a diversity of approaches and the examination of many permutations and combinations of experiment conditions.

A brute force approach to such a complex problem is obviously expensive and may not be particularly enlightening. An alternative is to proceed explicitly and consciously through the time-honored process of hypothesis building and testing. In our case the nature of our problem, the exploration of variability, requires that hypotheses are articulated in the form of models. The idea then is that a process is initiated where models explicate "the influence of physical processes on ocean ecosystems dynamics", the models are then tested via field programs, the tests yield new information upon which new models are elaborated and tested, and so on.... A critical element in the cycling process is that its quality is constrained by our capability to actually observe the system. That this capability is relatively limited is well documented. The potential for major improvement in acoustics, software, and computing holds promise that the cycle of model building and field testing can be made to be much more efficient than it has been in the past.

Accordingly, in what follows we consider the quantitative hypothesis, the models. Next we discuss the kinds of field programs that would be appropriate to (1) test the models, and (2) be most stimulative with respect to model reformulation. Finally we point out the range of options available for the development of advanced technology.

A. Modeling

The first step in any investigation is to determine what we know and do not know about the topic. We propose that the first step in the GLOBEC program should be a modeling effort to determine how well we are able to put together our present knowledge of physical oceanography with the known population biology of marine organisms that have numerous, distinct, planktonic life stages. There have been few, if any, theoretical models that have successfully addressed this question (Wroblewski and Hofmann, 1989). We see this activity as a necessary first step to uncover the limits to our present ability to utilize existing information to predict the variability in marine populations.

This use of the modeling exercise to initiate GLOBEC is a "probe" - an exploratory probe to determine where our knowledge breaks down. It should accompany any major investment in new technology and field studies, for solid progress in the coupled investigation of physical and biological processes. In this probing fashion we can uncover those crucial parameters about which we possess little empirical information; we can clarify the limits of our ability to perform a crucial measurement, suggesting where we need to develop new instrumentation. Furthermore, models can be very effective at suggesting additional variables that have greater power to discriminate among several potentially acceptable explanations for an observed phenomenon. It becomes the first step in the iterative, interactive process between theory and experimental measurement.

There are also pragmatic reasons why theory and modeling studies should appear in the earliest stages in GLOBEC. Little "start up" time is required, as opposed to the efforts required for instrumentation development and design of multi-ship, multi-investigator field programs. Moreover, the cost of theoretical and modeling investigations is substantially less than that of other efforts.

We have identified three broad categories that are critical to explore: conceptual studies of simplification and predictability; prototype investigations of biological processes in idealized flow fields; and site-specific models. We elaborate upon these three categories below. We make no claim that these are the only categories that could be profitably explored: we are confident, however, that a synthesis of efforts in these three fields can yield especially useful results. Finally, we anticipate other future GLOBEC activities, especially experimental and field measurement programs. The initiative should include, at a minimum, a requirement for participation in a yearly workshop devoted to bringing together theoreticians and empiricists. Moreover, an additional modeling/theory gathering for those working at disparate tasks is a "must".

1. Simplification and Predictability

a. Simplification: Scaling, Pooling, Averaging

Researchers have put little effort into the systematic dimensional analysis of equations that contain biological parameters (but see Wroblewski et al., 1975; Hofmann et al., 1980; Lyne, 1983). This lack is especially apparent for models that incorporate the higher trophic levels beyond phytoplankton. The technique has proven to be extremely powerful in physical oceanography (and in fluid dynamics, generally); one can predict with confidence that any coupled modeling effort will have to address the issue of the "proper" non-dimensionalization, the "proper" scaling, early on.

In many population models quantities are pooled. For instance, we refer to "phytoplankton" or "zooplankton", pooling all the phyto- or zooplankton species together. Age or size classes are averaged, or pooled, and equations written for the pooled (averaged) quantities. One cannot be sure what the effects of such a simplification(s) are in various coupled physical-biological models. Arguments can be made that such averaging may miss important effects (Frost, 1980), especially when different life stages react to the physical environment in different fashion - some swimming more vigorously than others, perhaps, or seeking different depths or light environments.

Both scaling and pooling are related to the basic question of how one measures some non-dimensional group (a group that incorporates both physical and biological quantities) all age classes can be pooled, or all species of, say, phytoplankton can be pooled. Similarly, more formal investigations into these questions may tell us whether we can average over certain space and time scales.

b. Predictability in a "Chaotic" Environment

The consequences of coupling biological processes to a physical environment that has variability over a very broad range of space and time scales could be profound. There may be fundamental limits to predictability of biologically interesting quantities in such a "chaotic" environment. What such limits are, if any, is an important question with substantial ramifications. It may not be possible to predict beyond a certain point in time what the effects of changing global environments are upon marine animals, because of the fundamental limits to predictability in the coupled physical-biological systems of the sea. It may be possible to predict some quantities (e.g., biomass), but not others (e.g., abundance and distribution of individual species). Platt et al. (1977) considered this question when discussing models of phytoplankton productivity; and it seems profitable to extend their work. Perhaps there may be some guidance from more recent mathematical studies in nonlinear dynamics. Though it is not known whether the ocean as solely a physical system is chaotic (in the strict mathematical sense), one of the characteristics of chaotic (as opposed to deterministic but non-chaotic) systems is a broad spectral range. This contrasts to the narrow "line" - type spectra found in a non-chaotic, deterministic system (see Andereck et al., 1986).

The proposed approaches to both simplification and predictability are solely theoretical topics. This does not rule out applications to specific marine systems or populations of organisms, of course. Researchers should be encouraged to explore such applications of the ideas as they develop.

2. Biological Processes in Idealized Flows

Biota are not mere passive tracers in the flows that characterize the sea's motions. At each life stage, an organism (planktonic or otherwise) will have behavioral responses, and will interact with the physical environment as well as with other organisms. These facts, of course, make the totality of the GLOBEC program extremely complicated (and extremely interesting). The effects of specific flow regimes might be investigated by considering the behavior of, and interaction between, organisms in simple models for these flows. A researcher might select one from a number of common flow pattems (i.e., homogeneous, three-dimensional turbulence; organized coherent structures, like Langmuir circulations; fronts and convergences; eddying structures; upwelling circulations; plumes; mixed zones and/or wakes around islands, to name several). Then, mimicking this prototype with simple, yet satisfying, physical dynamics, ask two kinds of questions. First, how do these flow regimes affect the biological properties one associates with individuals, or the properties one associates with single populations? For example, one might study the effects of small-scale turbulence on feeding success (Rothschild and Osborn, 1988). The important phenomenon of aggregation into schools or swarms (Okubo, 1986), including the effects of such processes on feeding or predator avoidance, would also be a likely candidate for investigation. Still another area for study might be how flow pattems at a variety of spatial scales affect the transport of the larval stages of benthic invertebrates (Jackson and Strathmann, 1981; Possingham and Roughgarden, 1990). How is the success of settlement of these larvae on the shore affected? How important is this settlement success relative to competitive interactions on the shore between sessile adult organisms? Second, how do these flow regimes specifically affect populations that are coupled into communities? How, for example, are competitive interactions altered (Roughgarden, 1978)? How are trophic relations modified? Perhaps the effects on size class models (or size spectra models, a la Denman et al., 1989) can be approached in investigations such as these.

It is well to note four aspects of such prototype studies at this early "proposal" stage. First, there is the well-developed field of mathematical ecology that has been little utilized in oceanographic (and only slightly more in fisheries) investigations (see Roughgarden et al. (1989) for a modern perspective). Some insights from this previous work may be useful. Second, though it may be possible to mimic a few simple flow pattems analytically, numerical simulations of the dynamics (e.g., turbulence) will certainly be very useful in these types of investigations. We should encourage investigators to consider how their "simple" models might be generalized in future studies to more complex settings that would demand numerical simulation (or, perhaps, substantially greater computer resources). Third, many of the formulations for the behavior of, and interaction between, biota are only approximate, even within quite wide confidence limits. We should encourage researchers to consider carefully what such limits mean for the predictions they calculate -- a "sensitivity analysis" for their efforts. Finally, these prototype studies are closely linked to the conceptual studies of simplification and predictability discussed above. The results of dimensional analyses of coupled physical-biological systems will surely form the bases for at least some of these prototypes studies.

3. Site-specific Models

We propose a two-step process to attack the question of how the modifications we anticipate from a changing global climate will make themselves felt on specific animal populations at specific sites in the sea.

a. The Coastal Ocean and the Open Sea

The only realistic way to attack the problem of how to predict effects in the future is to understand the present. Accordingly, we focus on a specific problem at a specific site to see how well we can "put it all together". As an example, let us imagine compiling our "best" assessment of the biology of the individual life stages of a given species of, say a copepod. Let us further construct the "best" model of the transport phenomena (advection plus mixing) at a site of limited extent, perhaps a coastal site. Then, given the observed physical forcing(s) plus the observed level(s) of predators upon the copepod stages (and prey items in the copepod diet) can we make a prediction about the concentration and distribution of the copepod population as the individuals progress through their life history? Recent work of this kind in the South Atlantic Bight (Hofmann, 1988) suggests that, so long as the time horizon is not too long, we may be closer to this specific goal than ever before.

Such attempts must be generalized to other environments, longer time horizons, and a variety of populations including benthic invertebrates, widely differing groups of holoplankton, and various fish and shellfish species. We target two "sites" initially: the upper ocean, anywhere on the globe, because it is so important biologically; and coastal areas, especially questions that address cross-shelf transport. The coastal cross-shelf transport focus is important because this transport process may be crucial to a wide variety of marine animals, especially benthic invertebrates (Roughgarden et al., 1988), and larval fish and eggs (Checkley et al., 1988).

Three aspects of such models are immediately apparent. First, these studies will be dominated by numerical attempts, because only such efforts are likely to incorporate sufficient detail to be useful at specific sites. We should begin to think about ways to interact rapidly and efficiently with models that may have many tens of thousands of lines of codes and are run at remote sites. We must insist that timely and constructive protocols allow us to interact quickly in a "predictor/corrector" mode. We anticipate taking advantage of the advances occurring in modeling of the upper ocean (e.g., the Price-Weller-Pinkel model (Price et al., 1986) and modeling of coastal circulation (see particularly, E. Hofmann's (1988) coupled models in the South Atlantic Bight). These efforts give us the confidence to continue the attempt to predict. Second, the incorporation of data into models is a critical topic that needs to be addressed early by any modeling attempts. The effort must be a cooperative one between empiricists (a measurement team) and modelers. This effort might assess the usefulness of the formal techniques of data assimilation (see Haidvogel and Robinson (1989), an entire journal issue devoted to this issue for oceanic modeling). These newer approaches have not been applied in biological models, whether coupled to the physical environment or not. Third, ensure that the "fit" between theory and measurement is good. For example, the output from present acoustic sensors is often a size-frequency spectrum. Will this quantity be easily extracted from multi-level, age-structured models? Is this the quantity we desire, and why? Similar remarks apply to the "fit" with remote sensed data, like ocean color, that appears to have great biological utility. Preparation for the use of time series data, perhaps from moored instruments, in more sophisticated ways than have previously been common in biological studies, should have a high priority for both empiricists and modelers.

b. Future Predictions

We have already alluded to one straightforward way in which the model studies we propose can be used to pursue the effects of global change. That is, drive the models with differing external forcing. For example; where a freshwater source of buoyancy is an important input, ask what circulation and transport pattems, as well as derived distributions of biota, would result from the hypothesized shifts in rainfall or ice melt. Comparisons with the results of present condition models could be readily pursued. These results would be short time scale in the sense that the numerical simulations would be run only so long as the analyst believed that the flow pattems did not deviate substantially from observations -- several weeks to a month, perhaps.

There may be ways to mimic climatologists' use of atmospheric GCMs (general circulation models) in the coastal ocean for long time scale assessments; that is, run the models for very long times until they reach "equilibrium", and then compare various equilibria (Mitchell, 1989). Such calculations have been performed for the ocean general circulation, but "the jury is still out" on how much confidence one should have in the results. Generalization of the same techniques to the coastal ocean is purely speculative at this time.

B. Field Studies

1. Criteria for Site Selection

GLOBEC study sites and field programs should fulfill a majority of the following criteria, for a variety of reasons which are both scientific and strategic:

a. Climate Change Context

The research program should have a demonstrable capability to link its results to climate change. Whatever the presumed linkage (e.g., increased seawater temperature, polar icecap melting, increasing El Niño-Southern Oscillation events), the conceptual and data collection infrastructure should allow specific hypotheses to be addressed via direct testing or modeling. Global climate change is the phenomenon on which GLOBEC and all other global geosciences funding initiatives are predicated; explicit attention to global change is critically important.

b. Target Species in Benthos, Holozooplankton, and Fish

The selected site should allow for simultaneous studies on at least one species among the benthos, one among the holozooplankton, and one among fish. The scientific rationale is that these are the three most significant groups of secondary producers in marine ecosystems, interactions among the species are probable, and thus studies on target species will complement one another. The strategic rationale is that such a study will allow for broad participation of biological oceanographers.

c. Definable Populations

The research should be designed in such a manner that the target populations are, to the greatest possible extent, demographically and geographically distinct. GLOBEC explicitly seeks to understand how populations fluctuate in abundance in response to physical processes. The scientific rationale is axiomatic: in order to study the fluctuations in a population, one must first be able to define that population.

d. Population Dynamics as the Output

Research conducted under the aegis of GLOBEC may focus on a variety of processes which do not expressly operate at the temporal/spatial scales of the population. However, such studies must be complemented within the broader research program by studies which establish their importance to population dynamics. Ultimately, GLOBEC research must describe the relation of population dynamics to physical processes many of which may be modified by climate change.

e. Focus on Processes and Mechanisms

A key element of GLOBEC research is to understand the processes which give rise to observed fluctuations in populations. Descriptive studies are a necessary, but insufficient, component of GLOBEC research. A greatly improved understanding of mechanisms is critical if we are to ultimately model and predict population dynamics.

f. Historical Database

The ideal study site would have a considerable historical database on the distribution and abundance of target species, their physiology and ecology, local climate, and fluid dynamics at multiple scales. To varying degrees, such databases do exist, or are presently being created, in certain parts of the ocean. Historical data will aid not only in planning research, but also in model verification.

g. Modeling Input

The improvement of our capability to predict, which is an ultimate aim of GLOBEC, presumes a significant emphasis on modeling. Modeling is considered sufficiently important that some effort, will be devoted to modeling which is not directly linked to field programs. However, any field program should be able to demonstrate that modeling will be employed to both plan its execution and test its results. Interaction with independent modeling efforts is encouraged.

h. New Technology

It is anticipated that new technology will be developed under the auspices of the GLOBEC program, for the express purpose of improving our ability, to sample, analyze, and interpret. Any GLOBEC field program should attempt to apply such new technology.

i. Integration with Other Global Change Programs

GLOBEC field studies should demonstrate conceptual, informational, and logistical linkages to other research programs of similar scale and complementary aims. Such programs would especially include the global change research initiatives (e.g., WOCE, TOGA, JGOFS, see section IV.C.l. of this report). Shared resources and information will serve to strengthen all related programs. Results of other global change studies may provide boundary conditions and input variables important to GLOBEC's assessment of how ocean ecosystems are likely to respond to global change.

j. Multiple Agency Support

The greater the inherent interest of multiple funding agencies within the United States, the greater the potential for significant long-term support of GLOBEC research. GLOBEC field research programs would optimize their own survival by possessing facets which are attractive to as many agencies as possible. Obvious agencies include NSF, ONR, NOAA, DOE, and NASA.

k. International Collaboration

A specific GLOBEC study site is best selected in collaboration with international efforts to understand the role of changing global climate on ocean ecosystems dynamics and secondary production. International collaboration can greatly expand the scope of GLOBEC studies by combining resources from multiple interested countries. Ongoing efforts such as France's National Recruitment Program and Canada's Ocean Production Enhancement Network (OPEN) are likely candidate programs on which to build collaborative studies.

l. Generality of System, Both Physical and Biological

The necessary limitations on research funding imply that it is impossible for GLOBEC to evaluate all the important interconnections between changing global climate and ocean ecosystems dynamics. Consequently, choosing study sites that best allow broad generalizations is an important goal. This implies that physical processes chosen for study should be widespread, perhaps ubiquitous, and that the biological connections of most likely significance should be targeted. Similarly, GLOBEC sites and studies should be complementary among themselves to provide thorough coverage of geography, physical processes, and biological interactions.

m. Excellence of Proposed Research

Above all, the choice of GLOBEC study sites needs to be supported by the excellence of the science. If the science is weak or the plan not feasible for a potential site, satisfying the other criteria is insufficient ground for selection of that study site. Extensive interactions with interested members of the ocean sciences community will provide our vehicle to evaluate the feasibility and excellence of science associated with the selection of each potential study site.

2. Northwest Atlantic Study

The GLOBEC steering committee has identified a contrast of Georges Bank with other banks and shelf systems of the Northwest Atlantic as the basis for a GLOBEC pilot study. The report of a joint Canada/U.S.. workshop held in Halifax in June 1990 to develop the scientific questions will be published by the GLOBEC steering committee in early 1991. The Northwest Atlantic working group in consultation with a large number of other interested scientists from both the U.S. and Canada is continuing to develop specific plans, which include requests for proposals by both NOAA and NSF in early 1991 to initiate modeling, analyze historical data, test new technology, and develop experimental designs in advance of the larger field projects of subsequent years.

The banks of the Northwest Atlantic such as the Grand Banks and Georges Bank have been exploited for fisheries resources since at least the 1500's. This trend has continued to the present, with 1988 New England landings of cod, scallops, and pollock amounting to $133.4 million dollars. Combined, this is approximately equal to the value of the lobster harvest for that period. Of the three species, the groundfish are at their lowest stock size on Georges Bank since estimates were begun. A rise in populations of elasmobranch species such as dogfish and skates suggests the possibility of a major shift in ecosystem structure. In a similar vein the most recent National Marine Fisheries Service report on the status of fishery resources off the northeastern United States concludes in the case of scallops the "current fishing effort is far beyond what the resource can sustain". Much of the stock decline is due to the effects of overexploitation. The effects of fishing on stocks are, however, strongly influenced by variations in the physical and biological environment within which the fishery exists.

Climatic effects on fisheries have been reasonably well established in a number of regions, although the exact processes by which these effects take place are not well understood in any situation. It is also well established that climate variations can substantially modulate the influence of exploitation and, within the extremes suggested in the recent climate record, can completely eliminate regional fisheries. These climatic variations range from the effects of the last ice age, which probably reduced the viable habitat for the species mentioned above by up to 90% through a combination of lowering temperature, salinity, and sea level, and increases in sea ice cover; to historically documented decadal time scale fluctuations in winds, sea temperature, and salinity that have a marked correlation with cod stock declines in recent decades. There is ample evidence for a broad range of climatic fluctuations in the past and some grave concerns about future variations tied to natural cycles, the effects of man through greenhouse warming, and modification to the marine environment tied to pollution. The GLOBEC steering committee suggests the following components of the U.S. portion of the Northwest Atlantic Study as a product of the Halifax workshop.

a. Site Selection

The Northwest Atlantic Ocean, including the multiple banks systems, is an ideal location in which to study the potential effects of global climate change on marine planktonic populations. Global climate models predict that significant changes are likely to take place there. The banks along the edge of North America from Georges Bank to the Grand Banks sit at the edge of the boundary between the subpolar and subtropical gyres. They are therefore sensitive to fluctuations in the current systems, the Gulf Stream and Labrador Currents, which form this boundary. Variations in these current systems are likely to be some of the strongest signals expected as part of global climate change.

b. Target Species

Target fish species should emphasize cod and include haddock. Local populations should be defined by frequent surveys, and molecular and biochemical techniques, with a focus on locating key spawning sites. A key objective of population dynamics is to study the development of larvae with respect to the onset of seasonal vertical stratification. Process studies should focus on mechanisms controlling population dynamics, such as how food and feeding may change with climate, how adults locate spawning sites, and how the population is retained or exported from the area. Historical data should be exploited to a great degree. An Historical Data Working Group should be established to make quality data sets available to the community; paleoecological studies should be encouraged. Modeling is particularly required for understanding the physical dynamics of Georges Bank and other contrasting banks and shelf systems, annual energy budgets of the target species, distinguishing between the effects of fishing pressure and climate change, and as a means to improve statistical techniques. New technology is needed to improve hardware and software for hydroacoustics, and to develop a variety of techniques relying on biochemistry and molecular biology to provide indices of physiological state such as growth, feeding, and reproduction.

Target zooplankton species should emphasize *Calanus finmarchicus* and include *Pseudocalanus* spp. and *Centropages* spp. Local populations of *Calanus* are thought to overwinter in the nearby Gulf of Maine; the dynamics of their springtime advection onto Georges Bank should be studied in detail. Population dynamics studies should focus on understanding reproduction, growth, and mortality in relation to physical transport processes. Process studies should be aimed at understanding how local physics controls the distribution of zooplankton, and what processes control overwintering. Historical data are not as abundant as for fish, but are sufficient to determine the magnitude of signal required to detect effects of climate change. Modeling studies could make new sampling technology (e.g., acoustics and optics) more effective by helping to understand the relation between animal size and physiology; population dynamics could be better understood through coupled biological/physical numerical modeling. New technology is needed to rapidly assess physiological state, and to rapidly sample distributions of zooplankton from both moored and mobile platforms.

Target benthic species should include sea scallops (*Placopecten magellanicus*), but the focus might best be on contrasting different types of meroplanktonic larvae and evaluating the relationships between cod feeding success and benthic habitat character. Local populations could be studied by comparing how a variety of larval types (e.g., feeding vs. non-feeding larvae, spring vs. fall spawners) respond differently to physical processes. Population dynamics studies should focus on larval dynamics of any species which might produce distinguishable cohorts of easily identifiable larvae from a well defined adult population, and should not necessarily be restricted to scallops. Process studies should focus on understanding the relation between fundamental population dynamics parameters (e.g., growth, reproduction) and physical and biological forcing such as tides, storms, food availability, and temperature change. Historical data are less abundant than for other groups, but efforts should be undertaken to use what data do exist. Modeling studies could help to understand how local physical processes favor different reproductive strategies, what causes interannual variation in scallop recruitment, and how changing physical and biological factors affect larval life histories. New technology is acutely needed to rapidly sample and identify larvae of different species.

c. International Interactions

GLOBEC activities should be coordinated with existing international studies including World Ocean Circulation Experiment (WOCE), NOAA's Atlantic Climate Change Program (ACCP), and the Joint Global Ocean Flux Study (JGOFS). A U.S. focus on Georges Bank should be closely coupled with two new Canadian programs: the Ocean Production Enhancement Network (OPEN), a $23M, four-year program focusing on cod and scallops on Sable Island Bank and the Gulf of St. Lawrence; and the Northern Cod Science Program (NCSP), a $43M program focused on fisheries oceanography off northern Newfoundland and the Labrador coast, with a specific emphasis on cod. An ICES (International Council for Exploration of the Sea) working group on Cod and Climate Change (CCC) and the new SCOR (Scientific Committee on Oceanic Research) working group on pelagic biogeography present opportunities for broadening GLOBEC's activities across the North Atlantic.

3. Pacific Basin Study

The Steering Committee will also recommend one or more GLOBEC field programs in the Eastern North Pacific. Several alternative "large marine ecosystems" (Sherman and Alexander, 1986) have been considered:

- An eastern boundary current ecosystem as typified by the California Current.
- A buoyancy-driven coastal current ecosystem as typified by the Pacific Northwest and Alaska continental margin.
- An open ocean ecosystem as typified by the Alaska Gyre.

These sites each individually satisfy many or all of the selection criteria established previously. Each would also strongly complement the planned North Atlantic program by emphasizing a distinct but broadly relevant subset of physical/biological linkages, forcing time scales, and dominant life history pattems. The following paragraphs outline the planning status and some of the major opportunities (and disadvantages) we have identified for each of these regions.

a. Eastern Boundary "Upwelling" Ecosystem - the California Current

In its September 1990 meeting, the steering committee decided to proceed immediately with planning for a California Current field program. The first step will be a community-participation meeting, similar in scope and mandate to the Halifax Northwest Atlantic planning workshop. This meeting will take place in late 1991.

Several features of eastern boundary current ecosystems make them attractive as GLOBEC study sites. First, they are quantitatively significant both to human populations and in the global biogeochemical balance. Many of the world's most productive fisheries are found in and near coastal upwelling regions. Particularly for adjoining developing nations, these ecosystems have great economic and sociologic importance and their demonstrated and potential biotic variability is a major concern. In the United States, the California Current is also the "backyard ocean" for a concentrated, affluent, and environmentally-conscious human population. This group places considerable aesthetic and moral value on understanding and preserving the health of the local marine environment.

Second, eastern boundary currents are oceanographically and ecologically distinctive. The dominant life history and energy transfer pattems contrast with those in higher latitude continental shelf ecosystems: most species are holoplanktonic/pelagic rather than meroplanktonic/demersal and often have relatively short life spans (e.g., anchovies, sardines, and scombrids vs. gadids, herring, and flatfish). Flow fields and their effects on organisms are also distinctive. Mean wind stress is typically alongshore with large temporal variability. Surface-layer flow is on average divergent from the coast. Ibis divergence is often particularly intense in the vicinity of major headlands. Continental shelves are usually narrow and large offshore bathymetric features are rare. The resulting current pattems provide strong temporal and spatial patchiness but few geographically fixed and predictable opportunities for horizontal recirculation and retention. Perhaps in consequence, higher trophic levels are often strongly migratory. For planktonic and larval organisms, advective input and loss rates are large. Behavioral orientation to, and utilization of, small-scale shears and convergences appears to play an extremely important role in reseeding and population persistence.

Third, eastern boundary current systems are particularly appropriate for examining the higher frequency components of global climate variability. Biological and physical response to forcing at interannual to decadal time scales (e.g., ENSO events) is known to be very strong (Chelton et al., 1982). The local response almost certainly involves a variety of proximate physical coupling mechanisms (e.g., altered wind speed and direction, pycnocline depth, alongshore and cross-shore advection, buoyancy inputs). Important lower frequency components of biological variability (decades to centuries) are also clearly evident in reconstructions from historical and sedimentary data.

Fourth, many of the dominant species extend over a broad latitudinal range and are exposed to large differences in the intensity and timing of seasonal circulation patterns. Particularly for the nearshore benthic community, strong spatial gradients in probability of successful recruitment appear to be linked to differences in upwelling intensity (Ebert and Russell, 1988; Roughgarden et al., 1988). There is clear potential for within-region comparative studies of the controlling mechanisms.

The historical knowledge base for the California Current is excellent. This is one of the few oceanographic regions for which there is a long time series of archived plankton and larval fish samples (the CalCOFI program, 1949-date). Commercial catch statistics are available from the early part of this century. Sediments from anoxic basins (e.g., Soutar and Isaacs, 1974) provide a longer record of changes in relative abundance for major fish species. There have also been a number of major shorter term studies of the physical and biological oceanography of this region. Recent examples include the CODE, OPTOMA, NCCCS, FRONTS, and CTZ programs.

Subarctic, Transition Zone, and Subtropical faunal groups are all represented within the California Current system; field and modeling studies will probably have to examine a relatively large number of species and trophic linkages. Some candidates include:

- *Merluccius*, *Engraulis*, *Sardinops*, *Sebastes* and *Scomber* among the fish;
- Euphausiids (*E. pacifica*, *T spinifera*), copepods (*Calanus*, *Eucalanus*, *Metridia*), and thaliaceans (*Salpa*, *Thalia*, *Dolioletta*) among the holozooplankton; and
- Crab (*Cancer magister*), barnacles, and perhaps kelp forest ecosystems among the benthos.

Potential for international and interagency collaboration is good. Canada and Mexico adjoin the region and share some of the migratory stocks. Other Latin American countries (especially Peru and Chile) have an interest in Pacific coastal upwelling ecosystems and especially in the effects of ENSO events. The Soviet Union and Poland have major jointventure hake fisheries in U.S and Canadian waters. The same or similar species are present in northern Japanese waters. Within the U.S., ONR, MMS, NOAA, DOE, Cal. Fish and Game, and other NSF programs (e.g., CoOP and JGOFS) have overlapping interests.

Probably the major weakness of a California Current study site is the practical difficulty of tracking populations in such an advective system. Ship time and technology commitments (especially acoustics and genetics) will have to be substantial to do a good job.

b. Buoyancy-driven Coastal Current -- the Alaska Current and Bering Sea Shelf Systems

Exchange across coastal current systems is likely to be an important topic for both the GLOBEC and CoOP programs and early CoOP planning documents identified the Pacific Northwest as an attractive study site. The GLOBEC Steering Committee has therefore decided to ask CoOP if they wish to sponsor jointly a field program in this region.

We know that large coastal inputs of fresh water have strong effects on both the alongshore and cross-shore circulation of major estuaries and the adjoining continental shelf. One common and important situation is the interaction with Coriolis force to produce an intense baroclinic current that hugs the coastline and is maintained or intensified by additional downstream freshwater inputs (Royer, 1981 a,b). These buoyancy-driven coastal currents are relatively narrow, fast, often seasonal (depending on the timing of precipitation and snowmelt) and typically have a sharp front along their seaward margin. In addition to the expected salinity and temperature gradients across this front, there is often a strong contrast in nutrient content, water color, and plankton biomass and species composition. Nursery areas and migration routes of both juvenile and adult fish parallel the frontal boundary; the coastal current may be both a "conduit" for alongshore transport and migration and a "barrier" to cross-shore motion (Thomson et al., 1988).

Freshwater input to the coastal ocean reflects the balance between precipitation, storage, and evapo-transpiration on the continental shelf and from the adjoining drainage basins. Climate models and empirical analyses suggest that all of these processes will be sensitive to generalized global climate change (e.g., Bolin et al., 1986). Seasonality of both weather and biology is strong at high latitudes. If key life cycle events are "tuned" to the past average seasonality of the physical environment, the phasing as well as the amplitude of runoff and resulting coastal circulation may be critical. Seasonal ice cover is an important variable north of the Alaska Peninsula and in many inlets along the Gulf of Alaska.

A large fraction of the Pacific coast is strongly influenced by coastal freshwater input, roughly from the Columbia River north to the Bering Strait. The southern end of this range overlaps at least seasonally with the California Current upwelling system. Dominant species are mostly from the Subarctic faunal group. Although there are important homologies with the North Atlantic study area (herring, cod, euphausiids, and large and small calanoid copepods), there are also important and interesting additions (all of the Pacific salmon, halibut, walleye, pollock, pandalid shrimps, several crab species, large "zonal migrating" copepods).

The historical knowledge base is good for commercially harvested species. Other taxa have been studied intensively but intermittently. Most major studies (with the exception of the DOE Columbia River program off Washington and Oregon) have less than a 10 year time base. Examples include ISHTAR, PROBES, and FOCI in Alaska, the La Perouse and MASS projects in Canadian waters.

Unlike the California and Oregon coasts, the Washington, British Columbia and Alaska coasts include many deep water embayments that could serve as semi-enclosed isolates for some of the population and process studies. This is a very important practical advantage because it reduces the scale of essential but relatively tedious boundary monitoring.

International collaboration is likely with Canada, and perhaps with Japan, Norway, and/or the Soviet Union. Within the U.S., interagency collaboration is likely with NOAA, ONR, MMS, DOE, and the NSF COOP program.

c. Open Ocean Ecosystem - the Alaska Gyre

The open subarctic North Pacific contrasts with the North Atlantic in several ways. First, winter deep convection and mixing is greatly restricted in the Pacific by density stratification from a circa 100 m thick "cap" of low salinity surface water. Second, the annual cycle of phytoplankton biomass is very different: there is no major spring phytoplankton bloom in the subarctic Pacific. Third, concentrations of major nutrients (nitrogen and phosphorus) are much higher in the Pacific, both above and beneath the main pycnocline. However, there have been recent suggestions that the North Pacific phytoplankton are limited by availability of micronutrients such as iron.

Biologically, the system is truly pelagic. The subarctic zooplankton are dominated by large copepods with distinctive seasonal migrations (e.g., Miller and Clemons, 1988), euphausiids, and salps. The nekton are dominated by the Pacific salmonids, saury, myctophids, and gonatid squids. For GLOBEC purposes, there is no significant benthic component. However, there are potentially interesting and important links between the epipelagic and migratory mesopelagic communities. The southern boundary of the gyre is highly variable, and Transition Zone fauna are also frequently locally important. The real or potential bycatch from the high seas drift net fishery (primarily by Japan, Korea and Taiwan) is an important international issue, and is aggravated by the discrepancy between mapped fishing zone boundaries, and the meandering frontal boundaries that appear to actually control fish distributions.

The Alaska Gyre is bordered on the south by the North Pacific Current, and on the northeast, north, and west by the Alaska mainland and the Aleutian Islands. The wind-driven circulation is broadly divergent. Water from beneath the pycnocline mixes with and is diluted by freshwater inputs (probably mostly direct precipitation but including some coastal runoff) to the surface layer. There is good evidence for teleconnection of weather pattems between the Subarctic and Tropical Pacific (Philander, 1983; Rasmusson and Wallace, 1983), and winter/spring storm activity shows considerable interannual variation.

The Canadian weathership sampling program (1956-80) provided a long and relatively detailed time series of zooplankton and water properties for the southern part of the gyre. Strong interannual variability has been noted in zooplankton biomass and in fish distributions, but mechanistic causes (mixing vs. advection) remain poorly understood. Project SUPER (1984-88) examined in detail the processes controlling lower trophic levels; results highlighted the role of microzooplankton and the importance of late winter storm events.

As a GLOBEC study site, the Alaska Gyre presents major practical difficulties in long-term measurement of demographic parameters. Adequate sampling will be particularly difficult for the larger migratory species. However, ship-mounted ADCP, bioacoustics, and new satellite remote sensing technologies may allow valuable "feature-oriented" studies over shorter time scales.

International collaboration is likely with many of the Pacific Rim nations, as this is a region with substantial shared use by migratory fish stocks. The steering committee felt that planning of any "high seas" Pacific site needs to be closely coordinated with future open ocean activities in the Atlantic, Indian, and Southern Oceans.

4. Indian Ocean Study -- Arabian Sea Response Initiative

a. Overview

Based on a combination of past work and current interests in the nature of the biological and chemical environment in regions with strong physical forcing, an initiative to investigate the monsoon driven regime in the northwestern Indian Ocean is proposed. This region represents a zone with steady wind forcing during the alternating northeast (December-February) and southwest (May-August) monsoons with accompanied wind lulls in spring and fall. These reversals in the wind make the region one of the few places on earth where one can plan to encounter a complete switch in wind forcing direction and regular wind lulls. This makes the region unique with respect to the problem of understanding air-sea interaction problems such as mixed-layer development in three dimensions, adjustment of the interior density and current fields, and the response of the ecosystem to changes in the physical environment. The unique attributes of the northwestern Indian Ocean also extend throughout the trophic levels. Phytoplankton blooms occur during the monsoons with inter-monsoon crashes in plant biomass returning the system to highly oligotrophic conditions. Similar massive variations in grazing zooplankton and predator species occur on up the food chain to large pelagic fishes such as the tunas. The temporal signal imposed on the biology by the monsoon winds therefore leads to major changes in the optical and acoustical properties of the region through the year. Finally the large turn-over in the carbon cycle associated with the monsoon plankton blooms makes the northwestern Indian Ocean the site of one of the largest vertical carbon fluxes in the ocean. This flux is responsible for the creation of a deep oxygen minimum which further modifies the biology and chemistry of the region.

Before going on to more specific questions concerning the northwestern Indian Ocean and the Arabian Sea, it is worthwhile to put this region in perspective with other areas of the globe. Here we will consider the differences in two high latitude sites, the Alaska Gyre and the North Atlantic in the same latitude belt, and two low latitude regimes, the equatorial Pacific and Arabian Sea. All four of these areas experience seasonally variable atmospheric forcing which produces responses in biological production and biogeochemical cycles. The resulting response is quite different in the four regimes, however, with comparatively higher but less variable biomass concentrations occurring in the Alaska Gyre compared to the Atlantic, which experiences pronounced bloom phenomenon. The low latitude regimes have similar contrasts: the Arabian Sea undergoes pronounced bloom cycles as opposed to the Pacific where both the maximum biomass and its variations are much smaller.

The different responses in these strongly forced regimes can be attributed to a combination of the type of physical forcing, the nature of the mixed layers and underlying stratification, and the nature of the biological/chemical response. The current rationale for the difference between the high latitude Pacific and Atlantic is the strong vertical stratification in the Pacific that limits deep mixed layer formation and therefore does not allow convective deepening to mix phytoplankton below their critical depth as occurs in the Atlantic. Differences in species composition in both the phytoplankton and zooplankton in the two regions further amplify this effect. It is possible to hypothesize a similar physical connection to explain the difference between the equatorial Pacific and the Indian Ocean. Here one can suggest that it is both the nature of the mixed layer development and the seasonal variation of the forcing with respect to the capabilities of organisms to withstand the changing environment that determines the contrasting conditions.

Three of the regions contrasted here have been extensively studied as part of past efforts such as SUPER, MLML, JGOFS Atlantic Bloom, or in upcoming efforts such as the JGOFS Equatorial Pacific Experiment. Planning on the part of various global initiatives (WOCE, JGOFS, GLOBEC) has suggested the Arabian Sea as an important site with respect to air-sea interaction and its role in determining the nature of the ecosystem. Specifically both JGOFS and GLOBEC have suggested the Arabian Sea as a priority experiment site. This U.S. interest is complemented by a sizable commitment to the region by the Germans and expressed interest in cooperation by Pakistan, India, Holland, France, and Great Britain. This system thus provides an opportunity for a joint JGOFS-GLOBEC study (perhaps including WOCE also) that could be greatly beneficial to the U.S. Global Change Program. GLOBEC collaboration could help assess the degree to which prediction of carbon fluxes by JGOFS requires specific knowledge of ecosystem composition and processes. JGOFS participation could help GLOBEC incorporate a much better understanding of the nature of primary production and its role in ecosystem dynamics.

In summary, the Arabian Sea provides a unique site to study air-sea interaction in relation to the marine ecosystem both in terms of intercomparison with other regions and in several unique aspects of the region including the following:

- Strong low latitude air-sea interaction site;
- Intense seasonal blooms interspersed with inter-monsoon oligotrophic periods;
- Large gradients in zooplankton biomass/rate processes in response to monsoon driven physio-chemical-biological factors and;
- Anomalous near-surface biogeochemistry and animal behavior tied to oxygen minimum and seasonal carbon fluxes.

b. Possible Components of an Indian Ocean Study

A field program in this area will most likely consist of a multiplatform effort to survey conditions in the Arabian Sea over several monsoon periods and a combination of moored and free drifting sensors to quantify the biological and physical responses to the monsoon cycle. This field program would be supported by a modeling effort involving a refinement of existing regional models and the development of improved mixed layer models with biological and chemical components. A remote sensing component can provide synoptic maps of sea surface temperature radiation fields, sea surface height anomalies, wind fields, and an assessment of phytoplankton biomass.

The proposed effort will seek to address the following sets of questions:

- What is the large scale circulation/ecosystem response to the periodic forcing by the monsoons? What is the vertical extent of the monsoon response? To what degree can numerical model simulations, which seem to be reasonably successful in depicting the major features in the boundary current regimes, predict the evolution in the interior? Can models be developed which include biology and chemistry in a predictive manner?

- Can surface layer models be developed which simulate the three dimensional development of the mixed layer in response to the monsoon forcing? Is it possible to specify the momentum and heat fluxes over the basin and isolate the mechanisms governing SST variability in the Arabian Sea? What are the dynamics of the cross basin front associated with the wind stress maximum in the southwest monsoon? How do biomass and speciation vary with respect to mixed layer dynamics?

- How does the timing of the forcing and its interaction with the stratification control the structure of the marine ecosystem? In particular, what factors control the seasonal variation in biomass, species composition, and rate processes? How does the presence of the thick oxygen minimum layer affect the vertical and horizontal distribution of zooplankton and micronekton?

5. Antarctic Study

a. Relation to Climate Change

Global climate change is predicted to be greatest at high latitudes (Manabe and Stouffer, 1979, 1980), with dominant effects anticipated in the form of increased concentrations of atmospheric CO_2, increased temperature, and changes in ocean circulation.

The Antarctic has a high negative radiation budget; its immense masses of both continental ice and annual sea ice act as a refrigerator, moderating global temperature on a seasonal and multiannual basis.

The continental ice sheet contains 90% of the world's fresh water, representing a potential sea level rise of approximately 60 meters. Major portions of the ice sheet grounded below sea level, such as the current West Antarctic ice sheet, have undergone disintegration on time scales of the order 100 years during past northern hemisphere glaciations. Whether the ice sheet is currently growing or shrinking is unknown.

Seasonal sea ice coverage in the Southern Ocean increases from approximately 4×10^6 km^2 in summer to 20×10^6 km^2 in winter (Zwally et al., 1983). During the austral summer the sea ice melts back almost to the edge of the Antarctic continent. During the last glacial maximum the sea ice in the Antarctic extended outward an additional 15×10^6 km^2 and its retreat in the summer was much reduced (CLIMAP, 1981). These fluctuations in sea ice extent represent one of the most dramatic manifestations of climate change in the Southern Hemisphere. Recent paleoclimate studies (e.g., Crowley and Parkinson, 1988 a, b) have indicated that changes in atmospheric CO_2 may be a major factor in regulating the sea ice extent in the Southern Ocean.

b. Climate Change Relation to the Dominant Physical Mechanisms

The addition of meltwater to the Southern Ocean, whether derived from continental ice or from annual sea ice, may be the major determinant of spatial and temporal changes in the structure and function of Antarctic marine communities. As the pack ice retreats in the spring and summer, relatively-fresh meltwater at the ice edge reduces surface density and creates vertical stability. This stability, coupled with increased incident radiation, promotes ice edge phytoplankton blooms, which in turn provide the basis for the production of zooplankton and higher trophic levels. The annual formation and retreat of pack ice, and its concomitant impact on the production cycle, affects approximately 50% of the area of the Southern Ocean. In coastal regions, seasonal meltwater from the continental ice sheet produces a similar effect on local productivity. Because nearshore regions are fed throughout the spring and summer by continental meltwater, phytoplankton blooms are sustained for longer periods of time than ice-edge blooms, and attain levels approximately one order of magnitude greater (Smith and Nelson, 1985; Holm-Hansen and Mitchell, 1991). Thus, despite their relatively minor contribution to the total area of the Southern Ocean, coastal shelf regions may contribute a significant proportion of the total annual primary productivity.

Pack ice modifies the marine environment in other fundamental ways. It creates habitats with biotic and abiotic characteristics that differ from those of open water habitats and the extent of these habitats varies seasonally. Furthermore, in the winter it forms a barrier between the atmosphere and water and thereby dampens wind-forced motions. Interannual cycles and/or trends in the annual extent of pack ice may also have significant effects on all levels of the Antarctic food web, from total annual primary production to breeding success in seabirds.

The timing and maximum extent of the sea ice in the Southern Ocean is forced to a large extent by large-scale atmospheric processes. The same processes also influence the position of the major frontal systems and the strength of the various currents in the Southern Ocean. Since the type and abundance of species can differ on opposite sides of fronts (or in different water masses) a shift in the circulation or change in the intensity of a current can change the type and abundance of prey and predators.

The effect of atmospheric warming in the Southern Ocean may be to reduce the areal extent of annual sea ice, which could reduce total annual photosynthetic carbon fixation (Walsh, 1990), destroy habitats, and disrupt the life cycles of marine zooplankton and animals at higher trophic levels, whose present-day biogeographic ranges are directly related to the extent of sea ice coverage. Increased meltwater input from the continental ice sheet might have a compensatory effect, further extending the coastal production zone.

c. The Antarctic Marine Ecosystem

The Antarctic marine food web is more complex than the simple linear food chain (e.g., diatoms-krill-higher consumers) that has often been described for this system. However, the links in the Antarctic food web are often short and may be dominated by fewer than half a dozen species. The shortness of these trophic connections arises because the basic prey types available to predators in the Southern Ocean is limited and because among the basic prey types, predators tend to concentrate on a core group of species, such as some abundant euphausiids and fish near the base of the food chain. Croxall et al. (1988) suggested that because of the apparent close coupling between trophic levels, long-term studies focusing on these predator-prey relationships and their environment will not only be critical to understanding variability in Southern Ocean ecosystems in general, but may ultimately form the basis for monitoring the effects of man-induced perturbations on the system.

At the base of the Antarctic food web are the phytoplankton, or primary producers. The phytoplankton are eaten by herbivorous zooplankton such as copepods, salps, and Antarctic krill (*Euphausia superba*). In most oceanic food webs copepods are the dominant macrozooplankton grazers, but the Antarctic planktonic ecosystem is unique - its biomass can often be dominated by Antarctic krill. The krill in turn are a major component of the diets of birds, fish, many species of seals and baleen whales, and represent about half the total animal biomass available as food to the larger carnivores. In fact, in the food web of the Southern Ocean, all the vertebrates either directly or indirectly depend on krill as a food source (Laws, 1985). The dominant consumers serve as good indicators of ecosystem processes and of second order effects of decreases in key species because they show the cumulative effect of changes in ecosystem dynamics. For example, Adelie penguins comprise 60 to 70% of the entire Antarctic avian biomass (Prevost, 1981). Because their diets are dominated by krill (Emison, 1968; Volkman et al., 1980; Trivelpiece et al., 1987), aspects of the reproductive biology of the Adelie penguins have been proposed as sensitive indices of krill abundance and availability (CCAMLR, 1987).

Although consumers can serve as indices of local krill abundance and availability, to understand the mechanisms behind changes in resource levels for the consumers requires knowledge of many other factors affecting krill abundance and availability, such as changes in pack ice extent, water mass distribution, reproductive and recruitment success, and food availability. Food availability, or primary production, in turn depends on other environmental factors such as light, turbulence, and nutrients. Many of these biotic and abiotic parameters are directly or indirectly related to or affected by ice cover.

d. Overview

Biological processes tend to be well tuned to annually repeat. Disruptions or changes in populations or community interactions occur if repeating events change in intensity or frequency. Thus the study of multiannual patterns will allow the development of an understanding of long-term population dynamics and reveal the linkages between the environment and the recruitment of keystone species such as the Antarctic krill. Understanding how these changes influence recruitment and the magnitude of change necessary to force significant changes in community structure and function will allow the linking of recruitment variability to large-scale global climatic change. Long-term fluctuations in the mesoscale abundance of the Antarctic krill are well documented (Rakusa-Suszczewski, 1988), and although years of low krill biomass have been attributed to krill redistribution by physical forces, the mechanisms controlling abundance are not well understood. Recruitment to the krill population can be very localized (Huntley and Brinton, in press), but the processes which determine recruitment success are not understood.

Even the immense spatial extent of the Antarctic marine ecosystem does not provide sufficient buffer against departures caused by global changes in environmental conditions, the stress of pollution or exploitation of renewable resources. If stress on any segment of the ecosystem continues for long periods of time, the system may be permanently altered. Documentation of natural population cycles and the mechanisms underlying these cycles of natural variability is important if we are to predict how changes in the environment due to such things as global warming impact the biology of the Antarctic ecosystem.

e. Previous Studies and Data Bases

Considerable historical data exist on the structure of the marine planktonic ecosystem of the Southern Ocean. Many individual countries have undertaken oceanographic voyages studying various physical, chemical, and biological aspects of the region. A new era of international cooperation began in Antarctic marine research with the advent of the BIOMASS program in the early 1980's. In the last decade research interests also began to descriptive studies of ecosystem structure. The AMERIEZ (Antarctic Marine Ecosystem

Research at the Ice-Edge Zone) and the RACER (Research on Antarctic Coastal Ecosystem Rates) programs are two examples of such projects. Recently the U.S. National Science Foundation funded a long-term ecological research program in the Antarctic. The program is funded initially for three years, beginning in 1990, but has a commitment from the National Science Foundation-Division of Polar Programs for at least ten years. The focus of the program is on understanding the physical and biological processes that affect krill and penguin recruitment to Palmer Basin.

f Cooperation with Other Agencies and Programs

Under the terms of the Antarctic Treaty, Antarctica is not the sovereign territory of any nation. Given the long-standing tradition of international research, any scientific program carried out in the Southern Ocean has an unusually high potential for international cooperation. It is expected that a Southern Ocean GLOBEC study will involve participation by many other nations. Most countries maintain research establishments devoted exclusively to Antarctic or polar research; examples include the British Antarctic Survey, the Alfred Wegener Institut für Polar- und Meeresforschung, and the National Institute of Polar Research of Japan.

Numerous countries are interested in this region and international groups such as CCAMLR (Convention for the Conservation of Antarctic Marine Living Resources) have an active interest in Antarctic marine studies. Presently the U.S. has several agencies with strong interests or ongoing programs in the Antarctic, including NSF-Division of Polar Programs and NOAA (which holds the responsibility for carrying out U.S. CCAMLR activities). Other global geoscience initiatives such as WOCE and JGOFS have planned, or are now planning, research components in the Southern Ocean. It is expected that JGOFS field studies there will begin in 1992, although the precise locations of the research have not yet been finally agreed upon. The GLOBEC steering committee plans to hold a community workshop in 1991 to initiate planning for a potential GLOBEC study in Antarctic waters.

6. Other Field Studies

Our elaboration of potential study sites is not intended to be complete. We expect that as we learn more about the nature and extent of global change, as we reach some further understanding of what can and can not be generalized about the role of physical processes in ecosystems dynamics, and as members of the ocean sciences community propose compelling unanswered questions at new sites, the GLOBEC plans will incorporate these additions. Two reasonable candidate systems for inclusion in future GLOBEC plans are a coral reef ecosystem and a Lawrentian Great Lake ecosystem.

Coral reef ecosystems are widely recognized as among the most diverse ecosystems on earth. In addition, tropical reef systems are characterized by extensive and often intricate are found on islands at varying degrees of isolation from other reefs, interesting questions arise about how reef animals successfully complete recruitment and maintain populations. For example, Lobel and Robinson (1986) evaluated the role of island eddies in retaining larvae of reef fishes and thereby promoting successful recruitment. Sammarco and Andrews (1989) demonstrated how relatively large-scale circulation pattems influence recruitment of corals themselves on the Australian Great Barrier Reef. The impact of changing global climate on recruitment and dynamics of coral reef ecosystems is unknown and likely to be substantial. This could threaten maintenance of diversity of a highly diverse ecosystem.

The Great Lakes share many of the physical and biological characteristics of the oceans. Nevertheless, sufficient differences in both physics and biology may exist to justify establishment of a GLOBEC study within one or more of the Lawrentian Great Lakes. The bounded nature of even large lakes, the potential for substantial change in their physical dynamics with variation in rainfall regime, and various specific attributes of lacustrine biota imply that understanding the impact of global change on the dynamics of ecosystems of the Great Lakes may require a lacustrine field study.

C. Technology Development

1. Background Information

GLOBEC is founded in part on a belief that fundamental progress can be made in solving a long-term problem in the population ecology of marine organisms, the problem of what determines population fluctuations of marine animals. The central charge of the GLOBEC working group on technology is (1) to identify those available technologies that have not been adequately applied to solving the population variability problem, and (2) to suggest if and how new technologies could be produced to overcome present barriers to our understanding of potentially critical processes.

Planning for the large multi-disciplinary research programs currently underway or being considered (e.g., Joint Global Ocean Flux Studies - JGOFS; Global Ecosystem Dynamics - GLOBEC; the Accelerated Research Initiatives of the Office of Naval Research, such as Flow Over Abrupt Topography, Marine Light-Mixed Layer) has recognized the need for data collection on a continuum of time and space scales. Ideally, biological data should be obtained, processed, and analyzed on scales commensurate with physical data. To accomplish this as yet unachieved objective, emphasis has been placed on rapid discrete sampling, continuous in situ measurement, and remote sensing. The shipboard handling, processing, and analysis of biological samples, an important component in the physical-biological mismatch, has received little attention. For example, over eleven years ago the symposium volume "Advanced Concepts in Ocean Measurements for Marine Biology" (Diemer et al., 1980) contained a short chapter by T.T. Packard (1980) which emphasized the development of shipboard techniques to measure rate processes. Most of the remainder of the book, however, dealt with data collection, not shipboard analysis. Similarly, the recent Zooplankton Colloquium held at Lake Arrowhead (Marine Zooplankton Colloquium 1, 1989) focused almost entirely on "over-the-side" issues of data collection.

Progress in understanding how marine ecosystems interact with, and are affected by, physical processes requires further development of shipborne plankton sampling and processing techniques. The objective is to sample populations on appropriate time scales and with sufficient spatial resolution to compare with the concomitant data from the physical field. This linkage has been limited in the past (and present) by slow microscopic examination of collected creatures. There is strong feeling that there is insufficient information concerning key biological rates (especially growth). In order to study population dynamics, it is crucial to know rates of change and not just the levels of the population. One method to get rates is to take the difference of point measurements. It is also desirable to have measurements of rates that can be referenced to a single point in time, e.g., measure the size and growth rate of a zooplankter rather than measure its size at two different times. Some different systems for at-sea collection and analysis have been devised, developed, and proposed. Zooplankton identification and counting possibilities include immunological tagging technology, image analysis, size spectrum analysis, and acoustic information processing. Individual growth rates may be inferred from RNA:DNA ratios, lipid concentrations, gut contents (fullness), or some other ecological or physiological parameter.

GLOBEC proposes focusing resources on new technologies and new applications of old technologies which speed the processing of zooplankton samples or provide information on important biological rates and hence provide accurate biological data which can be used to link biological processes and the physical environment.

To achieve our goal of increased and improved instrumentation and methods, GLOBEC sponsored a special session at the AGU/ASLO meeting in February of 1990. There were 14 papers presented, five were on rates and eight were on population sampling systems, both acoustic and optical. The additional paper was on immunochemical identification of ciliate protozoa. The papers on rate measurements were heartening because the committee had hoped to emphasize the importance of such measurements to GLOBECs process oriented approach.

At this stage in GLOBEC planning, the most important criteria to establish are the scientific ones, that is, deciding on specific, well defined problems such a system in its broadest concept could help solve. Many relevant problems in zooplankton ecology have already been identified (see references above); the challenge will be to identify those most amenable to solution using shipboard technology. This challenge must include the consideration of the following criteria:

(1) Assuming the need for a technology is established, what will be required to validate the data obtained, not only to confirm that the technology is appropriate, but also to act in a near-real-time mode as the data is acquired (e.g., calibration-type problems)?

(2) Can the masses of data obtained be analyzed meaningfully? For example, are the available models and analyses adequate to delineate and study the processes involved? Can models be developed to use the potential data as input for predictive purposes or for comparison?

(3) Are the data relevant or appropriate to other areas of research? For example, while the data may not be directly applicable to a particular scientific problem, there may be relationships to other variables (i.e., transfer functions) that will make them so. Also, are the data suitable for incorporation in models?

(4) What is needed to manage all the data, given they can be collected? This must include serious consideration of the problem of data use; Gifford Ewing (1969) clearly described the hazards of the "turn it on and let it run" syndrome:

> "In the long run of time, data must be reduced at least as fast as it is acquired ... the necessity of adjusting sampling rates to ... the rate of consumption is already far from an academic question as can be seen from the volume of data presently being archived in various centers without serious perusal by anyone."

GLOBEC held a workshop to prepare a conceptual description for three population sampling instruments in conjunction with a meeting to develop a concept for an experiment in the northwest Atlantic. Workshops on technology development for biological rate measurements, and biotechnology and immunological methods were held late in 1990. As the reports from these workshops are produced they will be reviewed and used to encourage the appropriate funding agencies to support the technology development.

The three instrument systems that have been initially identified as warranting development are: 1) a shipboard automated plankton analyzer to operate from oceanographic research vessels and perform "real time" analysis of planktonic samples; 2) an instrument to map zooplankton density in the upper 200 m of the water column over a 2 km square region within 4 hours; and 3) a zooplankton "CTD" type profiler that can assess the 3-dimensional distribution of zooplankton, with the possibility that such a device could be towed or moored.

2. Proposed Instrumentation

a. A Shipboard Automatic Plankton Analyzer System

Much of the important work on biological samples collected at sea, whether living or dead, is accomplished in shore-based labs. The recognition of the importance of rapid analysis of samples after collection offers a chance to direct new efforts towards the development of shipboard analytical technology. The planning for the GLOBEC initiative, through the GLOBEC technology working group, has included discussions on rapid shipboard analyses of zooplankton. The other focuses have been on rapid *in situ* profiling of biological and physical variables (a "plankton CTD"), Lagrangian trackers, autonomous floats (e.g., "Slocums" - Stommel, 1989), and some type of rapid survey instrument (or instruments) to locate areas for more intensive studies. This discussion is an overview of the concepts that must be defined in order to implement, over the next five years, new and improved shipboard systems for rapid analysis of zooplankton samples. The overall concept has come to be called the "Shipboard Automatic Plankton Analyzer System" (SAPAS). Neither specifies of hardware definition nor details of the potential for biotechnological approaches are discussed. The major concern is with rapid analytical techniques, not those that involve extended sample preparation. The critical role for computers in equipment control, analysis, and interpretation will not be discussed. Attention is restricted to the needs for analysis of zooplankton in the generic sense; while "zooplankton" comprise a diverse range of size, morphology, chemical composition, and behavior, it is inappropriate at this stage to go into such details. Also not included is the important issue of designing a rational sampling program to optimize the use of such technology. Obviously, this is of critical importance; as Gifford Ewing (1969) wrote some 20 years ago:

> "In a science such as oceanography where the total population is enormous and the cost of sampling is high, the efficiency of the sampling plan is often crucial if the limited facilities are to be fully exploited. All too commonly, however, the sampling plan appears to be extemporized to fit intuition, custom or convenience rather than to satisfy a clearly formulated specification of the particular requirements of the experiment."

Whatever methods (continuous or discrete) are used to bring zooplankton on board a vessel, there would be need for three categories of instruments to accomplish or facilitate the analysis of the samples:

(1) Tagging devices These would mark organisms with such things as stains, isotopes or antibodies that, after a suitable time delay, could be used as the basis for separating, counting and/or later analyses.

(2) Sorting devices On the basis of tag attributes, sample volume, particle counts/size/volume/density, or the judgment of the optically or mechanically augmented human eye, the sample would be separated or aliquoted for further processing, laboratory experiments/ analyses or preservation.

(3) Data gathering devices Three existing technologies have potential for new or augmented uses in shipboard analyses.

- Electromagnetic

Particle counters based on sensing changes in the electrical impedance of a flow-through cell have been used sporadically for many years for *in situ* (e.g., Boyd and Johnson, 1969; Herman, 1989) and onboard underway sampling or vertical profiling (Mackas and Boyd, 1979; Herman et al., 1984) of zooplankton distributions. These techniques give measures of organism abundance and size ("volume"); only under low diversity conditions can taxonomic information be easily inferred from the data (Herman and Mitchell, 1981).

- Optical

Some of the applications and advantages of this diverse category for biological oceanography were reviewed by Yentsch and Yentsch (1984). Shipboard zooplankton measurements could be made using the following types of approaches:

Imaging--various techniques obtain images of organisms, either from stationary batch samples or from flow-through cells. For example, videomicroscopy, microcinematography, and silhouette photography have all been used to study zooplankton both in the laboratory and the field. To obtain information efficiently from the images requires specialized analysis systems, such as those described by Berman et al. (1990) and Rolke et al. (1990). Sequential images quantified by motion analysis systems can provide behavioral and perhaps taxonomic information.

Particle counting--Herman (1988) has developed a shipboard and *in situ* optical device analogous to the impedance counter described above. This technique provides abundance and size ("area") estimates of organisms over a size range that could approach, with proper development, 100 μm to several centimeters. Modification of optical detectors might give measures of shape as well for preliminary taxonomic information.

Flow cytometry--these techniques, now used for phytoplankton studies (Yentsch and Yentsch, 1984), could have potential for zooplankton, using either inherent organism properties (e.g., light scattering, fluorescence, absorption) or those added by tags as the sorting criteria. Besides providing data on organism attributes, it might be used as a sorter to provide samples for further analysis by other techniques.

Optical multichannel analyzers--devices have been developed to measure the spectral characteristics of bioluminescent flashes from zooplankton (e.g., Herring, 1983; Latz et al., 1988). These characteristics could provide taxonomic information. Further development could utilize the spectral characteristics of other optical properties, such as scattering, fluorescence, or absorption. This would be of particular value for non-bioluminescent organisms.

- Acoustic

Jaffe (pers. comm.) has pointed out that acoustics should be the technique of last resort for shipboard analyses because the optical and electromagnetic methods have much higher resolution, data rates, etc. Acoustic methods would be invaluable, however, to probe the internal structures of opaque organisms in order to rapidly estimate lipid quantities, reproductive state, etc. Several different techniques are available; the following is a listing of approaches together with potential applications. See Wang (1980) for good reviews of the various methods.

  - Pulse-echo sonars--multifrequency with forward and backscatter size behavior
  - Doppler--swimming velocities/limb motions
  - Intensity mapping--sector scanning and scanning acoustic and laser acoustic microscopes ascertaining internal structure
  - Phase-amplitude--acoustic holography and tomography for internal structure

One advantage of using several different techniques to analyze the same samples is the potential for merging results. While any one method alone might not provide a specific type of data, together with others it may be possible to deduce otherwise unobservable properties. Some attention should be given during the development stages of a SAPAS to the possibility of such synergistic interactions of components.

Figure 1 presents in block form the basic components that might be integrated to comprise a SAPAS. The input to the system is assumed to be a profiling plankton pump operating in conjunction with environmental sensors such as acoustic backscattering transducers, fluorometer, spectral radiometers, turbulence probes, and temperature/conductivity sensors. The output would be estimates of: biomass and abundance in various size/shape and taxonomic categories; behavioral characteristics; biochemical parameters (e.g., enzymes, lipids, genetic traits); and direct or indirect measurements of rates (e.g., growth, respiration, excretion). The output is shown coming from the adjacent column of five data source blocks surrounded by the dashed line; the input to these blocks comes from the physical components of the SAPAS. These components are shaded according to their readiness for incorporation into a system. Fully shaded means these technologies should be feasible now, requiring only minor adaptation for shipboard use. Half-shaded indicates either that portions of the technology are feasible now, or that it would take perhaps five years to develop the technique. Unshaded means it may take longer than five years to provide the methodology, depending on the priority given to development. The dashed lines surrounding some of these blocks indicate that the input and output arrows are not necessarily tied to the specific block adjacent to the base or tip of the arrow.

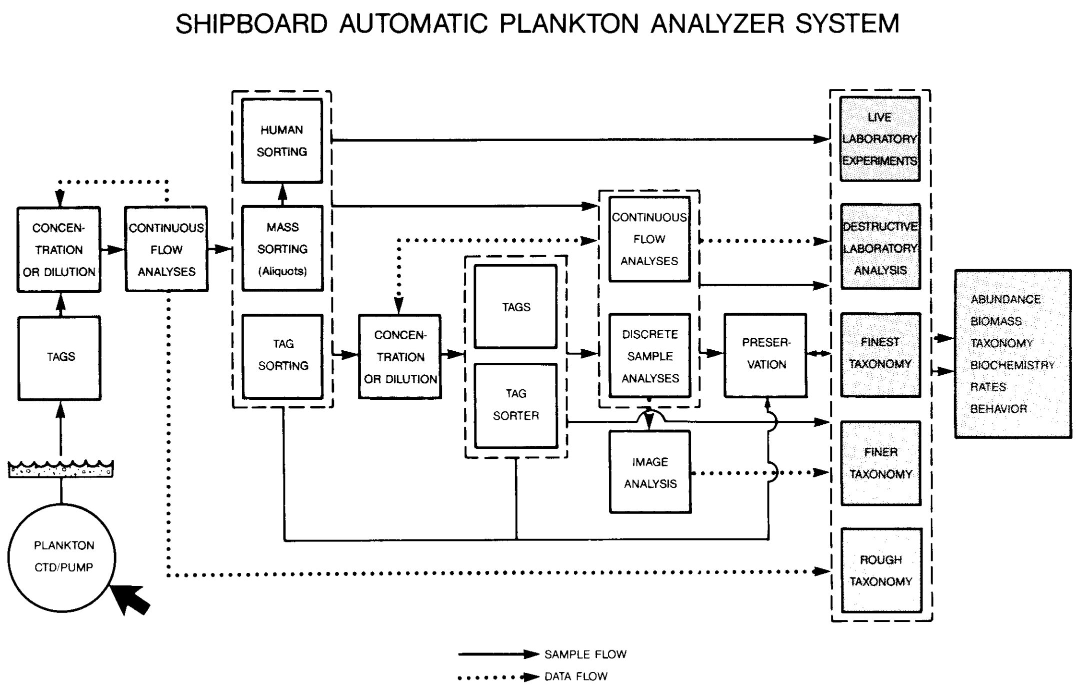

Figure 1. Basic components that would probably be integrated to comprise a shipboard automatic plankton analyzer system (SAPAS). See text for detailed description of figure.

Rather than describe each component block of the SAPAS separately, the five data source blocks will be explained by referring to their input sources. Proceeding from the bottom block up the column, these are:

(1) Rough taxonomy--this level would provide size-frequency information of all particulate components of the tagged or untagged and sorted or unsorted sample stream in a continuous mode using the optical or electromagnetic counting techniques. In low diversity ecosystems, some taxonomic information could be inferred.

(2) Finer taxonomy--identification of organisms to levels above species (e.g., copepods, calanoid copepods, chaetognaths, gelatinous organisms) using available techniques of image analysis. It would be hoped that the categories could be assigned ecological meaning, such as trophic level, feeding mode, etc. With present capabilities, this mode would most likely operate on tagged or untagged discrete samples analyzed using acoustic or optical image formation techniques.

(3) Finest taxonomy--the acquisition of information at the individual species level or below; for example, variety or form of a species, stage, sex, reproductive status, etc. With present capabilities, this information would come from human analysis of living or preserved aliquots of the sample stream. Hopefully this tedious process could be accelerated by automated sample handling and separation techniques. Some detailed taxonomic information could be obtained from taxa sufficiently unique for image analysis systems to identify or from tags with sufficient discriminating power.

(4) Destructive laboratory analysis--in the near future, most of these analyses are likely to be carried out manually. Automation could provide a source of animals or sample fractions with desired attributes. Development of automated analyses themselves would make obtaining data on enzymatic, lipid, or genetic attributes much more efficient.

(5) Live laboratory experiments--some types of information, particularly rate data, must come from shipboard experiments done on living animals. To increase the efficiency of these experiments, the labor of sorting out and pretreating experimental animals could be reduced by utilizing automatic or augmented human sorting and manipulation. Automated culturing systems like those developed by Cabell Davis at WHOI should be adapted for shipboard use and integrated into other analytical systems to provide data on rate processes.

Other components and comments: Because of the wide range of abundance of planktonic organisms, concentration or dilution of the sample stream at various stages of processing will be necessary for optimum operation. Feedback loop-controlling devices to do this, primarily from the continuous flow analysis systems, will have to be incorporated to accomplish this efficiently.

b. Mapping Plankton Patch Morphology

An important question in marine ecosystems concerns understanding the gross morphology of plankton patches. What are the sizes of these patches, how do they evolve in time, and what are their relationships to the driving physical processes? Current instrumentation does not permit the measurement of these phenomena although an examination of the technical possibilities makes these goals attainable.

Acoustics is the natural method for obtaining the gross morphology of these plankton patches as the ocean is too opaque to light to permit successful use of optical techniques. There are many possible designs for this type of system, however they should all share several common features: that is, they should be able to resolve the mean acoustic backscatter within a 3-dimensional volume of the ocean. These mapping systems are 3-dimensional imaging systems.

In designing a 3-dimensional imaging system there are many issues which need to be considered. In sonar imaging a distinction is usually made between range resolution and cross range, or azimuth, resolution. The range resolution is usually quite high because this is a function of the pulse length, which can be made quite short. On the other hand, the cross range or azimuth resolution is usually much worse, the principles of geometric optics requiring quite large arrays for equivalent spatial resolution. There are also many options for the array configurations themselves, ranging from large area imaging systems which would necessarily have coarse resolution, to small area systems which would have finer resolution. These trade-offs are a result of the physical trade-offs between frequency of insonification, and spatial and temporal resolution. It is probably true that we will need to imagine a smaller system which would provide finer resolution and could be towed to provide data over large spatial areas.

One example of an instrument that could be developed is a side scan sonar system for mapping patch morphology using acoustic backscatter information as mentioned above. This sonar would have an omni-directional beam pattern in one axis and a narrow beam pattern in the other planes. It would obtain range information from time delay data and do beam forming to obtain azimuthal resolution. Towing would result in mapping a tube of ocean. Gridded transects would result in mapping a larger volume. Periodic deployment would result in a set of high resolution environmental and biological data within a large volume of water sampled at the repetition rate of the survey.

More specifically, it is envisioned that this system would have a center frequency between 100-500 kHz. This seems like a natural frequency band to use when considering spatial resolution, temporal resolution, and acoustic attenuation. System range would then be on the order of 100's of meters and range resolution of 2-10 centimeters should be possible. Azimuth resolution could be 1 degree. Resolution cells would be of width 8 cm at 5 meter range, and 1.7 meters at 100 meter range. The system would provide acoustic backscatter in real time as a function of 3-dimensional position. This would then be related to biomass to compute the distribution of biomass in 3-dimensions in a large volume of sea water at periodic intervals. Finally, a ship towing this type of sonar at a rate of 5 knots could map a volume of water approximately 2 km x 2 km and 300 meters deep every 2 hours at 0.3 meters cubed resolution.

It is also important to realize that various studies will need to be performed in order to make sense of this information. In particular, more *in situ* studies to correlate acoustics and organism density will be necessary. This will include target strengths for volume scattering. These can be performed concurrently, as the instrumentation becomes available. Then, the relationship between organism densities and the acoustic reverberation can be inverted to obtain the latter. Other issues as to navigation, communication, signal design, and processing seem more straightforward, with digital techniques being an inexpensive and high fidelity option.

c. Acoustic Plankton CTD Profiler

Since 1979, the University of Southern California and Tracor have been conducting an interdisciplinary research program titled "Dynamics of small-scale spatial distributions of zooplankton". During the last 5 years, this program has been jointly sponsored by the National Science Foundation and the Office of Naval Research. This research program has resulted in the development of new technology to quantitatively measure small-scale plankton distributions on scales of meters in depth, over 10's of kilometers horizontally. Zooplankton distributions determined acoustically, by size (0.1 to 10 mm), have been compared to phytoplankton distributions measured fluorometrically and to the physical environment. The technology developed in this research is embodied in the Multi-frequency Acoustic Profiling System (MAPS), a 21 frequency acoustic echo-ranging, echo-integration system which operates in an acoustic frequency band, 100 kHz to 10 MHz, which is appropriate for detecting and quantifying zooplankton biovolume (biomass). The MAPS has been employed in both a cast mode and in a towed (sawtooth in depth) mode at speeds up to 10 knots. Acoustic data collected with this system are transformed from acoustic volume scattering strengths to plots of zooplankton abundance versus size and depth for individual casts or oblique tows along a transect. in one operating mode, acoustic estimates of abundance versus size for individual casts are combined to illustrate two dimensional spatial distribution. In a second mode, sequential casts at a drogue location are combined to illustrate temporal variations. In both of these operating modes, the observed zooplankton distributions are compared with data collected at the same time for temperature, salinity, and chlorophyll fluorescence.

Successful use of this system has occurred in the Southern California Bight, in the Coastal Transition Zone off northern California, in the Gulf Stream (across the western wall of the Gulf Stream off Cape Hatteras and off Cape Canaveral) in the western Atlantic slope water, and in the Irish Sea.

Analyses of the various MAPS data sets have shown that zooplankton distributions were usually related to some aspect of the physical (oceanographic) system in which the animals live. The pattern of distributions, however, were different in the various oceanographic systems that we have investigated. Off southern California there was a trend towards a general coherence between zooplankton distributions of all size classes, the chlorophyll maximum and the permanent thermocline on vertical scales of 10's of meters. This pattern broke down on smaller vertical scales. In the Gulf Stream, measurements showed that different size classes of zooplankton had similar distributions. These pattems varied with physical boundaries and water mass intrusions, and were not coherent with chlorophyll peaks.

Distributions in the Coastal Transition Zone (CTZ) off northern California and in the Irish Sea revealed quite different results. In these areas, different sizes of zooplankton exhibited different distributional pattems. Distributions in the CTZ region appeared to be controlled by the various current systems. Some organisms were most abundant in the cooler filament water, while other abundance peaks were on the filament boundary or outside of it. As in the Gulf Stream, pattems of distributions appeared to be more related to physical events, or behavioral activities in response to physical events, rather than chlorophyll distributions. Oceanographic complexity in the waters of the Irish Sea again seemed to control distributions, with peaks of different size classes in different oceanographic regimes. For example, some organisms were associated with the stratified water off the Irish coast, while others showed peaks near the bottom (90 m) just above an undersea ridge. Other zooplankters were more concentrated in the mixed waters off the English coast and yet another group were near the boundary between the stratified and mixed water-column areas.

The above data sets represent snap shots of one brief period with the MAPS in different areas. Each area was unique and illustrated the complexity of the various oceanographic systems. Our results indicated the importance of a systems approach to studying any area. This includes concurrent measurements of the various physical and biological parameters and, hopefully in future studies, measurements of how these vary over time. Out-growths of this work are the functional designs for some 2-frequency moored instruments, a 5-frequency mini-MAPS, a dual beam/envelope statistics instrument, a towed multi-frequency system, and even some expendables for use in places like Antarctica.

IV. Implementation of GLOBEC Plans

A. Management - Role of Funding Agencies

Three agencies of the U.S. Government have been cooperatively planning global ocean ecosystems dynamics research since 1987, the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), and the Office of Naval Research (ONR). All three were underwriters of the pivotal GLOBEC science workshop at Wintergreen in 1988. This cooperation continues to date in both planning and research support.

All three agencies (NSF, NOAA, and ONR) are active participants in the U.S. Global Change Research Program (US-GCRP), and more specifically in its ecosystems dynamics research theme. As part of the US-GCRP, representatives from each agency sit on the Committee on Earth and Environmental Sciences (CEES) interagency Task Group on Ecosystems Dynamics. This body is responsible for planning and coordinating ecosystems dynamics research (including GLOBEC) and funding in the US-GCRP, coordinating development with other relevant task groups (e.g., climate and biogeochemical dynamics), and advising CEES on the developing Program.

The current cooperating offices within each agency are the Ocean Science Divisions at NSF and ONR, Polar Programs at NSF, and the National Marine Fisheries Service and the Office of Oceanic and Atmospheric Research at NOAA. Anticipated are joint interagency announcements of opportunity for research support, academic and agency, in global ocean ecosystems dynamics, as well as interagency cooperation on the provision of needed resources and facilities.

NOAA and NSF formalized cooperation on global ocean ecosystems dynamics research in 1988 in a document signed by the NSF Assistant Director for Geosciences and NOAA's Assistant Administrators for both Fisheries and Oceanic and Atmospheric Research. A joint committee has the primary purpose of developing, with agency staff, academic researchers, and agency scientists, plans for research on large-scale studies of marine animal populations and ecosystems dynamics. Other agency participation on the committee has been invited. Under this agreement, NSF and NOAA are presently coordinating plans for U.S. participation in international GLOBEC research in the North Atlantic as described previously in this document. Initial planning for the Southern Ocean is also underway.

ONR and NSF cooperation in ocean ecosystems science is continuing within the context of GLOBEC through the joint support of new technology development. The first efforts are to develop a new long-term, moored array, and physical/bioacoustic sampling systems for assessment of ocean plankton populations and their interactions with ocean physical processes. ONR and NSF are also sponsoring in early 1991 the initial planning for an international research program on ecosystems dynamics in the Indian Ocean associated with the strong monsoon system.

B. International Planning

Various international activities are proceeding for all of the potential GLOBEC study systems. Discussions with IOC and SCOR are underway with regard to developing a "world view" of ocean ecosystems dynamics. The international context of the Northwest Atlantic study is most clearly defined in that our GLOBEC efforts will be the U.S. contribution to the ICES Cod and Climate Change (CCC) Program. ICES has endorsed a

GLOBEC-motivated study of the ecology of cod in the North Atlantic. In developing this study the role of physical processes was considered to be critical. Accordingly, under the auspices of ICES, scientists from the North Atlantic countries will be working on:

- a model of the North Atlantic circulation that provides increased detail in the coastal oceans;
- development of regional models in which various biological phenomena can be embedded;
- models of turbulent flow and their relationship to biology;
- models of the population dynamics of the dominant species of copepods in the North Atlantic;
- the development of sampling technology; and
- studies of phenotypic and genotypic differences among cod stocks.

An ICES study group will be meeting in Hamburg in mid-April to discuss implementation of the CCC program. A major symposium on cod and climate change will be held in Reykjavik in the summer of 1993.

The Canadian and U.S. scientists who met in Halifax in June 1990 discussed, among other things, Canadian - U.S. participation in CCC. This meeting had as its specific objective the planning of an experiment in the Northwestern Atlantic to study this marine ecosystem and its role, together with the roles of climate and physical dynamics, in determining fisheries recruitment. The meeting scoped out the beginnings of a multi-disciplinary program bringing to bear disparate techniques and approaches ranging from numerical fluid dynamic models of ocean circulation through molecular biology and modem acoustic imaging.

C. Relationships With Other Programs and Initiatives

The complexity and breadth of the issues surrounding problems in the area of global change are so great that interface with other related programs, especially those assessing other global change issues, is critically important to foster and maintain. Members of the GLOBEC steering committee serve as liaisons to other large initiatives as one means of promoting these interactions and exchanges of information on both planning and issues of science.

GLOBEC is expected to have ties to a number of national and international efforts currently underway or in the planning stages. These range from the various ongoing activities of organizations such as ICES down to investigators planning for possible coastal initiatives such as the COOP group. Of special relevance is the interrelationship of GLOBEC to its sister programs within NSF, WOCE and JGOFS. On the NOAA side it is expected that various components of the Global Climate Change Program will provide important background support for GLOBEC activities. Finally, there is the issue of GLOBECs part in international programs such as IGBP (International Geosphere Biosphere Program).

1. U.S. Programs

a. WOCE - World Ocean Circulation Experiment

In response to the World Climate Research Program (WCRP) goal concerning the prediction of climate changes over periods of decades, the SCOR and IOC Committee on Climatic Changes and the Ocean (CCCO) established a group to plan a World Ocean Circulation Experiment (WOCE). After over a half decade of planning WOCE is at the point of beginning its field phase. Efforts as part of WOCE are aimed at 1) developing models useful for predicting climate change and collecting the data necessary to test these models, and 2) determining the representativeness of the specific WOCE data sets for the long-term behavior of the ocean, and to find methods for determining long-term changes in the ocean circulation. To address these goals WOCE has been divided into three core projects covering a global description of the ocean circulation (Core Project 1), the Southern Ocean (Core Project 2), and the Gyre Dynamics Experiment (Core Project 3). A full description of the WOCE scientific background and initial plans can be found in the World Ocean Circulation Experiment Implementation Plan (WOCE 1988a, 1988b).

The U.S. commitment to the WOCE program consists of contributions to the global one-time survey, current meter arrays to monitor several key locations, portions of a global array of surface drifters and mid-level floats, and part of the efforts such as ship-of-opportunity and sea level measurement. There has also been an effort to develop a community model. It is expected that the results of WOCE will be relevant in general to the overall GLOBEC effort although it is difficult to picture extensive cooperative field programs. The global surface drifter program is of potential interest in relationship to the drift of organisms, but is likely to require augmentation to improve its nominal 500 km coverage if one wants to consider the details of the effects of drift in more localized regions. GLOBEC should keep informed on WOCE planning in order to identify areas of mutual interest.

b. JGOFS - Joint Global Ocean Flux Study

The primary goal of JGOFS is to quantify the vertical carbon flux that results from oceanic chemical and biological uptakes of CO_2. In particular, JGOFS wishes to quantify how much of the production which occurs in the upper ocean is due to new nitrate vs. the magnitude of the total primary production and its role in the global carbon budget. The biologically mediated CO_2 uptake and vertical carbon transports are dependent on a complex, ill understood, coupled physical, chemical, and biological system. JGOFS is a balanced mix of process studies, large scale ship and satellite surveys, time-series observations, models, and data base activities predicated on improved documentation of the ocean carbon cycle and budget and predictive models to understand oceanic response to change. Such models will form the basis for assessments of how the ocean carbon system is affected by increasing atmospheric CO_2 concentration and its impact on such increases. JGOFS forms a natural substrate for GLOBEC since it must document the physical, chemical, and biological parameters for oceanic primary production.

GLOBEC in contrast to JGOFS is concerned with developing an understanding of what controls the biotic population dynamics in the sea. Fluxes of materials such as carbon and nitrogen through the upper ocean are controlled and mediated by the biological populations and their production dynamics. Consequently, GLOBEC has the potential to contribute to JGOFS an appreciation of the degree to which it is necessary to understand the ecosystem composition and dynamics to be able to appreciate the variations in fluxes of biologically active materials, especially carbon and nitrogen, and to be able to make accurate predictions and generalizations. Mass fluxes of these bioactive materials in the sea are catalyzed by ecosystem dynamics. GLOBEC can help assess the degree to which global change will alter fluxes by creating major changes in the ecosystem dynamics that help determine those fluxes.

c. TOGA - Tropical Ocean Global Atmosphere Program

The Tropical Ocean Global Atmosphere (TOGA) Program is currently heavily focused in the Pacific. TOGA planning calls for extensive work as part of COARE (Coupled Ocean-Atmosphere Response Experiment) in the Western Pacific in the 1991-94 time frame. Efforts to follow this field work are currently under discussion. TOGA provides global climate modeling resources of relevance to GLOBEC aims. The possibility of eventual cooperation in the field should be pursued as planning for both programs continues.

d. GCCP - Global Climate Change Program

NOAA has launched an effort to explicitly consider the evidence for and the dynamics of global climate change. The initiative includes global efforts such as climate models and data networks along with regional efforts to understand climate change in various sectors of the globe such as the Atlantic. GLOBEC has a fundamental interest in this effort in relationship to planning field programs. Of particular importance is a timely identification of the aspects of climate change that are likely to be of major relevance to the marine systems GLOBEC proposes to investigate. GLOBEC and the Global Climate Change initiative have similar concerns in understanding historical variations in marine communities and populations. The efforts of the Global Climate Change initiative to improve historical data bases and to understand the manifestations of time dependence with the help of diagnostic and model computations are important to GLOBEC as well. GLOBEC should also remain aware of specific monitoring efforts planned as part of NOAA Global Change and their relevance to plans for GLOBEC efforts.

e. ACCP - Atlantic Climate Change Program

The NOAA Atlantic Climate Change Program (ACCP) can be expected to provide considerable support in terms of large scale data analysis to interpret climate signals. The ACCP monitoring work to follow climatic variations through the 1990's and the development of models with the explicit goal of better simulations of climate variations in the Atlantic will be of use to GLOBEC planning. An effort as part of ACCP to provide a higher resolution geological record for the Northern Atlantic is also relevant to GLOBEC goals.

f. LMER - Land Margin Ecosystem Research Program

The Land Margin Ecosystem Research Program (LMER) is designed to address questions of how coastal terrestrial ecosystems influence estuarine aquatic ecosystems. This program is involved in evaluation of the ecological impacts of alternative land use practices in the watersheds on the flux, fate, transport, and transformation of materials moving from land into the estuaries. As such, it requires strong contributions from biogeochemistry, hydrology, sedimentology, and ecology. The program is fundamentally two-pronged. One thrust is to measure the fluxes of materials as a function of variation in the land use of the terrestrial systems. The second thrust is to understand the consequences of those fluxes on the sedimentology, biogeochemistry, and especially the ecological processes and systems.

The LMER program has obvious relevance to GLOBEC. To the degree that LMER studies are successful in demonstrating what changing materials inputs can be reliably associated with the conversion of natural terrestrial ecosystems into agricultural, suburban, and urban landscapes, GLOBEC can utilize this information as one form of global change and can consider its impacts on animal abundance and production in the sea. Two of the members of the GLOBEC steering committee helped draft the document that defines the LMER objectives and program elements, so the inter-connections between GLOBEC and LMER are strong.

g. CoOP - Coastal Ocean Processes Program

The Coastal Ocean Processes Program (CoOP) is an interdisciplinary oceanographic research program designed to study the oceanography of coastal oceans. This program is based on the premise that inadequate attention has been devoted in the past to study of coastal ocean processes. Several processes are especially critical to understand in the coastal zone, including the role of physical dynamics and fluid motions on transport and fates of sediments on the continental margins and on recruitment of important biological species in this highly productive yet anthropogenically altered zone of the oceans.

CoOP has a fundamental overlap with GLOBEC interests in the coastal zone. The enhanced study of physical transfers and transport processes on the continental margin will contribute directly to solving problems articulated by this GLOBEC science plan. The two initiatives do have fundamental differences as well. GLOBEC includes an open ocean as well as a coastal prerogative, and GLOBEC is oriented around the problems of global change whereas CoOP need not be. CoOP also contains a much greater emphasis on geochemistry and sedimentology. Nevertheless, it is clear that close collaboration is needed between these two initiatives and some joint exercises may even be warranted. One member of the GLOBEC steering committee also serves on the present CoOP steering committee to facilitate such collaborations and exchanges.

2. International Programs

On the broader scale the GLOBEC Georges Bank initiative is part of a Pan-Atlantic effort to understand the interrelation between gadid stocks and climate change. An ICES working group on Cod and Climate Change (CCC) is presently in the process of completing an initial study plan which includes a large planning meeting to be held in Hamburg in early 1991. The basic idea behind this planning process is to stimulate an international effort to understand the impact of climate variability on cod stocks throughout the Atlantic. Of particular interest are the various responses in relationship to climate variations in different regions of the cod's range. Differences in the regional data bases available for addressing the question of cod and climate make inter-regional comparisons a high priority. For example, spawning, egg, and larvae distributions are much better known for the Arcto-Norwegian cod suggesting that some progress might be made in test simulations using regional physical models. The knowledge gained from such an exercise will in turn be useful for future attempts to simulate distributions on Georges Bank. Other areas of particular mutual interest between scientists studying the various cod stocks involve differences in genetics and cod physiology throughout their range. A combination of genetic, physiology, and paleobiology work should provide important information on the long term interrelationship between cod and climate.

Another international science working group of interest in the context of GLOBEC is a new SCOR working group on pelagic biogeography. This newly constituted effort is interested in understanding the factors the govern the range of various species in the marine environment. The working group and personnel involved in planning work as part of GLOBEC in the North Atlantic should exchange ideas and plans.

International aspects of the World Ocean Circulation Experiment (WOCE) are apt to provide data sets on the variation in conditions in the North Atlantic throughout the period of the envisioned GLOBEC work. In particular, Canadian and United Kingdom work in the subpolar Atlantic should provide data sets that address the nature of the oceans response to the North Atlantic Oscillation (NAO). A Nordic country effort at the Greenland-Iceland-Scotland sills will also provide important information in this context.

OPEN and NCSP - GLOBEC activities in the North Atlantic will be carefully coordinated with the Canadian efforts to understand their fisheries and the massive changes they are undergoing. The status of cod stocks has recently been reviewed by Harris (1990) in a report that is one of several pieces of evidence to the concern in Canada for the status of the cod fisheries. In response to these concerns the national government, local provincial governments, and industry have combined to fund a massive effort to better understand the ecosystem of maritime Canada and its fisheries.

One of these efforts is the Ocean Production Enhancement Network (OPEN) which is a four year program focusing on cod and scallops. Field work aimed at addressing the recruitment problem on Sable Island Bank, scallop distributions, growth and survival in the Gulf of St. Lawrence, and migration in the Labrador/Northern Newfoundland region will be complemented with laboratory, data analysis, and modeling studies as part of this $23M program. The program is outlined in a 115 page overview document (available from Prof. William Leggett of McGill University). The OPEN effort provides a wealth of opportunities for collaboration and with its data from alternative field sites provides excellent comparative data bases which complement the envisioned U.S. Georges Bank work. GLOBEC planning needs to be carefully coordinated with that of OPEN and should allow funding for active cooperation between Canadian and U.S. scientists.

Another program centered out of Newfoundland is the Northern Cod Science Package (NCSP). It is aimed at a fuller understanding of the oldest continuously exploited cod stock in the western hemisphere. The $43M program will focus on fisheries oceanography and predator-prey dynamics off Northern Newfoundland and the Labrador coast. Again, there is the opportunity for collaborative work on a range of issues. Of particular interest is the long time-series data and attempts on the part of programs like NOAAs ACCP to reconstruct and understand the physical mechanisms behind climate change in the subpolar regions.

Nova Scotian region efforts include ongoing programs on the Scotian Shelf, Gulf of Maine, and Georges Bank. Efforts such as the 1982-89 southwest Nova Scotia Fisheries Ecology Program (Smith et al., 1989) which focused on the Brown's Bank region provides many lessons for use in GLOBEC planning. Future cooperative field work should be strongly encouraged with an emphasis on interactions between U.S. and Canadian scientists.

D. Organization and Function of the Steering Committee

The initial GLOBEC steering committee was comprised of thirteen members. This set of thirteen served for two years until January 1991 with only one change in membership. Dr. Cheryl Ann Butman of Woods Hole left in July 1989 and Dr. Donald B. Olson joined the committee shortly thereafter. Beginning in January 1991, and recurring at the start of each subsequent year, the terms of approximately one third of the members of the steering committee will expire. Those members whose terms are expiring can stand for possible reappointment for a subsequent three-year term, but in addition nominations from the community will be sought to fill the areas of expertise identified as required by the steering committee. From those newly nominated and those willing to continue service on the steering committee, the new set of appointments will be made.

As of January 1991, terms of four steering committee members have expired. Michael Sissenwine, Jonathan Roughgarden, James Price, and Bruce Frost are leaving the steering committee. Seven new appointments have been made, not only to replace those four but also to provide additional help and expertise as the planning becomes more focused and evolves towards implementation needs. Joining the steering committee for three-year terms on January 1, 1991 are Allan Robinson of Harvard, James Eckman of Skidaway, John Hunter of NOAAs Southwest Fisheries Center, Dennis Hedgecock of UC-Davis and Bodega, Leonard Walstad of Oregon State, Sharon Smith of Brookhaven, and John Steele of Woods Hole. As future needs for expertise on the steering committee become apparent, further evolution of membership will occur.

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VI. APPENDICES

A. History of Planning Efforts for GLOBEC

The GLOBEC research initiative is designed to incorporate the results and recommendations of several independent planning meetings as well as the workshops and working group activities conducted under the auspices of GLOBEC. These independent planning meetings involved the communities of fisheries biologists, marine zooplankton biologists, nearshore marine benthic ecologists, and physical oceanographers.

1. Planning Processes Leading Up To GLOBEC

a. Fish Ecology I, II, III

In the early eighties, the Biological Oceanography Program of NSF developed documents in response to growing community interest in the underlying causes of population fluctuations from seasonal to decadal time scales in the ocean. One expression of that interest was a series of three workshops between 1980 and 1983 which were organized by John Steele, Brian Rothschild, and others. These workshops came to be known in retrospect as "Fish Ecology 1, II and III". Fish Ecology III, the culmination of this effort, was a large international gathering (Miami, 1983) sponsored by CIMAS, the NOAA/University of Miami Cooperative Institute of Marine and Atmospheric Science. It focused primarily on recruitment, food chains, and the coupling of physical forcing, and resulted in a substantial workshop report.

b. The Lake Arrowhead Marine Zooplankton Colloquium

In April 1988 a group of 58 biological oceanographers and marine ecologists interested in marine zooplankton biology met in a week-long workshop at Lake Arrowhead in Los Angeles, California to identify the new directions emerging in marine zooplankton research. The report of that workshop (Marine Zooplankton Colloquium 1, 1989) lists seven principal issues and areas of future research emphasis in the field of marine zooplankton biology, all of which are embraced by the science plan of GLOBEC:

- Characterization of individual small-scale behaviors leading to a better understanding of the dynamics of aggregation and dispersal;
- Determination of how environmental variability, rather than mean conditions, affects physiology and behavior;
- Relation of birth, death, and growth rates to environmental conditions, both concurrent and past;
- Determination of nutritional requirements;
- Long-term observations of population and community dynamics which would permit analysis of interannual variability and its causes;
- A critical need to maintain expertise in taxonomy; and
- Continued development of mathematical models encompassing biological, chemical, and physical parameters.

The Lake Arrowhead colloquium also argued compellingly for the urgent need to develop and deploy instrumentation for measurement of abundances with higher frequency and resolution and for assessment of vital aspects of physiological and demographic rates.

c. The Nearshore Marine Benthic Ecology Workshop

In September 1987 a group of 40 marine benthic ecologists interested in systems in the coastal zone met in Seattle at the campus of the University of Washington to discuss the emerging issues and new directions in the field of nearshore marine benthic ecology. The report of that workshop (Eckman et al., 1989) recommends establishment of a new research initiative, with the acronym of COAST (A Coastal Initiative), to explore several important scientific questions in the oceanography and marine ecology of the coastal zone. The report argues effectively that certain characteristics of marine benthic systems render them tractable for a variety of important tests of processes that are common to most marine animal populations. The report also presents the argument that the coastal zone is that portion of the oceans where anthropogenic changes in the marine environment are most likely to be expressed in important biological responses. Many of the recommendations of this workshop have been adopted by the GLOBEC plans, while others are appropriate to such initiatives as LMER (Land Margin Ecosystems Research) and COOP (Coastal Ocean Processes). Those recommendations that have been incorporated into GLOBEC are:

- Initiate coordinated interdisciplinary study of biological/physical interactions to address the degree to which observed temporal and spatial variation in important biological processes is caused directly or indirectly by concordant variation in advective and diffusive transport of mass and momentum through the water column and in the sediments;

- Design programs that will allow the study of processes that control abundance of coastal marine and estuarine populations to be conducted at the complete range of applicable scales of time and space, including a hierarchy of global, regional, and local spatial scales and incorporating the impacts of events that occur sporadically in time;

- Enhance the resources available to investigate questions concerning the transfer, transport, and transformation of materials, and the biological production of the coastal zone, including a more complete understanding of what controls secondary production, trophic transfers, and vertical and horizontal fluxes in the coastal zone.

The nearshore marine benthic ecologists also emphasized the need to develop and apply new technologies and instrumentation to solve some of these important scientific questions about the functioning of coastal ecosystems. There was concern that coastal oceanography, and especially biology, had not been receiving its share of resources to support development of new technology. Finally, this group of benthic biologists expressed a strong commitment to promoting greater interdisciplinary collaboration to address the most urgent problems in coastal zone ecology and oceanography.

d. Planning by CoPO - Coastal Physical Oceanography

In January 1988 a broadly representative group of physical oceanographers met in Gulf Park, Mississippi to discuss the urgent scientific questions in coastal physical oceanography. This initiated planning for a national program in Coastal Physical Oceanography (Brink, 1988), a planning process that has now been expanded in scope to include interdisciplinary aspects of coastal oceanography. The research initiative CoOP (Coastal Ocean Processes) is now being developed around these interdisciplinary problems. Nevertheless, the working group reports produced by CoPO also serve well to identify the important current questions in physical oceanography of the coastal zone and have been extremely helpful in guiding planning for the coastal aspects of GLOBEC.

The major goal articulated by the coastal physical oceanographers in CoPO is to understand better the processes of cross-shelf exchange of mass, momentum, and energy. To that end, working group reports on buoyancy-driven exchange, air-sea exchange, inner-shelf exchange, and benthic-interior exchange describe the fundamental problems to be addressed and provide some guidance to approaching these questions. The output of these working groups has been utilized and their recommendations adopted by GLOBEC in designing the coastal physical oceanographic elements of the GLOBEC science plan:

- The buoyancy-driven exchange working group recommended a closely coordinated plan of field observations and modeling. Regional models should be used to help design field sampling programs. These initial models should be three-dimensional, employ a rigid lid (omitting tides, etc.), and use a simple turbulence closure scheme. They should include regional topography and representative buoyancy and wind-stress driving forces. Subsequent simulation models need to deal with the problem of conditions at open boundaries with the deep ocean, and may address this issue through linking the regional model to a large scale ocean model. Adaptive sampling in the field will be important, especially when and where fronts are encountered. A compelling need exists to describe the Lagrangian flow field associated with freshwater discharge. The most advantageous sites to address these problems are probably the Gulf of Alaska and the Mississippi River Delta.

- The working group on air-sea exchanges stressed the need to integrate processes at several scales and to recognize and evaluate more fully the interactive feedbacks between the ocean and atmosphere that contribute to cross-shelf transport. Three physical problems of special interest are: 1) interaction of stable atmospheric layers with topography; 2) shelf and coastal frontogenesis; and 3) coastal circulation driven by severe storms. Among specific problems of special concern is the parameterization of surface fluxes in shallow water, where the wave field is different from that over the open ocean. Similarly urgent is the need to understand the degree to which coastal frontogenesis is related to variations in the shelf circulation versus the larger scale atmospheric forcing.

- The inner-shelf exchange working group addressed questions of the role of the inner shelf in cross-shelf exchange. The inner shelf was defined as the portion of the continental margin between the surf zone and the depth where surface and bottom boundary layers interact (about three surface Ekman layer depths). This zone has been largely ignored in previous physical studies because of the difficulty in making measurements in it and the presumed complexity of its dynamics. This meager knowledge base probably requires an initial exploratory field study to attain an observational base. This working group recommended focusing on wind and surface gravity wave driven flows initially because these mechanisms should be important driving forces for most inner shelves, because the dynamics governing these driving forces are not well known, and because under reasonably simple conditions progress might be attainable. More complex studies of tides and internal waves should follow after these initial issues have been approached.

- The working group on benthic-interior exchanges focused on identifying the most pressing issues involved in understanding the processes of exchange of materials, momentum, and energy in that zone of the sea where surface gravity waves, with their motions characterized by seconds, influence the drag of water motions on the sea floor, that occurs over periods of days. Further development of our understanding of the hydrodynamic interactions between waves and currents is critical. Laboratory and field investigations of the interactions and feedbacks between changing bottom topography (roughness) and the combined motions of waves and currents are needed to develop a quantitative understanding of the physical processes that occur at the sea floor of the continental margins. Analytical, numerical, and laboratory work is needed to describe how a sloping bottom alters mixing and drag. Much work needs to be done to understand the erosion, transport, mixing, and concentrations of sediments of differing sorts. Effects of differing bottom topographies must be evaluated. Integration of various time and space scales is needed, including especially the contributions of episodic events to mean transport rates. Finally, this working group identified a large void in our understanding of the effects of the bottom biota on materials transport between the water column and the sea bed and, conversely, the hydrodynamic influences on biological processes in the benthic boundary layers.

e. Deep-Sea Observatories Workshop

The Deep-Sea Observatories Workshop was held November 7-9, 1989 at the David Taylor Research Center in Carderock, MD. Over 60 people attended, including scientists from a wide variety of oceanographic and meteorologic disciplines as well as representatives from federal agencies and commercial firms. The focus of the workshop was to discuss the rationale and goals of deep-sea observatories (DSOs), and to discuss the possibility of refitting as DSOs radar surveillance platforms that the navy may establish for drug interdiction in the Gulf of Mexico. The scientific rationale and general goals of deep-sea observatories were defined as: a) to operate as bases for obtaining long-term, high- frequency, multidisciplinary time series for the study of variability in open ocean ecosystems, b) to function as bases for process-oriented experiments that would benefit from the time series data or need facility support form the DSO, and c) to function as stations for monitoring environmental change. Four working groups centered on frequency spectra of ecosystem variables, biogeochemical processes, coupled ocean-atmosphere processes, and the perspective of a regional Gulf of Mexico DSO program settled on several conclusions:

- Deep sea-observatories would promote a valuable, multidisciplinary program and should be advocated to the community and agencies.

- In the near future, when the Gulf of Mexico platforms are no longer used for drug interdiction, they would still be valuable assets of the federal government that could be adapted for oceanographic studies. The opportunity to use them for research should be pursued.

- Although the platforms are not currently outfitted as research facilities there is potential for a wide range of multidisciplinary time-series studies. Some physical modifications and enhancements of the platforms would be required for these studies, and these modifications should be considered in the refit plans now.

- The locations of the platforms would allow for new research on specific problems of the Gulf and would provide a facility that could enhance several ongoing and/or planned research programs.

- Future sites outside of the Gulf of Mexico should also be considered.

A more detailed summary of the working group reports and conclusions can be found in the Deep-Sea Observatories Workshop Report available from Wood Hole Oceanographic Institution.

2. Planning Efforts Explicitly for GLOBEC

a. The National Academy of Sciences Report on Recruitment Processes and Ecosystem Structure in the Sea

In the context of NSF, "Recruitment Dynamics" was identified as a sub-initiative in the first Ocean Sciences Division Advisory Committee Long Range Plan (1985). By the time of the Ocean Sciences Long Range Plan revision of 1987, the NSF Global Geosciences Program had begun. It was clear that the term, "recruitment dynamics" was too restrictive and was expanded to "global ocean ecosystems dynamics coupling", to reflect the broader issues of which recruitment processes were a special case.

After the issue of the original Long Range Plan, the Ocean Studies Board of the National Research Council, under the chairmanship of John Steele, called together a small working group in 1985 to advise on how to develop the recruitment initiative. This spawned a series of small working group meetings involving physical oceanographers that were arranged by Brian Rothschild, Ken Sherman of NOAA and others. The progress of these meetings culminated in a small workshop, chaired by Brian Rothschild and Mike Mullin, in July 1985 at the National Academy Study Center. The resulting report, which defined the scope of "Recruitment Processes and Ecosystem Structure in the Sea" was approved by the Ocean Studies Board and published in December 1987. Meanwhile, Brian Rothschild had organized a NATO Advanced Research Workshop (France, June 1987) on Biodynamics of the Sea, which explored the wider issues of biological/physical interactions in the ocean and the international scientific interest in it.

b. The Wintergreen Workshop on GLOBEC

In May 1988, 90 scientists representing interests in marine fish, zooplankton, benthos, physics, and technology met for a week in Wintergreen, Virginia at a workshop to explore the level of enthusiasm for the GLOBEC initiative and to help shape its future. This workshop had been preceded by meetings of several working groups, each of which prepared an extensive written report. These working group reports are assembled and published together with the results of the workshop as the Wintergreen GLOBEC Workshop Report (available through JOI). Working groups were organized around (1) oceanography and modeling, (2) benthos, (3) food chains, (4) population genetics and biotechnology, and (5) sampling technologies. Scientists at the meeting reached a consensus that fundamental knowledge of the interrelationships among physical processes, population dynamics, and other relevant phenomena could be materially improved, that new approaches are available to address these issues, and that such a program should begin immediately. This initial science plan follows directly from the recommendations of that Wintergreen meeting and adopts the GLOBEC guidelines articulated in the Wintergreen report:

- Concentrate on first principles rather than correlative approaches;
- Enhance the physical-biological partnership;
- Take account of advances in population genetics and related biotechnology; and
- Mount a major effort to further develop and fully utilize both advanced sampling technology and techniques for rapid identification of plankton.

The seeds for all the plans described in this initial science plan for GLOBEC can be found in the Wintergreen report. Perhaps the area of investigation most greatly elaborated since the Wintergreen meeting is the approach to how global climate change might be related to finer scales of events that influence individual organisms.

c. Activities of the GLOBEC Steering Committee

Following the Wintergreen workshop, a committee was named to nominate the initial GLOBEC steering committee. John Steele, Peter Niiler and Karl Banse solicited nominations and suggestions from the oceanographic community throughout the summer and autumn of 1988. This time frame was intentionally protracted to ensure that this large community of interested scientists had ample opportunity to provide input. The nomination period extended through and past the autumn meeting of AGU/ASLO in San Francisco. In February 1988, an initial steering committee of 13 scientists was named to further the planning process for the GLOBEC research initiative. All 13 accepted the invitation to serve on this committee (see the list of committee members in Appendix B). Important events in GLOBEC planning are given in Table A.

Table A: Chronology of important events in GLOBEC planning

	1989
May 1:	Initial meeting of the steering committee
Summer/Fall:	Working group meetings on technology, modeling, conceptual issues, and field programs
	1990
February 13:	AGU/ASLO technology session and GLOBEC workshop (New Orleans)
February:	Call for GLOBEC modeling proposals by NSF, due in May
June 18-21:	Northwest Atlantic workshop (Halifax)
June 22:	Technology workshop (Halifax)
November 12-13:	Workshop on biotechnological applications (Miami)
	1991
January:	NOAA call for proposals for GLOBEC studies
February:	NSF call for proposals for GLOBEC studies, especially biotechnology development

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**** - terms of appointment expired at the end of December 1990