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

Global Ocean Ecosystems Dynamics and Climate Change

A Long Range Science Plan 1995-2005

U.S. Global Ocean Ecosystems Dynamics

Report Number 12

April 1995

U.S. GLOBEC

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This long range science plan for the U.S. GLOBEC program was developed from discussions within the Long Range Planning Subcommittee, chaired by Allan Robinson. Other members of the committee are Mel Briscoe, Eileen Hofmann, John Hunter, Mark Huntley, Dave Mountain, Don Olson, Bill Peterson, Tom Powell, Paul Smith, Brian Rothschild and Leonard Walstad. The Scientific Steering Committee of U.S. GLOBEC subsequently made comments, provided oversight to the final editing of the document and approved this report.

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Executive Summary

U.S. GLOBEC's goal is to understand how physical processes influence marine ecosystem dynamics in order to predict the response of the ecosystem and the stability of its food web to climate change. A combination of field studies, model and technology development, and retrospective data analysis will be mounted to address this ambitious goal. U.S. GLOBEC will undertake a series of field programs over the next ten years to: 1) assess basic ecosystem characteristics including the natural variability of populations and their environments; 2) measure the rates of biological and physical processes; and, 3) characterize ecosystem sensitivity to climate forcing at regional to planetary scales. On the basis of these comparative studies U.S. GLOBEC will 1) determine critical global change variables; and, 2) design an operational ecosystem monitoring system that couples observations and modeling.

These field studies are coordinated with other activities: the development of coupled biological/physical models; retrospective analysis of data collected over the last century by oceanographers, climatologists and fisheries scientists; and, development of improved technology for making coupled observations of biology and physics. The vision of U.S. GLOBEC is that the models and scientific insights that arise from these field studies will ground an ecosystem monitoring program to predict variability in living marine resources. Accurate near-term forecasting of several important ecosystem properties (e.g., stratification, chlorophyll concentration, perhaps zooplankton biomass) in the sea is feasible, but can only be realized by an operational predictive system incorporating coupled biophysical models and judicious injection of standard monitoring data via data assimilation. Near-term predictive capacity is a prerequisite to predicting the long-term effects of global climate change.

U.S. GLOBEC has identified several ocean ecosystem types for emphasis. These include: banks, shelves and shallow seas; eastern boundary currents; the Southern Ocean; and critical regions of the open ocean. The first U.S. GLOBEC field study is occurring in the Northwest Atlantic on Georges Bank—the site of oceanographic and fisheries studies for more than a century and a region thought to be highly sensitive to climatic change. Eastern boundary current systems have strong biological and physical responses to climate forcing at interannual (e.g., ENSO events) to decadal (e.g., regime shifts) time scales. Global climate change is predicted to be greatest at high latitudes, with dominant effects being increased temperature and changes in ocean circulation. Fluctuations in the extent of sea-ice in the Southern Ocean may be the most dramatic manifestation of climate change in the Southern Hemisphere and may already be affected by changes in atmospheric greenhouse gas concentrations. The physical and biological environment in the open ocean differs dramatically from that found in coastal, polar, and marginal seas; so too may the coupling of physical and biological processes, and U.S. GLOBEC will investigate such differences.

The program is committed to modeling coupled physical and biological processes in the sea. Efforts to date have focused on incorporating basic ecological processes into regional scale transport models. More research is needed on refining the ecological aspects of these models, linking existing regional scale biophysical ecosystem models to ocean basin scale models, and assimilating biological and chemical data into interdisciplinary models.

Retrospective data analysis of fisheries, ecosystem, hydrographic and paleoecological data is crucial for expanding U.S. GLOBEC site-specific results to the larger scales that characterize the biogeographic distribution of populations and climate. From its

inception U.S. GLOBEC has acknowledged that a program focused on coupling physical to biological processes in ocean ecosystems at local to global scales will be data limited. Existing data are often inadequate to answer the questions posed by U.S. GLOBEC—in part because the biological and physical data are collected over different time and space scales, and satisfactory coupling cannot be achieved. U.S. GLOBEC field studies will make efficient use of state-of-the-art technologies and methods, so that truly interdisciplinary data are collected.

U.S. GLOBEC will advance fundamental knowledge of ecosystem dynamics in the context of changing climate, and will provide input to research on, and management of, living marine resources. U.S. GLOBEC will help direct applied oceanographic and fisheries research towards the development of an observational network and data assimilative model system for monitoring and management. Such a system will provide the timely information base critical to informed decision making by environmental policy makers, economists, commercial leaders and resource managers.

Introduction

U.S. GLOBEC is a global change research program concerned with the impact of global climate variability and climate change on the dynamics of marine ecosystems, specifically with the impact upon animal populations. **It aims to sufficiently understand ocean ecosystem dynamics and how they are influenced by physical processes to be able to predict the response of the ecosystem and the stability of the food web to climate change.** Physical processes strongly influence ecosystem dynamics in the sea. U.S. GLOBEC focuses primarily on the linkages between physical forcing variables and the dynamics of the planktonic stages of marine organisms, which are presumed to be the most vulnerable to changes in physical forcing associated with climate change. Target species include both the holoplankton, species resident in the plankton throughout their life cycle, and the meroplankton (including ichthyoplankton), which are planktonic for only a fraction of their life cycle and for the remainder are either benthic or nektonic. Moreover, changes in plankton populations can critically affect the distribution, abundance and maintenance of living marine resources.

Physical processes, structures and characteristics in the ocean change when climate variability or climate forcing change. These modifications in physical pattern and process impact the distribution, abundances and dynamics of animal populations in the sea. U.S. GLOBEC will examine biological responses to existing natural climatic forcing in order to provide predictions of how future climatically–driven physical forcing and potential anthropogenic changes impact the marine ecosystem. U.S. GLOBEC must consider scales ranging from the very small to the planetary. Examples of large-scale considerations include (but are not limited to): 1) regional intercomparison of generic ecosystem types; 2) the basin scale linkages of regional ecosystems; and, 3) the dynamics of zoogeographic boundaries.

The importance of multidisciplinary research in ocean science was recognized more than half a century ago by pioneering ocean scientists such as F.E. Bigelow and H.U. Sverdrup. Only now are the individual disciplines (physical, biological and chemical oceanography) sufficiently advanced so that physical, biological and chemical processes can be sampled on the same temporal and spatial scales. While U.S. GLOBEC focuses upon zooplankton, understanding of zooplankton dynamics requires concomitant knowledge of phytoplankton populations and processes and the dynamics of biogeochemical cycles. These are the focus of the U.S. JGOFS program, and U.S. GLOBEC will collaborate and interact with U.S. JGOFS as closely and efficiently as possible. U.S. GLOBEC will also benefit from cooperation with GLOBEC International and other global change research programs [e.g., Inter-American Institute for Global Change Research (IAI), Land-Ocean Interactions in the Coastal Zone (LOICZ), Past Global Changes (PAGES), and Global Change and Terrestrial Ecosystems (GCTE)]. U.S. GLOBEC research results will eventually be used to direct the development of a system for monitoring and management of living marine resources in a changing climate. Such a system would include both an observational network and a data assimilative operational model. It would be an invaluable component of the Global Ocean Observing System (GOOS).

The scientific origin of U.S. GLOBEC is rooted in the inherently, interdisciplinary formulation of modern ocean science and its ongoing interest in living marine resources. The beginning of the present program is, however, associated with the NSF, NOAA and ONR sponsored Wintergreen meeting of 1988 which led to the formation of the Scientific Steering Committee in 1989. The U.S. GLOBEC program is organized around a number of inter-related elements and activities including process-oriented field programs, modeling, retrospective studies, environmental monitoring, technology development and exchange of scientific information. U.S. GLOBEC research is supported by the U.S. National Science Foundation—Division of Ocean Sciences and Office of Polar Programs, and by the U.S. National Oceanic and Atmospheric Administration—Office of Global Programs, National Marine Fisheries Service, and Coastal Ocean Program. It is a component of the U.S. Global Change Research Program. A bibliography of U.S. GLOBEC program reports is in Appendix B.

Scientific Goal and Objectives

The overarching goal of U.S. GLOBEC is **to understand ecosystem dynamical processes in order to be able to predict the response of the ocean ecosystem and the stability of the marine food web to climate change**. It embraces the following more specific objectives:

- To determine physical influences and biophysical interactions in planktonic communities;
- To understand the dynamics of zooplankton (i.e., holoplankton, meroplankton, and ichthyoplankton) and their interactions with both lower and higher trophic levels; and,
- To identify probable changes in living marine resources resulting from climate change.

To achieve these objectives U.S. GLOBEC will: 1) assess basic system characteristics; 2) benchmark populations and their environments including their natural variabilities; 3) measure biological and physical processes and rates; 4) characterize ecosystem sensitivity to climate forcing at regional to planetary scales; 5) determine critical global change variables; and, 6) design an operational ecosystem monitoring system which couples observations and modeling. See Table 1.

U.S. GLOBEC has identified several ocean ecosystem types for emphasis. To date these include: banks, shelves and shallow seas; eastern boundary currents; the Southern Ocean; and, critical regions of the open ocean. The detailed scientific objectives for these systems are presented in the next section.

Scientific Program

The Scientific Steering Committee of U.S. GLOBEC has prepared a long–term program to address these scientific objectives (Table 1, Table 2). This document focuses on the next ten years. Field process studies at several sites in the world ocean are planned for intensive activity in the next ten years—several are in advanced planning stages (the California Current System, and the Southern Ocean) and one (the Northwest Atlantic) has already begun. All emphasize the advancement of coupled biological/physical modeling in the sea, and the analysis of underutilized historical data resources that oceanographers, climatologists and fisheries scientists have collected over the last century. The integration of these historical data into the contemporary regional and global scale data collection efforts of U.S. GLOBEC investigators (as well as those from other programs) is considered to be critical. Further, U.S. GLOBEC is committed to the intercomparison of the results of coupled biological–physical investigations among the several sites where U.S. GLOBEC process studies occur. It is anticipated that this intercomparison endeavor will be extended to regions other than those where U.S. GLOBEC data collection efforts are focused, and both the modeling and historical data analysis activities will include a

Table 1. U.S. GLOBEC Scientific Overview

Ocean Ecosystems

Part A. Banks and Eastern Boundary Currents

Approach / Activities

Approach / Activities	Banks	Eastern Boundary Currents
System Characteristics	1. Nearly Isolated / Long Retention Time 2. Deep Ocean, Shelf Exchanges	1. "Flow-through (advection) 2. Coastal Boundary 3. Wind-driven Upwelling
Benchmarking Natural Variability	1. Distinct Populations? 2. Stratification Regime 3. Circulation 4. Fronts	1. Abrupt Species Changes 2. Energetic Mesoscale Features 3. Large-scale Gradients
Biological and Physical Processes and Rates	1. Local Growth *vs.* Retention / Exchange 2. Role of Stratification 3. Episodic Gains, Losses and Exchanges 4. Role of Mortality	1. ENSO Effects 2. Biological Response to Interdecadal atmospheric shifts 3. Ecological Role of Mesoscale Features 4. Changing Ecosystem Properties along a Latitudinal Gradient
Climate Sensitivity	1. Shifts in Biogeographic Boundaries 2. Differential Effects of Stratification Timing and Intensity on Cod and Haddock	1. Altered Ecosystem Productivity 2. Shifts in Biogeographic or Physical Boundaries 3. Altered Mesoscale Activity / Patterns 4. Strength / Timing of the Spring Transition
Critical Variables	1. Identify critical "global change" variables 2. Design an Operational Monitoring / Modeling System	

Table 1. U.S. GLOBEC Scientific Overview

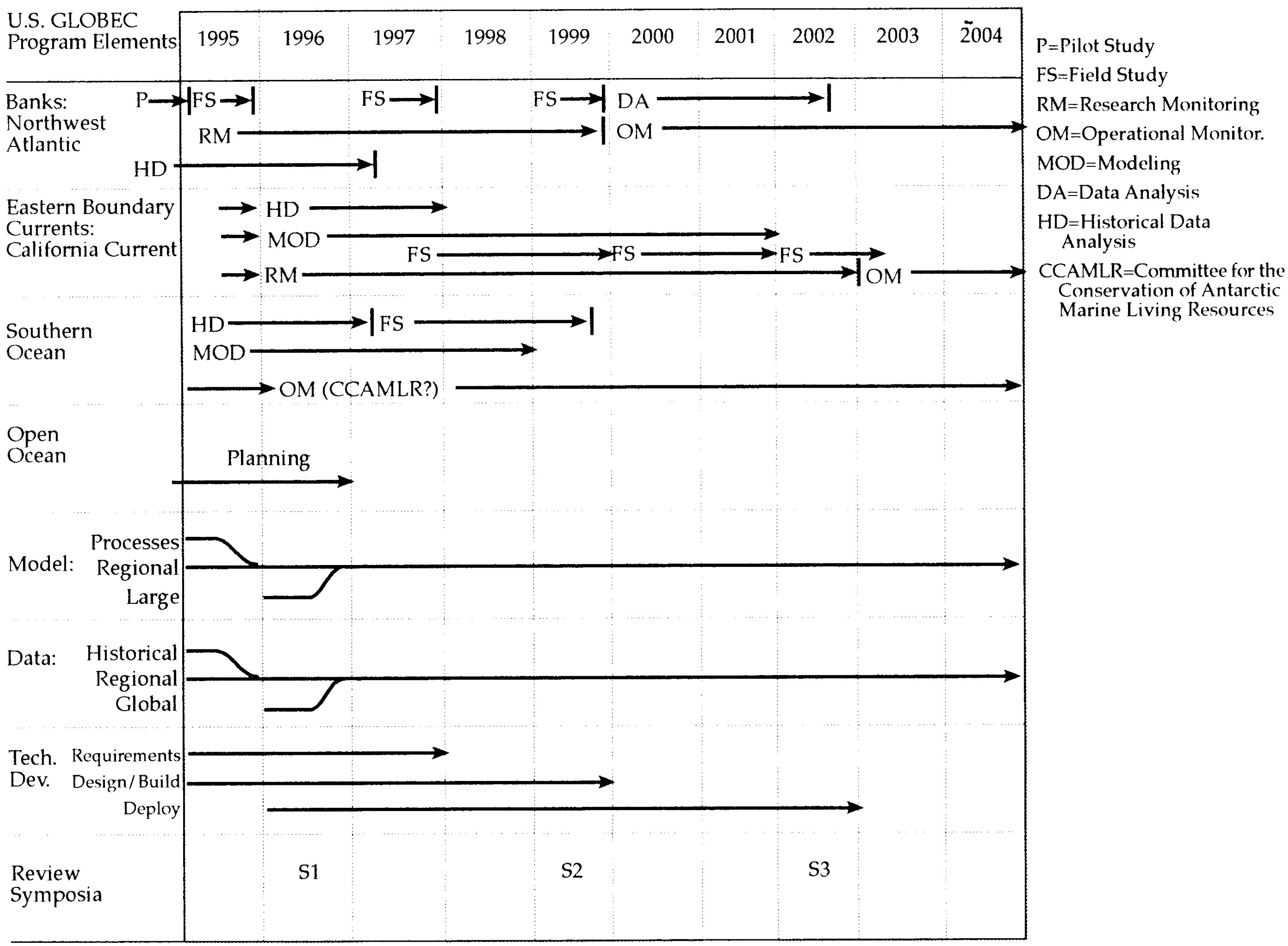
Part B. Southern Ocean and Open Ocean

*—Under development

Ocean Ecosystems

Approach / Activities	Southern Ocean	Open* Ocean
System Characteristics	1. Ice Cover 2. Short Food Webs 3. Importance of Predators	1. High Species Diversity 2. Low Physical Variability; Long Retention Time?
Benchmarking Natural Variability	1. Shifts in Ice Coverage 2. Ocean Circulation Patterns 3. Biomass Fluctuations, esp. krill	1. Species Composition and Abundance 2. Long-Term (Community) Stability 3. Spatial Heterogeneity in Mesoscale Eddy Fields
Biological and Physical Processes and Rates	1. Krill Population Dynamics 2. Animal / Sea Ice Interactions	1. Predator Control *vs.* Resource Limitation ("Top-Down" *vs.* "Bottom-Up") 2. Vital Rate Comparisons: Oceanic *vs.* Coastal Species
Climate Sensitivity	1. Sea Ice Cover 2. Stratification 3. Productivity 4. Large-Scale, Circumpolar Circulation	?
Critical Variables	1. Identify critical "global change" variables 2. Design an Operational Monitoring / Modeling System	

Table 2. Projected Schedule of U.S. GLOBEC Activities.



strong comparative perspective. Integrated instrument systems which meet the needs of coupled biological-physical measurement programs are crucial elements of all U.S. GLOBEC field studies. Design of field studies in U.S. GLOBEC will consider the special data requirements that coupled biophysical models demand.

Eventually, the data and scientific insights which arise from this 10–year study will ground the ecosystem monitoring program needed to predict variability in living marine resources. Accurate near-term forecasting of several important ecosystem properties (e.g., stratification, chlorophyll concentration, perhaps zooplankton biomass) in the sea is feasible and can become an integrated component of operational monitoring. The need is clear—e.g., commercial fishing interests routinely request information on the location of fronts to direct their fishing effort. Moreover, with such a system, decisions about harvesting policy for living marine resources will be better informed, perhaps to the benefit of both the marine resources and the industries dependent upon them. Our vision is that a program of limited ecological prediction—analogous to early efforts at weather forecasting—is feasible, but demands the advances in knowledge and methodology that we anticipate achieving in U.S. GLOBEC. It can only be accomplished through the coupled use of operational biophysical models, supplemented by the judicious injection of standard monitoring data appropriately assimilated into the models.

Field Process Studies

Understanding the coupling of physical and biological processes in the sea is the core of U.S. GLOBEC. This understanding has been limited by our ability to sample, process, and analyze biological data on scales commensurate with physical data. To accomplish this, U.S. GLOBEC emphasizes improved rapid discrete sampling, continuous *in situ* measurement, and remote sensing in ongoing and future field studies. The emphasis is on sampling marine populations on appropriate time scales and with sufficient spatial resolution to compare with the concomitant physical data. In addition, process studies are necessary to elucidate the actual mechanisms coupling biology and physics. Only by understanding mechanism can we extrapolate, generalize, and make predictions about the influences of global climate change on marine ecosystems.

Banks, Shelves and Shallow Seas

These environments are the home of many of the world's most important fisheries. The first U.S. GLOBEC field study is occurring in the Northwest Atlantic on Georges Bank—the site of oceanographic and fisheries studies for more than a century (Backus, 1987). The cod, haddock and other groundfish stocks of Georges Bank have historically been important to the economy of New England. In recent years the stocks of these species have declined, in part due to overfishing. One challenge that U.S. GLOBEC faces on Georges Bank (and elsewhere) is that of deciphering natural population fluctuations from anthropogenic impacts. Georges Bank is thought to be highly sensitive to climatic change because it is positioned in a faunal, climatic, and oceanic boundary region. Moreover, model results indicate that the Georges Bank region will be more heavily impacted by climate change than other areas in the North Atlantic Ocean (Manabe et al. 1991). Finally, Georges Bank is an excellent site for a study of the population biology of marine animals because it is of sufficient size and has a physical circulation pattern resulting in distinct, trackable populations that persist for long periods amenable to time-series study. The focus of the Georges Bank study is to determine how biological and physical processes interact to control the population dynamics and retention of specified target species on the Bank (see Appendix A.1). The information provided by the Georges Bank field studies will permit assessment of the potential fate of these zooplankton and fish populations under various plausible global climate change scenarios. More information can be found in U.S. GLOBEC reports Nos. 2 and 6 and Appendix A.1.

Eastern Boundary Currents

Eastern boundary current (EBC) systems are particularly appropriate for examining both high and low frequency components of climate variability. Biological and physical responses to forcing at interannual (e.g., ENSO events) to decadal time scales (e.g., regime shifts) are known to be very strong. The local biological response almost certainly involves coupling to a variety of physical processes. Some of these prominent physical processes are: wind speed, direction and wind stress curl; pycnocline depth; alongshore and cross-shore advection; and buoyancy inputs. These are influenced by larger-scale (basin-wide) oceanic and atmospheric circulation. Lower frequency components of biological variability (decades to centuries) are clearly evident in reconstructions from historical and sedimentary data. Equally important, several EBCs, including the California Current System (CCS), have long biological and physical records, making them ideal for examination of long-term changes, such as might occur due to gradual global climate change. In the CCS, quantitative surveys of zooplankton and fish have been conducted off British Columbia, Washington, Oregon, California, and Baja California (Mexico). The best of these is perhaps the CalCOFI investigations of the past 40 years. Data and scientific insights developed from one EBC may be applicable to others, providing global significance to such studies. EBCs are oceanographically and ecologically distinctive; the dominant life history patterns and trophic pathways contrast with those of other continental shelf ecosystems. Moreover, in the CCS, some species extend over a broad latitudinal range and are exposed to large differences in the intensity and timing of seasonal circulation patterns. Conversely, other planktonic, benthic and fish species are restricted to smaller regions, perhaps due to the population's responses to the differing mesoscale physical variability in different regions. Finally, eastern boundary current systems are important economically—approximately 35% of the global marine fish catch is taken from the EBC systems of the Atlantic and Pacific, and the U.S. west coast fishery in 1992 produced an impact of $4 billion on the economies of California, Oregon and Washington (U.S. Department of Commerce, 1992). More information can be obtained from U.S. GLOBEC Reports No. 7 and No. 11 (U.S. GLOBEC 1992, 1994) and Appendix A.2.

Southern Ocean

Global climate change is predicted to be greatest at high latitudes, with dominant effects being increased temperature and changes in ocean circulation. The Antarctic has a high negative radiation budget; its immense masses of continental ice and annual sea-ice act as a refrigerator buffering seasonal and multiannual changes in temperature. The extent of sea-ice in the Southern Ocean is not, however, constant from year to year. The fluctuations in sea-ice extent may represent one of the most dramatic manifestations of climate change in the Southern Hemisphere. Recent paleoclimate studies indicate that changes in atmospheric greenhouse gas concentrations may have already affected the extent of sea-ice.

Were atmospheric warming in the Antarctic to reduce the areal extent of sea-ice, this would almost certainly reduce photosynthetic carbon fixation, destroy habitats, and disrupt the life cycles of marine animals. Marine zooplankton, like krill, and higher trophic level animals, whose present-day biogeographic ranges are directly related to the extent of sea-ice coverage, might be most seriously impacted. On the other hand, increased meltwater input from the continental ice sheet might have a compensatory effect by altering water column stability, stratification, and extending the high production zone further from shore. It has been suggested that because of the tight linkages between trophic levels (producer–herbivore–carnivore) in the Antarctic, long-term studies focusing on predator-prey relationships and their environment are an efficient way to monitor the effects of man-induced perturbations on the entire regional ecosystem (Croxall et al. 1988). The focus of a U.S. GLOBEC Southern Ocean study will be how variability in sea-ice extent determines variability in the population dynamics of the target species. To understand the mechanisms responsible for changes in resource levels for the higher trophic level consumers requires knowledge of the many inter-related factors affecting krill abundance and availability. These include water mass distribution, reproductive and recruitment success, and food availability, which may depend directly or indirectly on ice cover. Further information about the Southern Ocean GLOBEC study can be found in U.S. GLOBEC Report No. 5, GLOBEC International Report No. 5, and Appendix A.3.

Open Ocean

The physical and biological environment in the open ocean differs dramatically from that found in coastal, polar, and marginal seas. So too may the coupling of physical and biological processes. We presently do not know whether open ocean ecosystems will be resistant to climatic variations, or shift dramatically under such potential forcing. For example, there may be less variability in physical forcing over time scales of days to several months and over both small (e.g., meters to km) and large (10's to 1000's of km) spatial scales in the open ocean than is commonly found in the coastal ocean. Further, the frequency distribution of numbers of individuals in a species in much of the open ocean appears to be more stable year-to-year than in coastal environments. If the apparent stability of open ocean biological communities is due to internal biological checks and balances, then the biomass and food-web relations of oceanic communities might be relatively resistant to changing physics caused by climate change. Conversely, if the stability of the open ocean biological communities is due to the near constancy of the physical environment, then oceanic communities may be more susceptible to physical perturbations resulting from global climate change. Some open ocean environments, for example the Arabian Sea (U.S. GLOBEC Report 9), do not fit the paradigm. The Arabian Sea is subject to extremely strong physical forcing due to seasonal reverses of monsoonal winds. Quite likely the biological community is also strongly seasonally variable.

Comparison of zooplankton vital rates and population dynamics of various oceanic and coastal habitats will be essential. In fact, several circumglobally distributed species might be targeted for study. In this way some of the inherent variability associated with different habitats in different regions of the world's oceans might be minimized and the biological responses to global climate change extracted from records of seasonal and interannual variability. Possible U.S. GLOBEC studies in the open ocean were discussed at a workshop held in September 1993 and a report of the workshop discussions and recommendations is under review. Possible U.S. GLOBEC studies in the Arabian Sea were discussed at a workshop in June 1992. Recommendations and further information can be found in U.S. GLOBEC Report 9.

Modeling

U.S. GLOBEC is committed to a vigorous program of modeling coupled physical and biological processes in the sea. We emphasize model development well in advance of field investigations. Relatively mature efforts from two modeling groups were ready for use on Georges Bank in advance of major field processes studies, and have provided directions for the field research that recently have begun.

Modeling studies of the relevant physics and biology in marine ecosystems will be used to investigate how changes in global climate affect the forcing and physical characteristics of the systems and how the distribution and abundances of animal populations respond to changes in that forcing. Models can integrate information from a variety of sources into a common context and link biological and physical information from various temporal and spatial scales. While the ultimate goal of the modeling studies is to predict and assess likely consequences of global climate change on marine animal populations, they can also assist in satisfying important nearer term objectives. These include hypothesis testing, sensitivity experiments, and planning and evaluating field research.

A long-term goal of U.S. GLOBEC is to bring predictive models for a limited set of ecosystem properties to an operational stage in the next decade. Efforts to date have been directed toward incorporating basic ecological process formulations into regional scale transport models. Several model activities must be expanded to achieve the operational model goal. First, ways must be developed to link existing regional scale bio-physical ecosystem models with ocean basin scale models which provide both the global physical forcing and the boundary conditions for the regional models. Only in this way can the large scale effects associated with climate change be accommodated, and their effects translated into specific phenomena at the regional scale. Thus, multiscale nested models must be developed. Second, many aspects of the basic ecological process formulations in these models need refinement. For example, animal behavior, such as vertical migration, may be critical; it can result in directed motion that is substantially different from that in the flow fields that transport passive organisms. The population effects of such small-scale individual organism behavior needs to be parameterized so that it can be incorporated into larger, e.g., regional, scale models. The effects of different ecological structures in coupled models must be investigated. When is a more complex food chain, perhaps including the microbial loop, needed to generate accurate predictions? Or, how will the episodic introduction of unusually large numbers of predators to a local environment alter mortality patterns, species composition and trophic structure? In fact, such introductions occur during strong El Niño's along the U.S. west coast. When is age– or stage–structure necessary in biological models of zooplankton populations, and when can it be neglected?

Many, if not most, models are not easily accessible to the wider oceanographic and fisheries community. This is particularly true of coupled biological and physical models. U.S. GLOBEC is committed to bringing such models into wider use within the appropriate scientific community.

Finally, much improved assimilation of biological and chemical data in interdisciplinary coupled models is necessary for efficient and rapid progress in research.

> *Data assimilation provides a mechanism for adjusting model parameters relative to a known distribution, updating the model at various intervals and improving the accuracy of simulated distributions. Data assimilation has been used with meteorology and ocean circulation modeling studies and is now starting to be used with biological models....Data assimilation can compensate for model deficiencies, maintain synoptic phase information in the presence of loss of predictability, provide dynamical space-time interpolation of sparse data, and estimate poorly known parameters...*[GLOBEC International Report No. 6 (p. 19, 1994)]

Improved data assimilation is crucial to the development of a prototype operational monitoring and prediction system (see section below; also GLOBEC International Report No. 6 and GLOBEC International Special Contribution No. 2). A lengthy bibliography of data assimilation issues can be found in GLOBEC International Spec. Contribution No. 2 (in press).

Retrospective Analysis

Existing data sets need re-examination, and data sets that are particularly useful for examining past ocean conditions in relation to climate change, for example, paleoceanographic records, need to be developed. Data from fisheries have been collected for centuries, large hydrographic archives exist, and extensive specimen collections and data from environmental monitoring surveys are also available and need to be explored in an interdisciplinary climate context. Moreover, paleoecological data exists which extends fisheries, ecosystem and hydrographic data back in time beyond the limits of historical observation. Such data provide a window to the long time scale processes that characterize climate variability. A special property of the long historical records of fish, mammals and birds, is that they provide not only a history of the variation in population size, but also provide estimates of the life table variables (growth, mortality, maturity, and reproduction) that regulate population growth. It is these variables that respond directly to changing environmental conditions and must be linked to physical forcing which will enable forecasting of the effect of climate change on marine animal populations. The need for retrospective work is obvious when one considers that the five year duration of U.S. GLOBEC field programs corresponds to only 2-3 generations of most living marine resources (fish, benthic invertebrates) and perhaps 5-10 generations of most macrozooplankton, while climate change effects will be mediated over many generations. The U.S. GLOBEC program recognizes that retrospective data are indispensable for expanding the results of site-specific process studies to the larger scales that characterize the biogeographic distribution of populations and climate. Consequently, the identification, assembly and analysis of relevant existing data sets is important to achieving U.S. GLOBEC's goal of understanding the interrelationships of animal populations to ocean physics, climatic variability and long-term change.

Data Management

Data management is another overarching area of concern to U.S. GLOBEC. In particular; 1) how will we facilitate regional intercomparisons of research results to provide a global picture? And, 2) how will we analyze and reduce data to best incorporate them into models and measurement (monitoring) systems? U.S. GLOBEC and other international programs have recognized the importance of regional intercomparison. For example, the ICES/GLOBEC International Cod and Climate Change working group has identified coordinated retrospective data analysis, including the establishment of a centralized database, as a unifying theme for their future program in the North Atlantic (GLOBEC International Report No. 4, 1993). Such considerations may have important implications for U.S. GLOBEC's activities in the North Atlantic. Building on the work of U.S. JGOFS, U.S. GLOBEC has adopted a community accessible object-oriented database system as a repository for the data. U.S. GLOBEC's Data Policy is specified in U.S. GLOBEC Report No. 10 (1994).

Technology, Instrumentation and Measurement Systems

From its inception U.S. GLOBEC has acknowledged that its program—focusing on the coupling of physical processes to biological processes in ocean ecosystems at local to global scales—faces the problem of inadequate data. Existing data (and sometimes the instruments) are often inadequate (and inappropriate) to answer the questions posed by U.S. GLOBEC. Even were the data good, too often the biological and physical data are collected over different time and space scales, and satisfactory coupling cannot be achieved. Toward this end U.S. GLOBEC has held three meetings on the subject of new technologies, releasing three reports on the broad topics of molecular techniques, acoustics, and optics. They appear as U.S. GLOBEC reports Nos. 3, 4, and 8 (GLOBEC 1991, 1991, and 1993, respectively). Several research programs dealing with new technology are presently being conducted by U.S. GLOBEC supported investigators. There is little doubt that U.S. GLOBEC field studies will have to make use of these state-of-the-art technologies and methods more efficiently, and that this represents a significant technology-transfer problem that will have to be addressed. One way that education and training of scientists—on state-of-the-art technology, advancements in coupled biophysical modeling, or database and data management issues—could be accomplished is through targeted workshops.

An ultimate goal of the U.S. GLOBEC program is to provide the scientific foundation upon which a large-scale operational monitoring/modeling system can be pursued for a selected set of marine ecosystem variables. It is not clear whether existing technology can provide such global-scale monitoring. Some quantities connected to ecological processes in the ocean are already monitored on a global scale. Satellite sensors have provided new views of the ocean surface, both in terms of temperature and pigment distributions, but also of large scale flow dynamics, wind fields, and mesoscale variability. Perhaps remotely sensed data, to the extent that those readily measured parameters (e.g., chlorophyll) covary with plankton biomass, can provide equally exciting information about animal distributions. For example, remote detection of oceanographic fronts is already useful to fishermen. To accomplish this general objective however, we will need to continuously measure animal abundances and distribution—perhaps using a sparse global array of moored (or drifting) telemetering acoustic sensors—and integrate this data with remotely sensed variables by efficient data assimilation into appropriate models. This last type of monitoring will require advances in some technological aspects, in particular, data transmission and processing, and sensor interpretation.

Global Change Science and Long Range Implications

The world ocean is densely populated with living organisms ranging in size from less than a micron to tens of meters. Their interactions result in a flow of energy and an exchange of materials. Multicomponent and multiscale interactions characterize the complex food web in the sea. These interactions are to various degrees regulated by physical processes in the sea that are themselves the result of atmospheric forcing. There is little doubt that climate change will alter these processes and thereby impact the abundance of organisms, including living marine resources, and their interactions in marine ecosystems. Finally, to the extent that the activities of zooplankton impact climate [i.e., through feedbacks (Banse, 1994)], they are also a concern of U.S. GLOBEC.

Global ocean ecosystems research necessarily involves regional scale, basin scale and planetary scale considerations. Given the diversity of marine ecosystems, regional intercomparison and contrast of various types of ecosystems—including banks and shallow seas, eastern boundary currents, and representative open ocean regions—are essential. For example, what are the similarities and differences in the ecosystem dynamics and climate sensitivities of stable high-nutrient/low-productivity regions (northeast Pacific, equatorial Pacific, Southern Ocean) versus regions with seasonally varying nutrients and productivity (central mid-latitude bloom regions of the North

Atlantic and North Pacific). Subbasin and basin scale transports of material into and out of regional ecosystems are important to the maintenance of such ecosystems and provide significant sources of variability. If the climate of a regional ecosystem is changing, these transports could be especially important. An example may be found in the appearance of tropical planktonic species in the northern temperate waters off the northwest coast of the U.S. during and following the intense 1982-1983 ENSO event. This, of course, was a temporary (interannual) climatic fluctuation. Basin scale processes also require substantial research. Empirical evidence for a possible Pacific-wide phenomenon is provided by the correlation of the intense variability of the sardine catch in Japan, California and Chile (Kawasaki 1992; Lluch-Belda et al. 1989; Figure 1). Another example might be the apparent connection between salmon stocks in the Pacific Northwest (Oregon, Washington, British Columbia, and Alaska) and North Pacific atmospheric pressure and circulation (Beamish and Bouillon, 1993). The mechanism may be related to winds, upwelling and production of the subarctic Pacific gyre and its effects on survival of salmon in their earliest marine phases. Long-term, large-scale changes in production have been hypothesized for the subarctic Pacific gyre (Brodeur and Ware 1992). There has been to our knowledge no quantitative demonstration of planetary scale biological phenomena or variability. It must, however, be expected to occur. Large-scale physical variability occurs on multiannual and decadal scales, e.g., regime shifts, ENSO and the North Atlantic Oscillation (see U.S. GLOBEC Reports No. 2, 7, and 11). These large-scale physical variabilities have planetary scale teleconnections and correlations which must be expected to cause related biological variabilities.

To address global research objectives will require dedicated observational, experimental and modeling studies, retrospective data analysis and data assembly and management. Experiments will need to be coordinated scientifically, methodologically and logistically. New instruments and sampling strategies will be necessary. Nested multiscale (local to global) interdisciplinary models for nowcasts, forecasts and simulations must be developed and made operational. Regional ecosystem simulations need to be nested within existing state-of-the-art global climatic models, and simple global ecosystem models will have to be constructed. Analytical and computational issues in physical, biological and chemical modeling are involved. Global data sets need to be assembled and studied. The identification of critical variables and standard parameters for global change ecosystem research and monitoring is of crucial importance. Factors in selecting these variables include: relevance, feasibility, and efficiency of acquisition. Concentration and distribution of phytoplankton biomass and zooplankton biomass by size class are potential standard variables. Given U.S. GLOBEC's emphasis on populations it will be essential to include zooplankton species composition as a standard variable whenever feasible. Retrospective data analysis can provide initial guidance for the selection of standard variables. Data sets from remote and *in situ* platforms will need to be acquired. Emphasis should be placed on ecosystem parameters that could be derived by statistical inference (correlations) from relatively easily sensed variables such as acoustic data (active and passive techniques) and color. Surface and near surface phytoplankton biomass from ocean color sensors, and zooplankton biomass by size class from acoustics, are examples. Less obviously correlated ecosystem parameters should also be explored. Perhaps proxy indices for parameters not directly measurable by inexpensive remote sensing could be developed by retrospective analysis. The global coordination, standardization, and intercalibration of national fisheries measurements and the use of fisheries vessels worldwide as ships of opportunity could represent a feasible and important means for acquiring the data sets needed to explore global change. All of these issues relate directly to research and development of a global monitoring and management system.

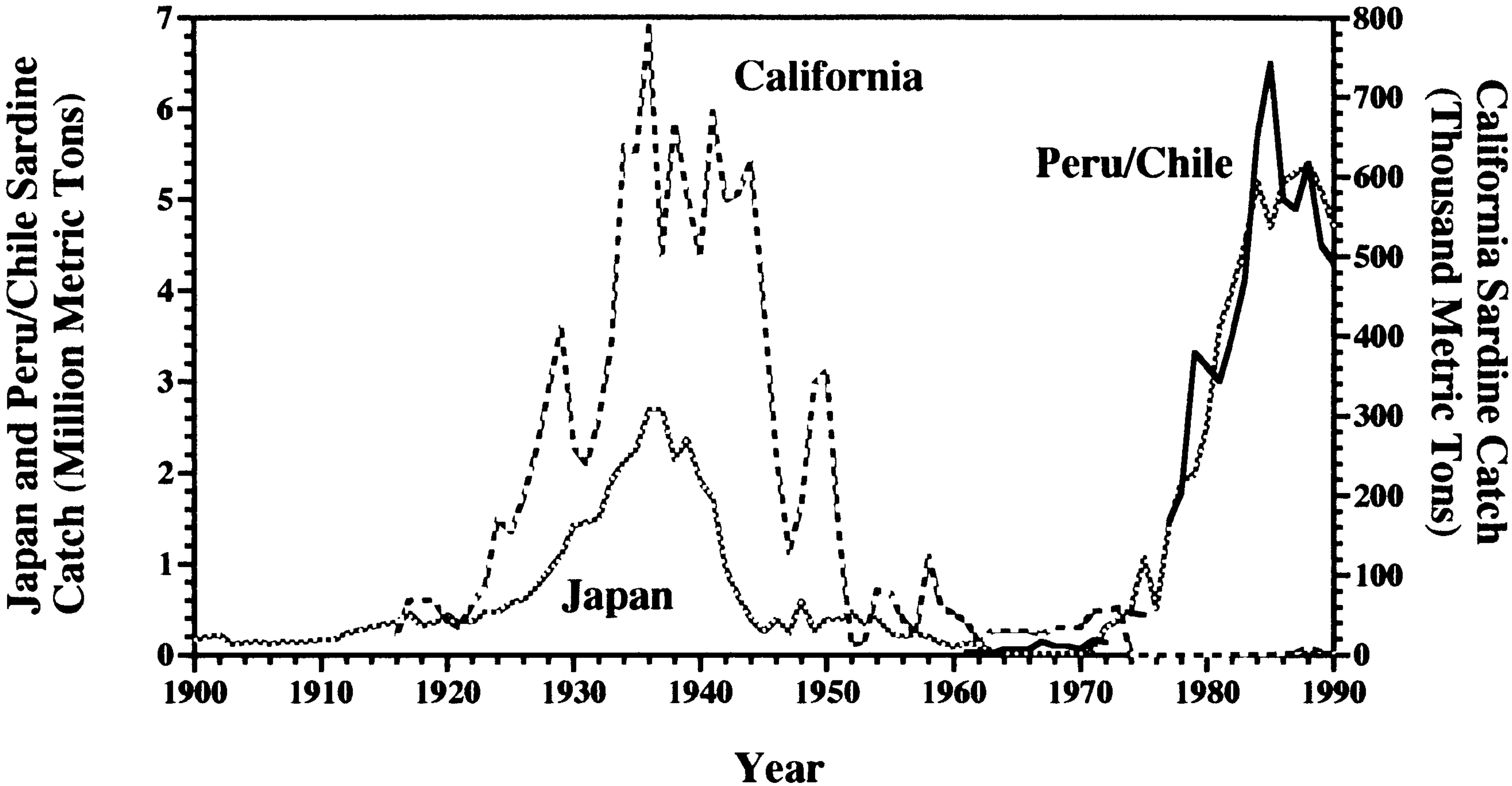


Figure 1. Historical catches in the sardine fishery of Japan (hatched line), California (dashed line), and Peru-Chile (solid line) have exhibited parallel patterns, possibly in response to global-scale changes in climate. (modified from Kawasaki, 1992)

The fundamental scientific knowledge on biophysical interactions in the sea to be acquired through U.S. GLOBEC research will be immediately applicable to the design of a system for monitoring, prediction and management of the ocean ecosystem. That system will consist of an observational network coupled to interdisciplinary numerical models. For efficiency and flexibility both the network and the model should be modular so that simpler or more complex versions can be utilized. The observational network should be an efficient mix of platforms and sensors and the models should be fully data assimilative, i.e., capable of including physical, biological and chemical data in near-real time. The network is envisaged to have both a sparse global component and a relocatable regional generic system. The former will provide the globally comprehensive long-term observations, but at low spatial resolution. The latter will provide the capability to enhance the spatial resolution in key areas for limited time periods. A successful operational system depends essentially upon 1) the identification of relevant global change ecosystem variables that can be remotely sensed and 2) an optimal allocation of sampling resources selected through analysis of observational system simulation experiments (OSSEs; see GLOBEC International Spec. Contribution No. 2). The U.S. GLOBEC program is designed to move from the deployment and exercise of research systems to the deployment of prototype operational monitoring systems. The ecosystem operational monitoring system designed, demonstrated and validated within U.S. GLOBEC should become an integral element of the Global Ocean Observing System program (GOOS).

The global research activities of U.S. GLOBEC will be implemented in cooperation with, and as a participating national program of, the GLOBEC International program. GLOBEC International was established in 1992 and is sponsored by IOC, SCOR, ICES and PICES. There are presently GLOBEC programs in China, Japan, Canada, Norway and the United States, and programs are being developed in the United Kingdom, Germany, and New Zealand; several other nations are also expected to participate. GLOBEC International will finalize its science plan in 1994. GLOBEC International will provide a forum for 1) focusing global ocean ecosystem research issues; 2) implementing global research activities; and, 3) coordinating regional studies (e.g., Southern Ocean, GLOBEC International Report No. 5, 1993; Cod and Climate Change, GLOBEC International Report No. 4, 1993). Important issues that GLOBEC International has been addressing include technology-transfer (methods, instruments, models) from advanced to developing nations and laboratories; intercalibrations of instruments; the definition of standard variables and techniques; coordination of research; exchange of ideas; and the generation of global and shared data sets.

The global ecosystem is of paramount importance to the United States not only because of our interest in global scale processes, but also because the seas of our own EEZ are almost certainly influenced by global processes. Such influences and interactions are poorly documented. U.S. GLOBEC will advance fundamental knowledge of ecosystem dynamics in the context of changing climate, and will provide input to research on, and management of, living marine resources. At the same time, U.S. GLOBEC will help direct applied oceanographic and fisheries research towards the development of an observational network and data assimilative model system for monitoring and management. Such a system will provide the timely information base critical to informed decision making by environmental policy makers, economists, commercial leaders and resource managers.

Appendices

Appendix A. Field Process Studies

A.1. Banks, Shelves and Shallow Seas

The specific scientific objectives of the Georges Bank program appear in Table 3; they are developed in greater detail in U.S. GLOBEC Report No. 6 (U.S. GLOBEC 1991b). The target taxa to be studied include the pelagic stages of cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), and the copepods *Calanus finmarchicus* and *Pseudocalanus* spp., which are their principal prey. The first measurement programs to address these objectives have begun. A pilot study of stratification variability—Table 3, Objective III—and its effects on larval fish survival was carried out in May 1992. A preliminary report of this study appears in the U.S. GLOBEC NEWS (No. 3, May 1993). More intensive studies of the impact of stratification survival and growth of these larval fish were conducted in 1994, with a full program of broad-scale investigations and process-oriented research planned for 1995. The effects of the exchange and retention of water and organisms on and off of Georges Bank will be examined in 1997. Frontal exchange processes will be the prime focus of field studies in 1999. Details of the overall program schedule are shown in Table 2.

Banks, shelves, and shallow seas afford a rich arena for regional intercomparisons. They are among the most studied parts of the world ocean. One candidate for a comparative study might be a collaborative project with Canadian researchers who study the banks off Canadian shores in the NW Atlantic adjacent to Georges Bank. A large and successful Canadian effort, the Ocean Production Enhancement Network (OPEN), directed toward that end has recently concluded. Canada GLOBEC has identified the Scotian Shelf off of eastern Canada as one of its three main field investigations. Comparative endeavors with European researchers may also be fruitful. The Norwegian program, Mare Cognitum, is devoted to examining the productivity of the Norwegian Sea, with a focus on herring and the interactions between herring and zooplankton and other fish stocks. The ICES/GLOBEC International Cod and Climate Change program is coordinating investigations of the effect of climate change on North Atlantic cod stocks, and has identified core study components of 1) cod trophodynamics, and 2) large- and 3) intermediate-scale physical processes as they impact cod stock dynamics.

Table 3. Scientific Objectives of the Northwest Atlantic-Georges Bank Program

I. Quantify Species Abundance in Space and Time

II. Determine Population Dynamics of Key Species

III. Examine Effects of Seasonal Stratification on Biological Populations

IV. Evaluate Physical and Biological Processes in Relation to Exchanges of Water and Biota across Boundaries

V. Examine Biological Rates (e.g., Predator/Prey Interactions) Considering Turbulence and Patchiness

VI. Determine Sensitivity of the Physical Transport, Stratification and Biogeographic Boundaries to Climate-Forced Changes

A.2. Eastern Boundary Currents

U.S. GLOBEC has published a science plan for research in the California Current Ecosystem (U.S. GLOBEC Report No. 11, 1994). The goal of a Califonia Current System (CCS) study is, "To understand the effects of climate change on the distribution, abundance and production of marine animal populations in the CCS". The approach is to study the effects of past and present climate variability as a proxy to better understand how the CCS may respond to future global warming and climate change. Dominant temporal scales of variability in the CCS are interannual, primarily due to the El Niño-Southern Oscillation linking atmospheric and ocean dynamics, and decadal, manifest primarily as large scale shifts in the structure (or productivity) of the system, due to large scale shifts in the position of atmospheric cells and associated physical forcing. In spatial terms, the dominant scales of variability in the CCS are: first, latitudinal, with large gradients in physical forcing and species composition from north to south; and second, mesoscale, with prominent squirts, jets, and filaments, especially off central and northern California. U.S. GLOBEC's research in the CCS will focus on these temporal and spatial scales of variability. Accordingly, we will investigate
the linkage between growth, reproduction, mortality, genetic composition, physiological condition, transport, and recruitment of holoplankton, meroplankton, and icthyoplankton and the dominant spatial and temporal variability of physical forcing. U.S. GLOBEC will attempt to understand how populations adapt to the different mesoscale dynamics that occur latitudinally in order to provide a better indication of the consequences of climate change to the ecosystem. Finally, we aim to better understand the abrupt shifts that occur infrequently so that perhaps we may recognize future shifts early and provide useful advice to managers of harvestable living marine resources in the California Current. Table 4 contains a summary of the scientific objectives and the approaches that will be used to meet these objectives. A tentative schedule of activities in the CCS appears in Table 2. More information can be obtained from U.S. GLOBEC Reports No. 7 and No. 11.

U.S. GLOBEC hopes to collaborate with other programs investigating the California Current Ecosystem, or other EBCs. Numerous field efforts already obtain large volumes of multidisciplinary data from the CCS. These are mostly sponsored by NOAA, NSF, ONR, and MMS; in addition, regular long term sampling programs are conducted by CalCOFI, NMFS, state agencies, and numerous regional academic and research institutions. The Coastal Ocean Processes (CoOP) program intends a multidisciplinary study of the U.S. west coast, as a representative example of a strongly wind-driven shelf system. CoOP and U.S. GLOBEC have been discussing how to best collaborate to achieve more than either program could achieve independently. Studies of other EBCs will either be ongoing or are planned for the period when U.S. GLOBEC will be studying the California Current ecosystem. Connections to the active programs off South America, the west coast of Africa, South Africa (Benguela Ecology Program—BEP), and the Iberian peninsula would be welcome and probably best coordinated through GLOBEC International. This offers an opportunity to undertake regional comparison to examine EBCs having different levels of physical forcing. International linkages will also occur through GLOBEC International's Small Pelagic Fish and Climate Change (SPACC) initiative. Mexico and Canada conduct frequent and regular physical and biological surveys off their west coasts. Collaboration would greatly facilitate the regional latitudinal comparison of biological response to mesoscale physical forcing and the study of transition zones along the west coast.

Table 4. Scientific Objectives of the California Current System Program

I. Examine Interannual Climate Variability (e.g., ENSO's) on Biological Populations

II. Describe Biological Responses to Demonstrated, Basin-scale, Interdecadal Changes in Ocean-Atmosphere Coupling

III. Examine Impacts of Mesoscale Features and Dynamics on the Biological Processes and Characteristics of Plankton Populations

IV. Evaluate Impacts of Large-scale, Latitudinal Variability in Physical Forcing on Recruitment, Retention / Transport, Predator / Prey Relations and Life History Strategies of Marine Animals

A.3. Southern Ocean

U.S. GLOBEC planning for a program in the Southern Ocean is well-developed (U.S. GLOBEC Report No. 5, 1991). U.S. research in the Southern Ocean will be part of a larger GLOBEC International effort involving many nations. The specific objectives of the U.S. GLOBEC Southern Ocean program can be found in Table 5. The foci will be 1) investigations of the variability of sea-ice on the life cycles, productivity, distribution and abundance of Southern Ocean fauna, and 2) the coupling between ocean circulation dynamics and population dynamics. Pelagic taxa that participants at the 1991 GLOBEC Southern Ocean workshop identified include the Antarctic krill (*Euphausia superba*) and a salp (*Salpa thompsoni*). Benthic forms with both pelagic and benthic larval stages among the bivalves, echinoderms, and crustaceans will also be emphasized. Higher predators might include a commercially harvested species (e.g., *Champsocephalus gunnari*), a nonharvested holopelagic species (e.g., *Pleurogramma antarctica*), and a nonharvested near-shore species (e.g., *Notothenia neglecta*). Other top predators should include a variety of penguin species, the crabeater seal, and the Antarctic fur seal. Further information can be found in U.S. GLOBEC Report No. 5. GLOBEC International has held two meetings to develop an implementation plan for a coordinated international Southern Ocean program. A report from the first meeting has been published (GLOBEC International Report No. 5, 1993), and a full plan for the Southern Ocean study should be published in early 1995. A tentative schedule for the entire Southern Ocean effort is shown in Table 2.

Table 5. Scientific Objectives of the Southern Ocean Program

I. Examine Animal—Sea Ice Interactions, esp. Seasonality

II. Describe Population Dynamics throughout the Full Annual Cycle including Austral Winter

III. Determine Coupling of Plankton Life Histories to Ocean Circulation Patterns

IV. Examine Potential Climate Induced Changes in Stratification and Productivity

A.4. Open Ocean and Other Initiatives

Discussions and planning for studies at open ocean sites under the aegis of U.S. GLOBEC are not as advanced as they are for the other ecosystem types. No specific U.S. GLOBEC activities are contemplated at this time. However many of the activities discussed in U.S. GLOBEC Report 9 on the Arabian Sea are being pursued under the auspices of U.S. JGOFS, NSF's Biological Oceanography, the Office of Naval Research, and the NOAA Office of Global Programs.

Evidence exists that the carrying capacity for zooplankton and higher carnivores, including salmon, in the North Pacific may be under climatic control. U.S. GLOBEC has proposed a workshop to address the themes that U.S. researchers might pursue under an international project, jointly sponsored by PICES and GLOBEC International, to investigate the carrying capacity of the North Pacific and its relation to climate.

Appendix B. U.S. GLOBEC Publications

Theory and Modeling in GLOBEC: A First Step. February 1991. 9 pp.

Initial Science Plan. February 1991. Report Number 1. 93 pp.

GLOBEC: Northwest Atlantic Program. GLOBEC Canada/U.S. Meeting on N.W. Atlantic Fisheries and Climate. February 1991. Report Number 2. 93 pp.

GLOBEC Workshop on Biotechnology Applications to Field Studies of Zooplankton. February 1991. Report Number 3. 29 pp.

GLOBEC Workshop on Acoustical Technology and the Integration of Acoustical and Optical Sampling Methods. September 1991. Report Number 4.

GLOBEC: Southern Ocean Program. GLOBEC Workshop on Southern Ocean Marine Animal Populations and Climate Change. November 1991. Report Number 5. 150 pp.

Northwest Atlantic Implementation Plan. June 1992. Report Number 6. 69 pp.

Eastern Boundary Current Program: Report on Climate Change and the California Current Ecosystem. September 1992. Report Number 7. 99 pp.

Optics Technology Workshop Report. March 1993. Report Number 8. 18 pp.

Implementation Plan and Workshop Report for U.S. GLOBEC Studies in the Arabian Sea. May 1993. Report Number 9. 105 pp.

U.S. GLOBEC Data Policy. February 1994. Report Number 10. 12 pp.

Eastern Boundary Current Program: A Science Plan for the California Current. August 1994. Report Number 11. 134 pp.

Copies of these reports are available from:

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GLOBEC International Report No. 6. 1994. Report of the first meeting of the international GLOBEC working group on Numerical Modeling. Villefranche-sur-mer, France, July 12-14, 1993. 60pp.

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U.S. Department of Commerce. 1992. Our Living Oceans: Report on the Status of U.S. Living Marine Resources, 1992. NOAA Tech. Memo. NMFS-F/SPO-2. 148 pp.

U.S. GLOBEC NEWS. 1993. A pilot study of stratification variability on Georges Bank and its effect on larval fish survival. No. 3. May 1993. 16 pp.

Appendix D. Index of Acronyms and Abbreviations

U.S. GLOBEC	U.S. Global Ocean Ecosystem Dynamics
CoOP	Coastal Ocean Processes
NOAA	National Oceanographic and Atmospheric Administration
NSF	National Science Foundation
ONR	Office of Naval Research
MMS	Minerals Management Service
CalCOFI	California Cooperative Ocean Fisheries Investigation
NMFS	National Marine Fisheries Service
ICES	International Council for the Exploration of the Seas
PICES	Pacific Marine Science Organization
OPEN	Ocean Production Enhancement Network
U.S. JGOFS	U.S. Joint Global Ocean Flux Study
ENSO	El Niño Southern Oscillation
OSSE	Observational System Simulation Experiments
GOOS	Global Ocean Observing System
EBC	Eastern Boundary Current
CCS	California Current System
SPACC	Small Pelagic Fish and Climate Change