U.S. GLOBEC

GLOBAL OCEAN ECOSYSTEMS DYNAMICS

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

Strategies for Pan-Regional Synthesis in U.S. GLOBEC

U.S. Global Ecosystems Dynamics

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Executive Summary

The goal of U.S. GLOBEC is to understand how physical processes affect the structure and dynamics of marine ecosystems and to predict the effects of climate change and variability on these systems. To meet this goal it will be necessary to effectively synthesize information derived from U.S. GLOBEC regional programs in the Northwest Atlantic/Georges Bank region, the Northeast Pacific, and the Southern Ocean in the form of quantitative models and to undertake pan-regional synthesis activities based on a comparative analysis among U.S. GLOBEC regional programs and other marine ecosystem research programs.

The framework for synthesis in U.S. GLOBEC regional programs entails the integration of information derived from individual studies within each using coupled physical-biological models. Necessary precursors to this integration include the development of intermediate synthesis products from primary data. Also needed are gap analyses in which the needs for model parameterization are evaluated in relation to data collected within the individual programs. Regional synthesis efforts now underway are critical building blocks of synthesis for the program as a whole. In this document, we review modeling approaches now being employed as synthetic tools in individual U.S. GLOBEC programs, advances in topics such as data assimilation and model skill assessment, and the prospects for fuller integration of climate forecasts and GLOBEC coupled physical-biological models.

The importance of comparative analysis in U.S. GLOBEC for pan-regional synthesis has been recognized from the inception of the program. Comparison of the dynamics of closely related taxa selected as target species in relation to specific physical processes (including stratification, mechanisms of retention and loss, upwelling and downwelling, and cross-front exchange) will be an integral component of the overall synthesis and integration effort in U.S. GLOBEC. Comparisons of closely related species within regions in relation to these physical processes will also be employed in conjunction with comparisons across system types to examine the effects of climate forcing on marine ecosystem structure and function.

The commonality of modeling approaches applied in U.S. GLOBEC regional studies provides opportunity for synthesis and comparison across systems and taxa. The convergence toward application of similar 3-D circulation models in each of the areas and the recognized importance of applying a common nested modeling strategy in each of the areas at the basin scale will facilitate model intercomparisons of key hydrodynamic forcing mechanisms. Similarly, in each of the U.S. GLOBEC study areas the same general classes of biological/ecological models have been applied including individual-based models for target taxa and simple ecosystem models such as NPZ(D) structures. The biological models for the target species employ a “middle-out” (or ‘rhomboidal’) modeling approach where focus is placed first on the taxa or trophic level of primary interest, with decreasing resolution in detail in the links up to predators and down to prey. This structure relies on providing necessary detail of the model for the target species and requires diminishing detail of neighboring trophic levels.

Facilitating synthesis activities in U.S. GLOBEC will involve:

- Adoption of calls for synthesis proposals in U.S. GLOBEC to allow for adjustment in relation to progress and perceived needs,

- Annual data and synthesis workshops for GLOBEC investigators with the goal of linking observations to models,

- Examination of all GLOBEC-funded projects in relation to requirements for modeling and synthesis to ensure full utilization,

- Assembling teams of modelers and field researchers to address requirements for model development,

- Continued development of special journal issues devoted to U.S. GLOBEC,

- Holding Special Sessions at national and international meetings devoted to U.S. GLOBEC results, and

- Holding Special Symposia devoted to U.S. GLOBEC results.

The specific products for the synthesis activities include the following:

- Special issues of journals devoted to U.S. GLOBEC. In the past, GLOBEC results have been presented as special volumes in Deep Sea Research, (Part II), Progress in Oceanography, and Oceanography.

- Multi-authored books for each region with chapters aimed at broad synthesis in identified topic areas. A book devoted to pan-regional synthesis in U.S. GLOBEC would complete the series.

- Contributions to ecosystem-based management based on GLOBEC findings and the transfer of operational monitoring and modeling capabilities to agencies involved with resource management.

To implement this strategy and to provide guidance as the synthesis effort unfolds, we propose to establish a Standing Committee for Synthesis (SCS) comprising selected members of the SSC. The Standing Committee will oversee the synthesis phase under the direction of the Chair of the SSC. Senior-level personnel supported within the U.S. GLOBEC National Office will have the responsibility of ensuring that the outreach and ecosystem-based management activities identified by the SCS are implemented. The over-riding importance of synthesis to the overall success of U.S. GLOBEC mandates a dedicated commitment to these goals.

1.0 Introduction

U.S. GLOBEC is a multidisciplinary research program designed to examine the potential impact of global climate change on ocean ecosystems. U.S. GLOBEC is a component of the U.S. GLOBAL Change Research Program. The objective of U.S. GLOBEC research is to understand and predict the effects of climate change and variability on the structure and dynamics of marine ecosystems and fishery production. Development of predictive capabilities in U.S. GLOBEC depends critically on achieving a synthesis of individual elements within each regional program and on a comparative analysis among GLOBEC programs and other marine ecosystem research programs. The goals of synthesis in U.S. GLOBEC are to:

- Undertake regional and pan-regional synthesis and comparisons among U.S. GLOBEC study locations and other programs (both national and international) to understand the impacts of climate change and variability on selected target species and marine ecosystems;

- Integrate process-oriented, observational, and retrospective studies through conceptual and mathematical models;

- Bridge the nested spatial temporal scales of these GLOBEC program elements through modeling to understand climates-scale impacts;

- Develop tools needed to predict the responses of populations and ecosystems to climate change and climate variability; and

- Contribute to management of living marine resources in an ecosystem context.

Models play a central role in U.S GLOBEC in its overarching objective of understanding long-term variability of target species identified in each of the regional studies. We adopt a broad definition to encompass validated models of all kinds – conceptual, mathematical, numerical, and statistical – but also qualitative comparative studies and direct, verified, data products.

The framework for regional syntheses in U.S. GLOBEC regional programs on Georges Bank, and in the California Current, the Coastal Gulf of Alaska, and the Southern Ocean has been established in the common research strategy applied in each. U.S. GLOBEC study sites have been selected to represent a range of system types and species potentially vulnerable to climate impacts. Regional synthesis efforts now underway are critical building blocks of synthesis for the program as a whole. The steps for synthesis in each U.S. GLOBEC study region include:

- Mapping of regional GLOBEC projects onto modeling needs for data assimilation, parameter estimation and model validation;

- Intermediate-level synthesis of data products (*e.g.*, derived or second-order estimates from primary data);

- Gap Analysis – identifying missing pieces and attempting to apply information from other programs, literature values, *etc.* where necessary; and

- Development of models, broadly defined, of the effects of climate forcing on the dynamics of target species and ecosystem characteristics within each region.

Regional synthesis will be achieved using both synthetic modeling and comparative analysis within systems. Two pathways for comparative analysis in regional synthesis are possible. We can compare changes in response variables over time (longitudinal analysis) or we can compare across system characteristics at a specified time (cross-sectional analysis; see Figure 1). An example of the former would be a comparison of abundance of a target species over a span of years encompassing different environmental conditions (*e.g.*, recruitment success of Atlantic cod on Georges Bank over a series of years in which losses due to advection from the bank during the spawning season varied). An example of the latter would be a comparison of two closely related target species with different life history characteristics within a year or season (*e.g.*, comparison of population variability of the euphausiids *Euphausia pacifica* and *Thysanoessa spinifera* in the California Current).

The overall goal of pan-regional synthesis will be addressed through comparative analyses among U.S. GLOBEC regions and with other research programs [see section 4.5]. This will build on both regional synthesis efforts and re-examination of data and model products from the regional studies (Figure 1). Strategies for developing understanding and predictive capability are explored in this document with particular emphasis on ways to build on regional synthesis efforts to achieve pan-regional understanding.

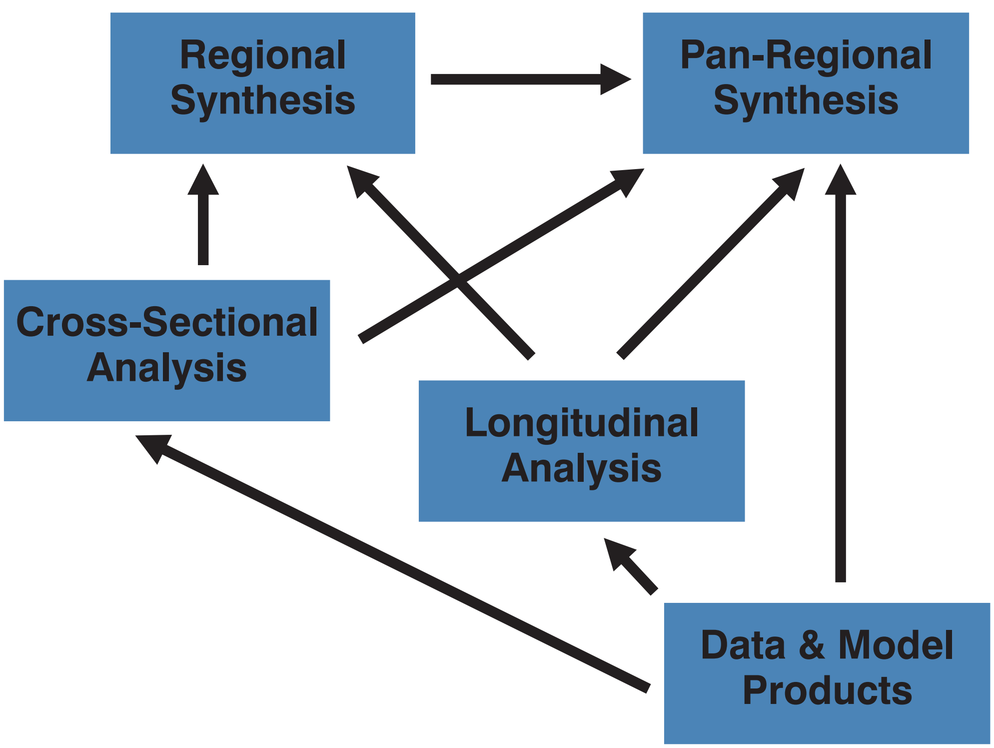

Figure 1. Options for comparative analysis within and among GLOBEC studies to achieve Regional and Pan-regional synthesis using a combination of longitudinal and cross-sectional analyses.

2.0 The U.S. GLOBEC Program

2.1 Research Strategy

From its inception, the GLOBEC research strategy has entailed an inter-related set of elements: modeling, process-oriented studies, meso-scale observations, retrospective analysis and technological innovation (Figure 2). The development of both conceptual and formal analytical models has served to frame the questions to be asked and the parameters to be measured. Models provide the principal synthetic and integrative tools for interpretation and prediction in U.S. GLOBEC. Field and laboratory process studies measure key variables required for models and are designed to provide a mechanistic understanding of critical inter-relationships in the systems under investigation. Meso-scale observation programs provide a broader spatial and temporal context for interpretation of process studies and measurements taken on finer spatial scales. Retrospective analyses provide yet a broader window in time (and in some instances, space) for the interpretation of change in the systems under investigation.

At the heart of understanding and predicting the effects of climate change on marine ecosystems is the development of research strategies that effectively bridge a broad spectrum of space-time scales relevant to individual organisms, populations, and ecological communities. At the organismal level, the relevant space-time scales can change dramatically throughout the life history. For many fish species which change in size over several orders of magnitude over the life cycle, the ambit ranges from fine-scale processes occurring over centimeters and seconds at the larval stage to thousands of kilometers and decades for adults of highly migratory species. Populations of marine organisms can occupy areas of tens of thousands of square kilometers or more over millennia

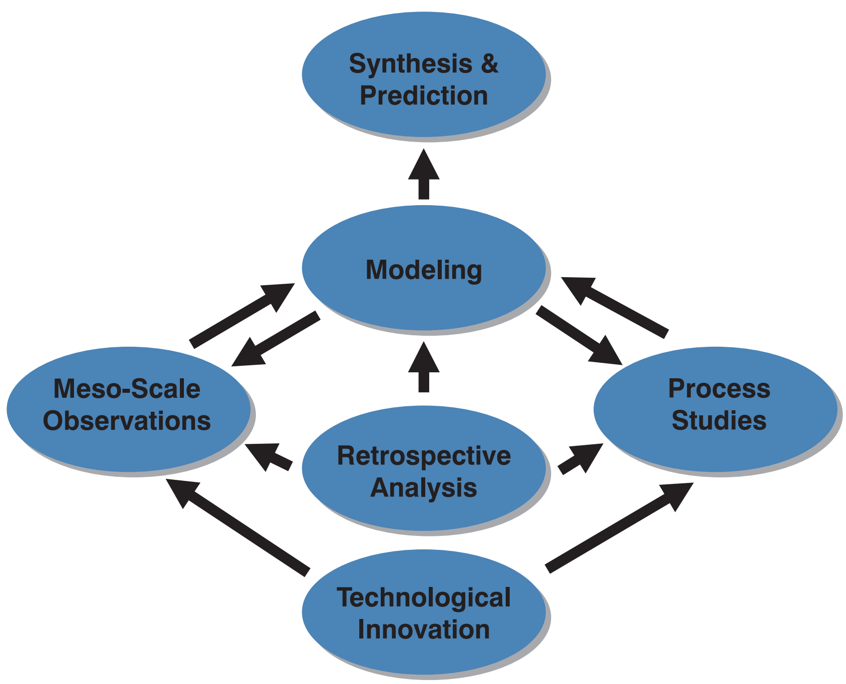

Figure 2. Key elements of the GLOBEC research strategy, culminating in synthesis

2.2 Study Areas

Consideration of the probable impacts of global climate change on ocean dynamics has guided the choice of U.S. GLOBEC study sites and processes for study (Table 1). U.S. GLOBEC study sites have also been selected based on the availability of previous studies in each region to provide both a basis for formulation of key hypotheses and a broader temporal context for interpretation of new process-oriented and observational research. Each region exhibits specific characteristics that will likely be impacted by global climate change.

2.3 Target Species

Target species in U.S. GLOBEC studies are selected for their ecological importance, their likely sensitivity to climate change, and (for some) their economic importance. In each regional study, zooplankton species are targeted for their importance in the food web (Table 1). In the case of krill in Antarctica, there also exist important fisheries for this species. In the GLOBEC studies in the Northwest Atlantic and in the Northeast Pacific, fish species have been selected for special emphasis because of their critical importance to the fisheries of these regions. In the Northwest Atlantic, cod and haddock have been mainstays of the commercial fisheries for centuries but are now depleted by over-harvesting. In the Pacific, salmon are important elements of local cultures, having supported native peoples for millennia and important commercial fisheries for over a century. Apex predators including marine mammals and sea birds have also been identified as target species in the Northeast Pacific and the Southern Ocean

3.0 Models in U.S. GLOBEC

The U.S. GLOBEC synthesis and modeling program requires a vigorous numerical modeling effort, including physical circulation models of the ocean and atmosphere, as well as coupled physical/ecosystem components of substantial complexity. All of these models, whether physical, biological or coupled, share a common issue: how to discretize the continuum of oceanic processes in such a way as to allow solution of the governing equations on a computer. Two primary approaches are available. Circulation and food web models are typically "solved" by integration of the governing equations over fixed intervals in space and time (the "grid space" and "time step", respectively). In contrast, higher trophic level response is often modeled by explicitly tracking a large, but finite, number of individual organisms, taking into account their behavior, mutual interactions and local environment. The two approaches will be recognized as Eulerian and Lagrangian in nature, respectively. In the following, we provide an overview of the central issues in the development and utilization of hydrodynamic models, biological models, the steps involved in effective coupling of these components and the challenges ahead for synthesis in U.S. GLOBEC. An overview of models currently employed in U.S. GLOBEC regional programs is provided in Table 2. We provide further description of models and analytical techniques employed in comparative analysis under Pan-Regional Synthesis (see Section 4.3 below).

3.1 Physical Models

The scales of oceanic processes of relevance to GLOBEC extend from millimeters to thousands of kilometers in space, and from seconds to millennia in time (Figure 3). This is not an inherent problem so long as we can afford to discretize our problem appropriately (*e.g.*, for an Eulerian model, with sufficiently fine grid spacing). Unfortunately, due to limitations in the speed and storage capacity of computers, ocean circulation models, and their atmospheric counterparts, are restricted to certain ranges of scales, and specialized classes of models have arisen for each. Global climate studies are focused on spatial scales from a thousand kilometers to global, and on temporal scales from a few months to many centuries. These scales encompass the dominant modes of climate variability and are explicitly resolved by current ocean climate models, as shown in Figure 3. Biological processes on these largest scales -- *e.g.*, horizontal migration -- are also in principle resolvable.

A difficulty with these coupled climate models is that the most energetic processes associated with horizontal redistribution of water properties (*e.g.*, boundary currents, mesoscale eddies, *etc.*) occur on yet finer spatial scales, typically tens to a few hundred kilometers in the ocean. Such processes are under-represented, if not absent, in today's global models, and must in principle be parameterized. An alternative is to forsake the global spatial and centennial temporal coverage afforded by the climate models, and to utilize finer-resolution, basin-to-regional-scale models capable of explicitly representing the effects of boundary currents and mesoscale eddies. By reducing horizontal resolution to approximately 5 to 10 kilometers, several groups have successfully reproduced these finer-scale processes on the basin-scale (*e.g.*, Boening and Semtner, 2001).

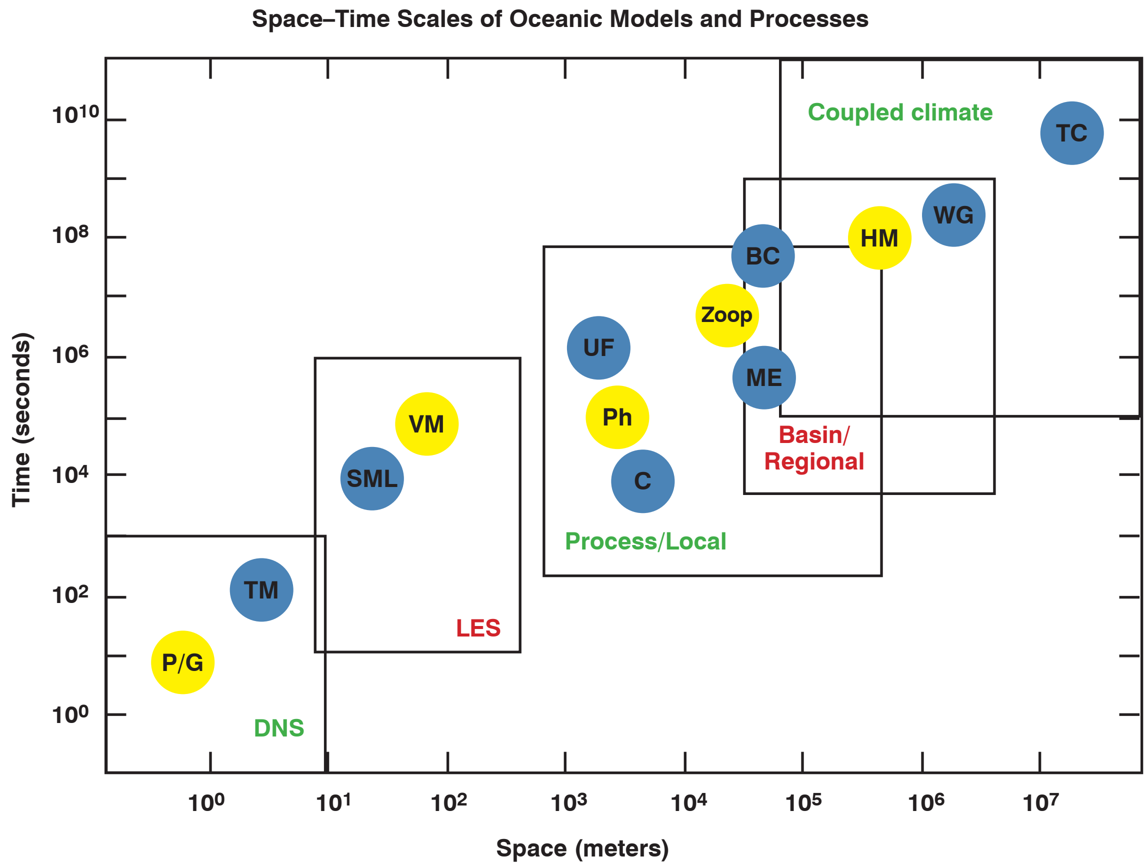

Figure 3. Space-time diagram showing some physical and biological processes of interest to the U.S. GLOBEC program. Physical processes are shown in blue, and include: turbulent mixing (TM), surface mixed layer processes (SML), upwelling fronts (UF), convection (C), boundary currents (BC), mesoscale eddies (ME), the North Atlantic Oscillation (NAO), El Niño-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). Biological processes (in yellow) are: predation/grazing (P/G), vertical migration (VM), horizontal migration (HM), and the natural scales of aggregation for phytoplankton (Ph) and zooplankton (Zoop). The rectangular boxes in green and red show the approximate space/time scales covered by five classes of ocean and/or ocean/atmosphere models: Coupled climate, Basin/regional, Process-oriented /Local, Large-eddy simulation (LES) and Direct numerical simulation (DNS). [from Mantua *et al.* 2002]

Despite this success, the class of basin-to-regional-scale ocean circulation models in its turn omits yet finer-scale processes of significance to the near-coastal, biologically active regimes of interest to GLOBEC. As examples, tidal and upwelling fronts and other internally generated mesoscale features have native scales of 1 to 10's of kilometers, and temporal scales of a few days. In addition, the natural scales of biologically induced variability of phytoplankton and zooplankton patchiness is believed to fall within this range of scales. Since basin-scale models are currently incapable of representing these processes, local models at even higher resolution are required to study them. Nor is that the end of the story. At scales of meters and below, topgraphic features, turbulence and mixing, as well as biological processes such as vertical migration and predation and grazing, become important. Specialized modeling approaches are again needed to study these processes, and parameterizations of their effects are in principle required in models with coarser resolution in space and time.

One of the great remaining challenges for the GLOBEC modeling program will therefore be to bridge the scale gap between these local GLOBEC regions and the global climate system. This will be necessary to fully assess the local impacts of larger-scale climate variability, and to allow comparative analyses among regions. Continued improvement of, and access to, enhanced computational resources will of course play a role in bridging this gap. Nonetheless, it is easy to show (*e.g.*, Willebrand and Haidvogel, 2001) that enhanced computer power alone is insufficient without parallel improvements in numerical algorithms. Many new ideas are under active study, including one- and two-way nesting of structured finite difference grids (Spall and Holland, 1991; Oey and Chen, 1992; Fox and Maskell, 1995), unstructured finite element (Lynch *et al.* 1996) and finite volume methods (Chen *et al.* 2003), block structured gridding for better coastline representation and some degree of region-specific resolution (Russell and Eiseman, 1998), two-way communication between unstructured finite element grids via the mortar element method (Levin *et al.*, 2000), horizontally adaptive meshes (Blayo and Debreu, 1999), and various generalized adaptive vertical coordinates (Song and Hou, 2006). Much progress in these areas, with consequent advances in multi-scale coupled modeling, can be expected in the next decade.

Of these methods, the first two (nested finite difference techniques, and unstructured finite volume/element methods) are the most advanced, and have figured prominently in the U.S. GLOBEC modeling strategy. Figure 4 shows a schematic diagram of one possible configuration for a multi-scale GLOBEC model based upon the nesting concept. The primary elements of the modeling system include: (1) a nested hierarchy of (global-basin-regional-local) physical circulation models for the ocean and the atmosphere (in principle, these may be of mixed algorithmic types); (2) one or more food web models of NPZ class embedded within, and evolving in response to, the physical environment predicted by the linked circulation models; (3) one or more individual-based models for the relevant GLOBEC target species (zooplankton, fish, mammals, sea birds); (4) mass balance ecosystem network models and, finally, (5) appropriate mechanisms (possibly utilizing advanced data assimilation) for comparison and/or fusion of these forward models with the available retrospective and contemporary datasets.

The challenge of developing and deploying such an integrated system is formidable; however, many of the individual pieces are already in place within the three regional GLOBEC programs. For example, nested circulation models covering basin-wide, regional and local scales have been successfully implemented on both the U.S. East and West coasts (Hermann *et al.*, 2002; Fennel *et al.*, 2006; Curchitser *et al.*, 2005). In these studies, the same numerical model – the Regional Ocean Modeling System (ROMS; Haidvogel *et al.*, 2008; Shchepetkin and McWilliams, 2004) – has been used across all scales. However, coupling across disparate algorithmic formulations is in principle possible, and would have enormous benefits, *e.g.*, the ability to formulate a multi-scale model by combining available basin-scale, regional, and local circulation models of arbitrary algorithmic type. Development of strategies for coupling of ROMS to the finite volume FVCOM model used in the U.S. GLOBEC Georges Bank synthesis effort, and to the operational HyCOM GODAE and MERCATOR North Atlantic Basin models, is underway to demonstrate the feasibility of heterogeneous multi-scale model nesting.

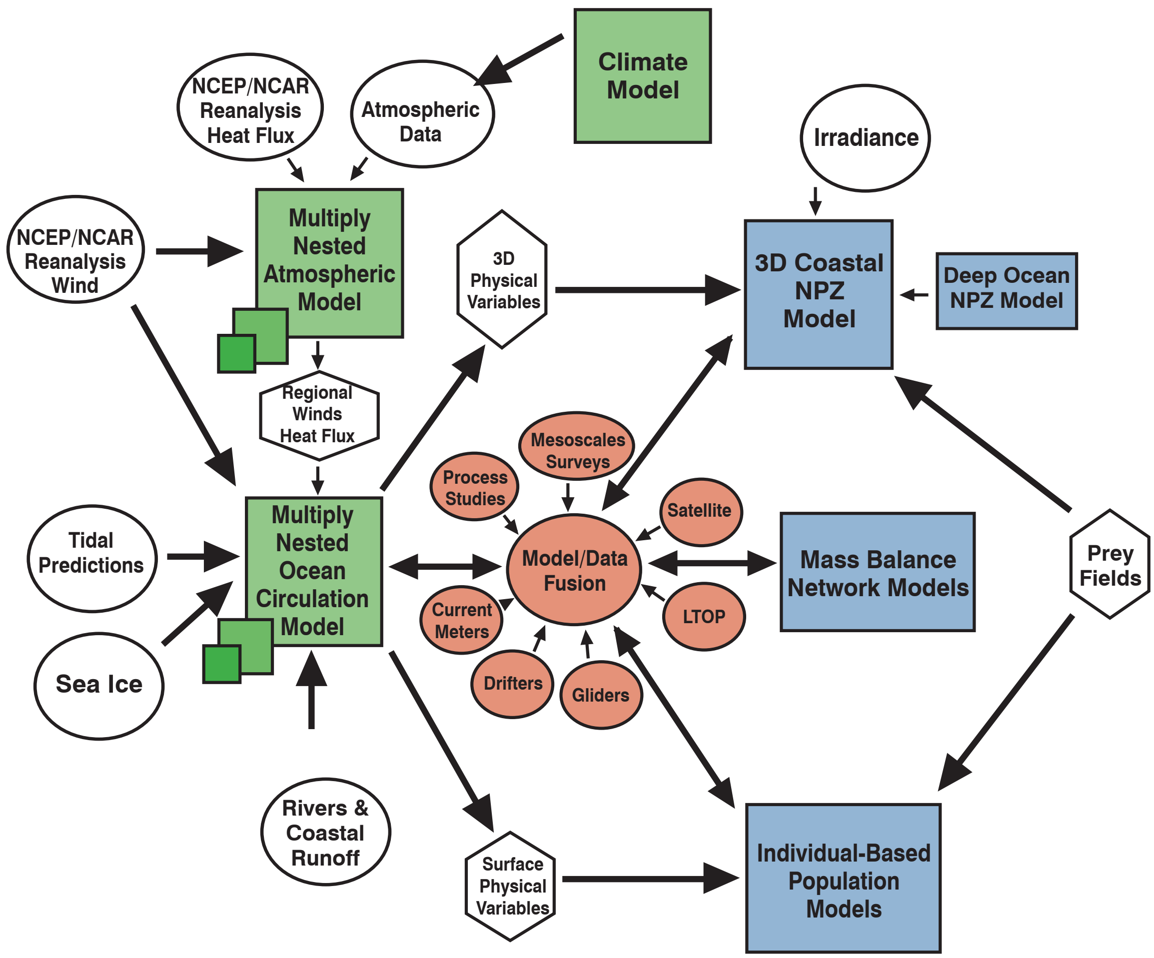

Figure 4. Schematic diagram of one possible configuration for a multi-scale GLOBEC model of the future based on the nesting concept. The primary elements of the modeling system include (1) a climate forcing model (2)a nested hierarchy of (global/basin/regional/local) physical circulation models for the ocean and atmosphere (3) one or more food web models including mass balance network models and NPZ models (4) one or more individual-based models for the relevant higher trophic level species and finally (5) appropriate mechanisms (possibly utilizing advanced data assimilation) for comparison and/or fusion of these forward models with the available retrospective and contemporary data sets (modified from Mantua *et al.* 2002).

3.2 Biological Models

GLOBEC models are used to simulate the variability in populations of fish and zooplankton, evaluate the causes of this variability, and ultimately to develop a predictive capability of climate effects. However, while there are a number of models of individual fish and zooplankton taxa, with an increasing number of them resolving 3-dimensional spatial variability, there are few examples where such models have been successfully coupled to dynamic representations of lower or upper trophic levels.   Part of the reason is that the processes in each system require detailed attention, and it is in the synthesis phase that the coupling should naturally take place.

Target species in GLOBEC modeling efforts may be defined by their dominance in the ecosystem, dominance in the diet of species of interest, economic importance, conservation concerns, or by their dominance as predators of a species of interest. Not all model formulations will be equally suited across target species.   A "middle-out" (or 'rhomboidal') modeling approach is recommended, wherein focus is placed first on the taxa or trophic level of primary interest, with decreasing resolution in detail in the links up to predators and down to prey (see DeYoung *et al.* 2004; Figure 5). This structure relies on providing necessary detail of the model for the target species and requires diminishing detail of the neighboring trophic levels. The effort in constructing such models lies in the target species and in achieving proper parameterizations of the processes and interactions with the neighboring levels. The approach should not be to develop an encompassing model, but rather, it should be recognized that:

- Each question is going to need a different model - but may be built according to some generic principles;

- There is a trade-off between number of target species and detail of representation, where often there is an inverse relationship between understandability and model complexity;

- The approach to developing GLOBEC models should be "middle-out", not "bottom-up". In other words, the recommendation is to focus first on the taxa of primary interest, and elaborate up to predators and down to prey, with decreasing resolution of detail in order to constrain the degrees of freedom in the model, rather than build extra components onto existing models.

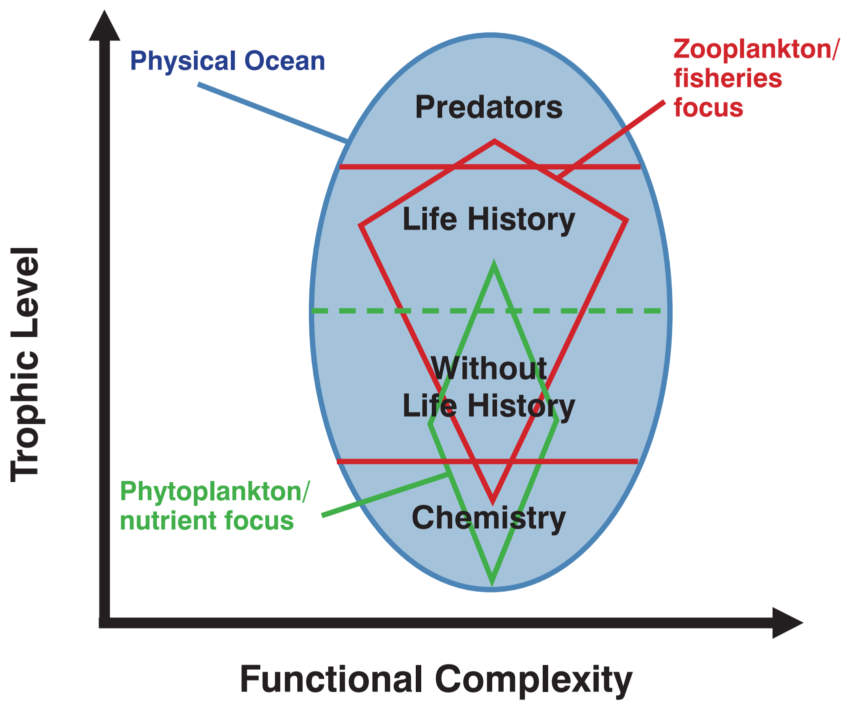

Figure 5. (from de Young *et al.* 2004). Schematic diagram illustrating the relation between trophic level, on the vertical axis, and functional complexity, on the horizontal axis, within marine ecosystem models.

The rhomboids in Figure 5 indicate the conceptual characteristics for models that have different species and differing areas of primary focus. The rhomboid is broadest, *i.e.*, has its greatest functional complexity, at the level of the target organism of the model. The line separating organisms with and without life history is dashed to indicate that this boundary is not fixed. The same organism, for example a specific species of zooplankton, could be on either side of this depending on the target species and the problem to be addressed. The magenta rhomboid applies to a model with a primary focus on zooplankton which go through a complex life history, thus requiring greater fidelity to their ontogenetic development. The green rhomboid applies to a model with a primary focus on phytoplankton and biogeochemical cycles, but which also includes zooplankton with less life history resolution. The blue oval represents the physical ocean in which the marine ecosystem models are embedded. Few models represent much of the functional complexity of predators; hence, the rhomboids only touch upon the uppermost trophic level.

There may be a number of ways of embedding detailed representations of the taxa of interest in less structurally resolved representations of the ecosystem. For example, Beaugrand *et al.* (2003) empirically link the recruitment dynamics of cod in the North Sea with aggregate measures of copepod prey composition. More formally, we could couple structured single species population models to ecosystem size spectrum models of the predator and prey assemblage in the system. Another would be to take the aggregated output of zooplankton density from an NPZ model and link to a multispecies size-structured model of managed fish species. The aim would be to reflect the ecosystem predation loading on the target species, and the resource limitations and feedbacks of the various life cycle stages of the target species, without carrying the overhead of explicitly representing all of the individual predator and prey species.

The application of these similar modeling approaches in U.S. GLOBEC regional programs affords the opportunity to compare results in the overall pan-regional synthesis effort.

3.3 Coupled Models

Taking advantage of the advent of sophisticated and robust circulation models which capture realism on relevant spatial and temporal scales, perhaps the best established use of spatially explicit coupled physical-biological models focuses on determining trajectories, or Lagrangian pathways, of planktonic stages of marine organisms in realistic flow fields. The simplest of these studies ignore biotic factors such as feeding and predation in their approach, but include imposed swimming behaviors, spawning locations, *etc.* Among the aspects successfully investigated by these studies are the space-time pathways of larval fish from spawning grounds to nursery areas (Werner *et al.* 1993), retention on submarine banks (Page *et al.* 1999), and effects of interannual variability of physical forcing on dispersal of larval fish populations (Lough *et al.* 1994). Similar approaches focusing on the downstream versus re-seeding of scallop beds on Georges Bank is discussed in Tremblay *et al.* (1994), and for the exchange between deep ocean basins and shelf regions for copepod populations described by Hannah *et al.* (1998).

Although lacking in key biological variables, the use of spatially explicit coupled physical-biological models in this simplified form has been clearly established as a necessary first step in describing the environment sensed by marine organisms. Approaches that consider feeding environment implicitly through its relation to temperature are those of Hinckley *et al.* (1996) and Heath and Gallego (1998). In Heath and Gallego (1998), temperature (resulting from a circulation model) was used as a proxy for feeding environment: prescription of the 3-D temperature field was used to determine individual growth rates of larval haddock. It was found that the model-derived spawning locations resulting in the highest larval growth rates (as the larvae are advected in the model domain) coincided with the observed preferred spawning locations.

After the determination of Lagrangian pathways, the next level of complexity commonly introduced into spatially explicit models is an imposed spatially dependent (but temporally fixed) prey field based on field observations. Using these approaches, Lagrangian trajectories that are considered favorable for retention or appropriate for transport into nursery areas are more narrowly defined to include only those trajectories where the individuals encounter favorable feeding environments resulting in appropriate growth rates. GLOBEC studies of this type include Werner *et al.* (1996), Hermann *et al.* (1996) and Lough *et al.* (2005).

3.4 Future Steps in Coupling Physics and Biology

The added complexity of more realistic prey distribution will invite advances in approaches to determine behavior. Externally imposed (and/or passive) behaviors may not make sense in view of the added detail of the feeding environment and will likely be replaced by model-derived behaviors that include components maximizing some biological characteristic, such as reproductive value (Fiksen and Giske, 1995). Dynamic programming methods allow organisms to "find" optimal habitats by balancing risks of predation, growth and advective loss.

In parallel to the application of coupled models to specific systems, theoretical studies are also underway addressing the issue of how to translate, or scale, the system from individuals into models for aggregated quantities such as densities. Pascual and Levin (1999) address the questions of when is variability at the individual level essential to population dynamics and at what spatial scales should populations be defined. In their study, they define spatial scales where certain predator-prey systems and other oscillatory ecological systems may display a dynamic regime at an intermediate scale of aggregation in which local interactions are still important. As advances in spatially explicit models continue, integration of such theoretical developments into modeling of specific (or pragmatic) studies will need to be considered.

As with the physical circulation, for which models on different space/time scales are needed to encompass the relevant phenomena, several types of biological models, of varying formulations, need to be employed to adequately incorporate specific biological processes that are known to influence distributions and/or demography. The food web models in use within GLOBEC are evolved forms of the carbon- and nitrogen-based, nutrient-phytoplankton-zooplankton (NPZ) concentration models solved in an Eulerian framework. NPZ models commonly represent all primary consumers as being of one, or at most a few, types, and similar simplifications are used for other trophic levels. Thus, these models aggregate (and thereby ignore) inter-individual and inter-specific variability that exists in real ocean ecosystems.

Many plankton species undergo functional shifts as they grow. The early life stages may be planktonic and herbivorous, while as larger adults they are closer to nekton and consume different prey. Some of the largest species, particularly at the higher trophic levels (macro-zooplankton, fish, birds, *etc.*), are capable of considerable directed movement, independent of the physical flows, and often influenced by an individual's recent experience. Often, bioenergetics of the individual organisms hold the key to understanding processes of importance to its response to climate and ecosystem changes. These and other examples illustrate biological complexity that is not easily incorporated within aggregated Eulerian NPZ models. However, individual-based models (IBMs), solved in a Lagrangian framework, are well suited to including this level of biological complexity (Batchelder *et al.* 2002; Hermann *et al.* 2001; Hinckley *et al.* 2001). In

IBMs, each individual, or a cohort of identical individuals, is modeled separately. One difficulty that arises is providing two-way connections when linking Lagrangian models of higher trophic levels with Eulerian models of physical variables and lower trophic level concentrations (potential prey of the larger organisms). Forcing Lagrangian models with Eulerian fields is simple compared to providing feedback from the Lagrangian models to the Eulerian models.

3.5 Data Assimilation

Coupled physical-biological models offer a framework for dissection of the manifold contributions to structure in population distributions. However, their utility is predicated on an ability to construct a simulation that is representative of the natural system. One technique for doing so (the "forward" problem) is to initialize a coupled model with a set of observations, integrate forward in time, and then compare with the next set of observations. A successful outcome results in minor discrepancies between observations and predictions, and the model solutions thus can be used as a basis for diagnosis of the processes controlling the observed patterns. Unfortunately, satisfactory completion of the forward problem is not always achievable, owing to limitations in the models, in the observed initial conditions and/or forcing fields, or in both. Inverse methods provide an alternative approach that is particularly useful in such cases. These techniques can be used to determine the model inputs (*e.g.* parameters, forcing functions) that minimize the misfit between observations and predictions, thereby producing an optimal solution from which the underlying dynamics can be determined. At the heart of this problem lies the topic of data assimilation, which is the systematic use of data to constrain a mathematical model (Hofmann and Friedrichs, 2001).

Data assimilation was first used in the 1960s in numerical weather forecast models, with the goal of providing short-term predictions of meteorological conditions. The use of data assimilation techniques was made feasible by the development of a world-wide atmospheric data network that could provide the needed measurements. Data assimilation has provided a methodology to use these observations to improve the forecast skill of operational models, which has led to important societal benefits. Such systems have also proven to be useful for scientific purposes, insofar as their hindcast products (so-called "re-analysis") provide realistic four-dimensional fields on which process studies can be based (*e.g.* Manobianco *et al.*, 1992; Whitaker *et al.*, 1988).

In the 1970s numerical ocean general circulation models (OGCMs) became an important tool for understanding ocean circulation processes (Hofmann and Friedrichs, 2001). Initial applications of these models focused on simulation of the large-scale structure of ocean currents. From these simulations, the limitations of the OGCMs were clear. Data assimilation was looked to as an approach for constraining these dynamical models with available data (Bennett, 1992; Wunsch, 1996). For example, data assimilation could be used to quantitatively and systematically test and improve poorly known sub-grid scale parameterizations and boundary conditions. With recent advances in data availability it is also now feasible to use data-assimilative OGCMs for global ocean state estimation, as has been done for the WOCE era (Stammer *et al.* 2002). Rapid improvements in coastal ocean models and observational infrastructure have led to realistic data-assimilative models in the coastal ocean as well (Brink and Robinson, 1998; Robinson and Brink, 1998).

Implementing data assimilation in coupled physical-biological models has been problematic because of the paucity of adequate data (Hofmann and Friedrichs, 2001). Historically, biological and chemical data were obtained almost exclusively by ship surveys, and thus were extremely limited in both space and time. However, recent advances in satellite, moored and autonomous instrumentation, as well as in the understanding of the structure and function of marine ecosystems, now makes it feasible to begin the development of data-assimilative coupled physical-biological models. As a result, the last fifteen years has seen a dramatic increase in the types of data that are input into such models, and the development of robust and varied approaches for assimilating these data (*e.g.* Ishizaka., 1990; Matear and Holloway, 1995; McGillicuddy and Bucklin, 2002; Natvik and Evensen, 2003; Moore *et al.*, 2004).

Initial results are encouraging and data assimilation approaches, such as adjoint methods, show promise for improving the capability of OGCMs (Hofmann and Friedrichs, 2001). For instance, assimilation of biogeochemical data can reduce model-data misfit by recovering optimal parameter sets using multiple types of data (Lawson *et al.* 1995; Friedrichs, 2002). Perhaps even more importantly, these data assimilation analyses can demonstrate whether or not a given model structure is consistent with a specific set of observations. When model and data are shown to be consistent, the specific mechanisms underlying observed patterns in simulated distributions can be identified. A recent example of such an approach applied to the population dynamics of *C. finmarchicus* using GLOBEC data from Georges Bank is described in Li *et al.* (2006). On the other hand, if a model is determined to be inconsistent with observations, it may be possible to isolate the specific model assumption that has been violated, and to reformulate the model in a more realistic fashion. Thus, although the assimilation of data into a model cannot necessarily overcome inappropriate model dynamics and structure, it can serve to guide model reformulation.

In the past decade, large interdisciplinary oceanographic programs (including GLOBEC) have included model prediction and forecasting as specific research objectives (Hofmann and Friedrichs, 2001). However, it is clear that much more work needs to be performed before this becomes a realistic and achievable goal. Until high-resolution biological and chemical data are available over large regions of the ocean, and until a better understanding of the dynamics of marine systems is attained, data assimilation in coupled physical-biological models will likely be used more for model improvement and parameter estimation than for operational prediction. A necessary precursor to the latter is the quantitative demonstration of forecast skill in specific applications.

3.6 Model Skill Evaluation

Simulation models coupling physics to biological processes in the ocean are the object of a large number of current research programs. Ocean physics has approached a high level of simulation sophistication, as the state space and the physical relationships within it are canonical; and modern computational technology for fluid mechanics has been advanced in scholarly communities for two generations or more. However the complexity of the biological state space presents an enormous expansion of state variables and their interaction. As a result, there is a recognizable mode of operation where either complex physics is coupled to reduced-complexity biology or complex biology is coupled to simplified physics. The upshot of this situation is enormous diversity in what is possible in ‘replicating observations’, and even more importantly, in assimilating them into simulations and creating forecast systems.

It is a feature of the oceanic research landscape that many important programs are currently facing the consequences of this diversity. The biological problems therein are of immediate human concern, and there is a sense that skillful simulations can be constructed. Yet what is meant by skill in this context is typically very different depending on the target problem. There is a need to develop the theoretical basis for the underlying problem of skill assessment in all of its relevant senses, across species and ecosystems, geographical places, and data types and availability. Generic theoretical problems need to be addressed in specific program contexts; the scholarly and practical aspects need to be developed, discussed, and shared across this diverse landscape. An example activity of this type, still in its initial phases, is described at: http://www-nml.thayer.dartmouth.edu/Publications/internal_reports/NML-06-Skill/

A scholarly basis of agreement is prerequisite to regulatory progress and public advisement. However it is a mistake to focus exclusively on the former, to the neglect of progress in the public sphere where real problems are originating and demanding attention. Exactly because of the broad diversity of phenomena covered in the rubrics of physical-biological interactions and ecosystem dynamics, scientific progress must not be allowed to become irrelevant to these practical problems. Accordingly, coupled to scholarly advancements should be a parallel effort to embed findings in regulatory practice.

4.0 Pan-regional Synthesis

Extracting the broader lessons concerning climate impacts on marine ecosystems from regional studies in the Northwest Atlantic, Northeast Pacific, and Southern Ocean will be the central challenge facing U.S. GLOBEC researchers now that field work is completed and synthesis efforts within each region are undertaken. A higher-order synthesis effort incorporating basin-scale modeling efforts and comparative analyses among U.S. GLOBEC studies and related programs is required to meet the overarching GLOBEC goal of predicting the effects of global climate change on marine ecosystems.

From its inception, the importance of comparative analysis in U.S. GLOBEC for ascertaining the effects of climate forcing has been recognized. Critical questions addressed in GLOBEC studies include "how does variability in populations of the target taxa differ under different physical processes and system types and how does climate change influence these differences?" Comparison of the dynamics of closely related taxa selected as target species in relation to specific physical processes (including stratification, mechanisms of retention and loss, upwelling and downwelling, and cross-front exchange) in a cross-sectional approach as described above will be an integral component of the overall synthesis and integration effort in U.S. GLOBEC (Table 3). Comparisons of closely related species within regions (*e.g.*, *Calanus* and *Pseudocalanus* on Georges Bank, coho and chinook salmon in the California Current, euphausiids of the genera *Euphausia* and *Thysanoessa* in the Gulf of Alaska) in relation to these physical processes will also be employed in conjunction with comparisons across system types to examine the effects of climate forcing. Comparisons of population and system states over time in relation to climate forcing in longitudinal analyses will also be employed.

As U.S. GLOBEC studies have progressed, it has become evident that factors such as top-down vs. bottom-up controls on productivity, and the importance of topographic controls on local and regional circulation patterns, provide important cross-cutting themes and foci for comparative analysis. Bottom-up controls mediated through mechanisms of nutrient exchange have been hypothesized to be critically important in the California Current System and the Coastal Gulf of Alaska, and to be related to the apparent inverse production regimes for salmon in these regions. In contrast, top-down controls by predators on the target species may be of central importance in the Southern Ocean and on Georges Bank. In the former, the relatively simple food web results in strong trophic linkages, while in the latter the direct and indirect effects of overharvesting have resulted in dramatic changes in community composition. Planktivorous fishes are currently at high levels of abundance on Georges Bank during spring and summer months; these species prey on copepods and larval fish. By adopting the rhomboidal modeling structure, a focus on the role of adjacent trophic levels on the dynamics of the target species can be easily accommodated to address issues such as top-down or bottom-up controls.

Retentive circulation features associated with the local topography have emerged as key features in each of the U.S. GLOBEC study sites. Comparisons of levels of population variability in retentive vs. advective systems and subsystems will provide important insights into the population dynamics of the target species.

It has become increasingly clear that tracking water mass dynamics and the implications for ecosystem productivity and other characteristics is critical in each of the GLOBEC study sites. For example, the occurrence of Labrador-Subarctic Slope Water in the Gulf of Maine and on Georges Bank has been linked to the North Atlantic Oscillation and these intrusions are related to changes in productivity states. Similar considerations hold for changes in water mass characteristics and ecosystem dynamics in the California Current, the Gulf of Alaska, and the Southern Ocean in relation to forcing due to (*e.g.*) ENSO events.

Consideration of the effects of climate forcing on the major system types represented in U.S. GLOBEC will require comparisons not only among the regional U.S. studies but comparisons and contrasts with results from related national and international programs. The worldwide GLOBEC research effort affords critical opportunities for comparative analyses and for consideration of basin-scale processes. In particular, comparisons with studies of calanoid copepods and gadoids on bank and shelf systems in the North Atlantic and copepods, euphausiids, and salmonids in the North Pacific will be critical

4.1 Variables for Comparison

Comparisons among U.S. GLOBEC study sites (and with other large-scale programs) can be made using a potentially large number of response variables (see Appendix Tables II-III) and methods of analysis (see Section 4.2 below). Here we provide some potential indicators that may prove useful in comparative analysis among GLOBEC regions. This list is intended to be representative but not all-inclusive. We will often be particularly interested in examining the functional relationships among variables within regions (*e.g.*, environmental 'drivers' and biological responses) and comparing these relationships across regions.

The measurement methods and data collected in different GLOBEC study sites have, necessarily, been tailored to the specific field locations and guiding hypotheses relevant to each region. While some similarity may be found among measurement methods, there are also differences. Such differences, in addition to the important measurement and sampling details related to specific acoustic technologies, net meshes, experimentally determined rate constants, *etc.*, require that care be taken in the formulation of comparisons across ecosystems. This will necessitate in many cases the development and application of appropriate conversion factors either from information in the literature or from new programs.

Even within a single ecosystem study, longer time series sometimes must contend with changes in measurement methods as technology evolves. Great care must be applied in the calibration and intercomparison of methods if robust analyses and interpretations of temporal changes in the properties of marine ecosystems are to result. To a considerable extent, physical measurements can be calibrated against absolute standards, which facilitate comparisons among study sites. Absolute reference standards do not exist for many biological measurements (*e.g.*, acoustic estimates of biomass, experimental determination of specific growth rate, or measures of instantaneous mortality rates), which therefore requires that researchers be attentive to meta-data and experimental details before beginning cross-system comparisons. We strongly encourage researchers interested in comparative analyses to discuss any data set of interest with the research groups responsible for generating those data and to invite those scientists' comments before embarking on their studies. Today's ease of access to electronically available data should not come at the expense of critical appraisal.

Some of the **physical characteristics** of the ocean environment to consider for comparative studies might include:

- Residence time of the fluid in relation to the generation time of the associated animal populations,
- Presence and persistence of mesoscale circulation features,
- Relative importance of cross-shore vs. alongshore transport,
- Extent and intensity of vertical stratification,
- Mixed layer depth and intensity of vertical mixing,
- Turbulent kinetic energy dissipation rates,
- Presence of horizontal density fronts and the extent of cross-frontal exchange,
- Rates of upwelling/downwelling,
- Volume and mass transport,
- Wave spectra,
- Atmospheric forcing, and
- Optical characteristics of the water column;

  as well as climate-scale properties of interest such as:
- Indices of atmospheric circulation (PDO, NAO, SOI, NOI, *etc.*)
- Heat budgets

Some of the **biological response variables** that might be appropriate for comparison include:

4.1.1 Population dynamics characteristics

- Egg production rate and instantaneous birth rates
- Instantaneous mortality rates and stage-specific survivorship curves
- Somatic growth rates
- Condition factors (depot lipids, RNA/DNA ratios, *etc.*)
- Molting/development rates of zooplankton
- Grazing rates and particle selection characteristics
- Phenology, including timing of juvenile/adult dormancy and production of resting eggs
- Reproductive characteristics, including egg brooding vs. broadcast spawning
- Pathway of larval development (*e.g.*, for euphausiid species having flexible life history pathways)
- Level of genetic structuring of subpopulations
- Spatial variation in the above characteristics

4.1.2 Abundance & biomass measures

- Abundance
- Population stage structure and size structure
- Horizontal and vertical distribution, including ontogenetic and diel vertical migration
- Biomass, by taxon and by size spectrum
- Acoustic proxies of biomass, *e.g.*, as volume backscattering
- Microzooplankton abundance and composition

4.1.3 Integrative measures

- Phytoplankton biomass and floristics
- Secondary production rates, by species and size classes
- Production per unit sea surface area at different trophic levels
- Patchiness of organisms
- Microzooplankton grazing by dilution experiments
- Stable isotope assessment of trophic levels
- Predation pressure by different predator guilds (carnivorous zooplankton, zooplanktivorous fish, birds, and mammals)
- Definition of strong /weak predator-prey linkages
- Trophic cascade effect
- Regime shifts, as defined by both biological and physical characteristics

In making comparisons with respect to these characteristics, the time- and space-dependence of these properties are of the utmost importance (see below).

Note that when a variable such as 'growth rate' is mentioned, the most appropriate way to make comparisons across systems will be to compare the functional dependence of that property on other, independent, variables such as temperature, food concentration, magnitude of water column stratification, *etc.* The functional form of such relationships is likely to best differentiate ecosystems, rather than the absolute values of the measurements themselves.

In addition to the variables noted above, in those instances where long-term data sets have permitted retrospective analyses to be performed, there may be additional characteristics of pelagic ecosystems available for comparison. These might include historical oscillations of pelagic populations in relation to climate forcing and changes in marine populations before and after the industrial era.

4.2 Mean fields and their variability

Some broad comparisons among different ecosystem types may be based successfully on the mean fields. For example, the average residence time of fluid and non-motile plankton on Georges Bank might profitably be compared with the average residence time in the California Current upwelling zone, the coastal Gulf of Alaska downwelling environment, and Marguerite

Bay, Antarctica in cross-sectional analyses. Similarly, the average per capita growth rate for different zooplankton taxa in these respective study sites may be a useful basis for comparison. However, since most biological response functions are nonlinear, time/space averages of these variables will frequently miss the important 'event' scale phenomena that can be key determinants of successful (or unsuccessful) population growth. For example, feeding success may be much more closely linked to bursts of turbulent mixing or to encounters with microscale prey layers than to the mean properties in the environment. Statistical techniques that are appropriate to nonlinear phenomena are therefore of critical importance.

Characterization of the variance spectrum of some properties can be done using spectral techniques. However, the assumptions of and data requirements for spectral analysis are not always met and alternatives are often required. For mapping and characterization of spatial fields, an array of spatial statistics is currently available, which should facilitate comparison within and between ecosystems.

We reiterate that in cross-system comparisons, the significance of short-duration or spatially restricted phenomena, or members of the population outside the norm, should not be underestimated. As often stated in individual-based modeling, the average individual is dead. It is often the tails of the frequency distribution that have particular ecological significance.

4.3 Analytical Methods for Comparative Studies

Comparative analyses in the oceanographic literature are usually concerned with comparisons of the magnitude or variability of state variables of interest, or physical or biological processes, over both space and time. Such analyses serve two primary purposes: they can be used to examine large-scale patterns in coherence (or lack thereof) of processes of interest, and (b) results of the analyses can be used to determine critical gaps in knowledge and therefore identify and prioritize the questions that need to be addressed and the experiments that therefore need to be designed and conducted.

Prior to detailing the analytical methods to be used for comparative analysis, it is necessary to structure the questions that are to be addressed. Questions associated with comparisons within regions might include:

- What is the primary cause of variations in species abundances: environmental forcing or trophic interactions?

- Does the primary cause vary among species and/or trophic levels?

- Rather than trying to determine the "primary cause" of variation, what are the relative effects (magnitudes) of all relevant factors, and can these be combined into some sort of weighted explanatory function?

Questions associated with comparisons across system types might include:

- Which systems are the most variable, and why?

- Which systems are the most diverse, and why?

- Which systems are the most productive, and why?

Both forms of questions can be specified even more fully by linking them to specific environmental factors or biological species or other relevant variables. Questions associated with comparisons across taxa will probably focus on the major taxonomic groups in common in one or more of the systems studied; *i.e.* copepods, euphausiids and salmon.

Once the questions to be asked and the validity of the comparisons are decided, there are many methodologies that can be employed. These include (more or less in order of sophistication):

- conceptual models;
- simple correlations;
- various types of paired comparisons, including both parametric and non-parametric techniques;
- other bivariate statistics;
- time series analysis, incorporating lags and transfer functions as needed;
- multivariate analyses such as principal components analysis, discriminant analysis, and other types of pattern analysis;
- meta-analysis; and
- mathematical models including both descriptive and predictive models; biological, physical, and coupled bio-physical models; ranging in scope from single-species or single physical phenomenon to integrated "ecosystem" models.

4.3.1 Conceptual models

Conceptual models can be helpful for organizing collective wisdom (global professional judgement) and generating hypotheses to test and experimental designs in situations where there is little known about a system. Although this may be a useful tool during the sampling and experimental design phases of GLOBEC programs, it is less likely to be useful in the synthesis and comparative analysis phase, which revolves around extensive datasets. Nevertheless, simple box and arrow diagrams showing linkages in systems selected for comparative analysis may be useful for summarizing the type and scale of data available and for focusing attention on the similarities and differences between the systems which, in turn, will delineate the types of questions that can be addressed.

4.3.2. Simple correlations and other types of paired comparisons

Simple correlations and other types of paired comparisons have historically been the most common methods used for comparative analysis but these and other simple statistical procedures suffer from the problem that data are almost always collected from multivariate systems and, as such, interactions between variables are affected by multiple confounding factors. In addition, time series of variables are often autocorrelated and need to be corrected for the time series bias prior to calculating correlations. Correction for time series bias can often render an apparent correlation between two time series non-significant. In addition, correlation analysis is notorious for ultimately breaking down; *i.e.* significant correlations make it into the published literature but often fail to hold up afterwards. Most importantly, it must be recognized that correlation does not imply causality. Correlational studies can be used to frame hypotheses but are no substitute for mechanistic understanding.

4.3.3 Time Series Analyses

In order to fully understand changes observed during the course of individual GLOBEC studies, these must be put into the context of much longer time series, and possibly combined with other relevant time series data such as long-term trends in biomass and fish landings. This is because all GLOBEC projects to date have been of finite, and relatively short, duration. In fact, there is a need for further research into techniques for merging (*i.e.*, intercalibrating) different time series containing similar types of data. An example of two series that should be intercalibrated is the Georges Bank GLOBEC data which covers the period, 1993-99, and the much longer time series of MARMAP data which runs from 1977 to the present. Standard time series analysis techniques could be applied to such intercalibrated time series to examine patterns of variability and trends in the time series. It may also be possible to use the more detailed data collected during the period of GLOBEC process studies to explain or to develop testable hypotheses about the fluctuation during that part of the joint time series.

Weaving of GLOBEC data into time series of other data of a similar type collected in the same general area over a longer period of years will be a challenging task. However, if this can be accomplished for two or more GLOBEC areas, much greater insights to addressing the over-arching GLOBEC question: “What are the most important determinants of variability in marine ecosystems?” could be obtained by examining the relationships between time series from the different geographic areas (provided, of course, that it is possible to construct comparable series; *i.e.*, series on the same state variables, or series concerned with similar physical or biological processes, over a similar time period). Relationships between the time series can then be examined using cross-correlations or cross-spectral analysis. One important reason for wanting to know whether there are cross-correlations between time series in different areas is to determine whether there are large-scale atmospheric forcing processes affecting the dynamics of widely spaced marine ecosystems.

It may be particularly insightful to address questions such as, “Is the extent of atmospheric forcing greater in the U.S. Pacific or the U.S. Atlantic?”; and “is the U.S. Pacific more prone to stanzas and time shifts of decadal magnitude?”. The basis for such questions is (a) scientists appear more likely to invoke “(decadal) regime shifts” as an explanatory variable for changes in biological communities on the U.S. Pacific coast than on the U.S. Atlantic coast, and (b) indices of atmospheric forcing in the Pacific (*e.g.* the Pacific Decadal Oscillation) appear to have more pronounced stanzas and timeshifts than do those for the Atlantic (*e.g.* the North Atlantic Oscillation). More specifically, it would be interesting to compare the magnitude of the variation of similar species groups between the two coasts (*e.g.*, calanoid copepods).

4.3.4 Multivariate pattern analysis

Although simple univariate and bivariate statistics can sometimes provide useful insights, or generate new hypotheses to be presented or tested, multivariate approaches are essential to fully comprehend the complex interactions between the multiple variables that may affect the processes or species of interest. Multivariate approaches are probably needed to answer the "why" parts of questions such as, "which systems are the most variable, and why?" and "which systems are the most productive and why?". Multivariate classification systems could be used to group systems with different levels of variability (or productivity) on the basis of factors that influence that variability (or productivity). For example, Link *et al.* (2002) and Choi *et al.* (2005) employ multivariate representations of natural and anthropogenic forcing factors on marine ecosystem structure and function in Northwest Atlantic systems. Many factors that potentially may affect the variability or productivity of selected components of marine ecosystems have been measured in GLOBEC programs.

Again, it will be necessary to consider systems other than U.S. GLOBEC studies in order to conduct a meaningful comparative analysis of the multitude of variables that influence system state and system dynamics.

4.3.5 Meta-Analysis

Meta-analysis is literally the analysis of analyses. It is a research synthesis that uses statistical procedures to select and combine results from previous studies in order to glean inferences on the overall important of phenomena of interest. There are three basic approaches to meta-analysis:

- "Vote counting" in which the number of significant results is compared to the number of non-significant results;

- Construction of an aggregated powerful test of a null hypothesis; and

- Investigation of patterns in the magnitude of the effect from each study.

"Vote counting" is the least powerful of the three approaches, in that it considers individual studies to either support or reject the hypothesis that the phenomenon of interest is globally important, while ignoring several complexities that may profoundly influence the conclusions. First, it ignores differences between studies in the statistical basis for tests of significance. For example, some studies may have much larger sample sizes than others, or some studies may have been conducted under controlled experimental conditions while others were potentially affected by multiple extraneous factors. Second, it ignores the magnitude of the effect in those cases where an effect is significant. Perhaps it may happen that an effect was significant in only 10% of studies, but in all or most of those cases, the effect was overwhelming. This would make it difficult to reach an unambiguous conclusion about the overall importance of the effect. Third, the sample of studies may be biased due to the fact that non-significant results are less likely to be published.

Aggregated tests combine information from individual studies in a single test of the null hypothesis. This approach includes the confidence profile method (*e.g.* Eddy *et al.* 1992) and factorial meta-analysis (Gurevitch and Hedges. 1999). Briefly, the confidence profile method is a technique for deriving maximum likelihood estimates and covariances (in non-Bayesian applications), or joint posterior probability distributions (in Bayesian applications) for parameters of interest. Both types of applications also incorporate methods for dealing with bias. Factorial meta-analysis is analogous to factorial ANOVA (Gurevitch and Hedges. 1999). Essentially, it enables quantification of the relative magnitudes of co-occurring effects and their interactions with one another. This is an important avenue to develop further because by far the majority of meta-analysis studies to date have tested for single effects in isolation from the multitude of confounding effects that may often exist.

The third category of approaches to meta-analysis also includes comparisons of the properties of time series of comparable data. In this case, evidence for general patterns is examined. For example, the null hypothesis that population variability is not affected by retentive characteristics might be tested by regressing the coefficient of variation of population size against an index of retention for different systems. This general strategy underlies much of the current approaches and interest in the emerging field of Macroecology (*e.g.* Brown 1992).

4.4 Comparison of Model Outputs

Several main themes emerge from the review of GLOBEC modeling approaches in Section 3. The commonality of modeling approaches applied in U.S. GLOBEC provides opportunity for synthesis and comparison across systems and taxa (see Table 3). The emerging convergence toward application of similar 3-D circulation models in each of the areas and the recognized importance of applying a common nested modeling strategy in each of the areas at the basin scale with common atmospheric and oceanic forcing will facilitate model intercomparisons of key hydrodynamic forcing mechanisms. Similarly, in each of the U.S. GLOBEC study regions, the same general classes of biological/ecological models have been applied including individual-based models for target taxa and simple ecosystem models such as NPZ(D) formulations. Models currently employed in some regions could be applied to other GLOBEC sites with profit. For example, application of size spectrum models now used in the California Current component of the Northeast Pacific Program could be made in the other locations. The application of an ecosystem network model as part of the Georges Bank synthesis phase offers a general framework for application in the other regions. It offers the opportunity of placing GLOBEC studies within the broader context of full ecosystem processes while providing another common basis for intercomparison among regions.

4.5 Comparisons with Other Programs

Opportunities exist for intercomparison between U.S. GLOBEC results and those of other national and international research programs concentrating on the role of environmental forcing on the dynamics of selected marine taxa. These programs include:

- GLOBEC Canada,
- Northern Cod Recovery Program,
- ICES Cod and Climate Change (CCC) Program,
- TransAtlantic Study of *Calanus* (TASC),
- Exxon Valdez Oil Spill (EVOS) Program,
- PICES Climate Change & Carrying Capacity (CCCC),
- Ocean Carrying Capacity (OCC) program,
- Commission for Conservation of Antarctic Marine Living Resources (CCAMLR),
- Southern Ocean GLOBEC Programs, and
- Small Pelagic Fish and Climate Change.

Comparison between the dynamics of cod and haddock populations on Georges Bank can be made with other gadoids (notably other cod populations) derived from GLOBEC Canada conducted on Western and Sable Banks, the Northern Cod recovery program off Newfoundland, and the ICES Cod and Climate program conducted on cod stocks throughout the North Atlantic. The potential for intercomparison with other gadoid stocks in the Pacific exists through the PICES Climate Change and Carrying Capacity Program. The dynamics of calanoid copepod populations can be made with results obtained during GLOBEC Canada and TASC. Opportunities for comparison of the dynamics of salmon stocks exist with the EVOS, CCCC, and OCC programs. Finally, information collected on krill dynamics conducted under CCAMLR provides an important point of comparison with Southern Ocean GLOBEC studies.

International GLOBEC programs in the Southern Ocean conducted by other nations both complement the U.S. effort in austral winter and provide another source of important comparisons.

5.0 Measuring Program Performance

Large transdiciplinary research programs present special challenges in the development of appropriate metrics with which to measure success. The set of proposed guidelines in Thinking Strategically: The Appropriate Use of Metrics for the Climate Change Science Program (NAS 2005; available at http://www.nap.edu/catalog/11292.html) is directly relevant to the U.S. GLOBEC program. The major theme areas identified by the Committee on Metrics for Global Change Research (NAS 2005 Appendix B) are consonant with the objectives of U.S. GLOBEC:

1. improve data sets in space and time (*e.g.*, create maps, databases, and data products; densify data networks);

2. improve estimates of physical quantities (*e.g.*, through improvement of a measurement);

3. improve understanding of processes;

4. improve representation of processes (*e.g.*, through modeling);

5. improve assessment of uncertainty, predictability, or predictive capabilities;

6. improve synthesis and assessment to inform;

7. improve assessment and management of risk; and

8. improve decision support for adaptive management and policy making.

The synthesis effort in U.S. GLOBEC should both evaluate the degree to which the objectives relating to theme areas 1-5 have been achieved and should take theme areas 6-8 as guiding principles for translating research results to an operational agenda.

The Committee on Metrics for Global Change Research (CMGCR) identified five major classes of measures including Performance, Input, Output, Outcome, and Impact Metrics. Issues related to Performance and Input metrics largely relate to program planning, organization, and structure which were confronted early in GLOBEC program development. Issues related to Ouput, Outcome, and Impact metrics are directly relevant to framing GLOBEC synthesis activities and in guiding and evaluating the transition to operational programs.

The CMGCR specified five elements related to Output metrics derived from a research program:

1. The program produces peer-reviewed and broadly accessible results, such as
   (a) data and information,
   (b) quantification of important phenomena or processes,
   (c) new and applicable measurement techniques,
   (d) scenarios and decision support tools, and

(e) well-described and demonstrated relationships aimed at improving understanding of processes or enabling forecasting and prediction.

2. An adequate community and/or infrastructure to support the program has been developed.

3. Appropriate stakeholders judge these results to be sufficient to address scientific questions and/or to inform management and policy decisions.

4. Synthesis and assessment products are created that incorporate these new developments.

5. Research results are communicated to an appropriate range of stakeholders.

In the course of GLOBEC program development, Elements 1 and 2 have been largely met. Aspects of community development for synthesis (Element 2) are now underway. Elements 3-5 are integral to work currently underway in GLOBEC synthesis with element four comprising the central focus of current activities with elements 3 and 5 to follow completion of the synthesis activities.

Any evaluation of the scientific success of U.S. GLOBEC will entail consideration of the proposed CMGCR Outcome Metrics (measures of results that stem from use of the outputs and influence stakeholders outside the program):

1. The research has engendered significant new avenues of discovery.

2. The program has led to the identification of uncertainties, increased understanding of uncertainties, or reduced uncertainties that support decision making or facilitate the advance of other areas of science.

3. The program has yielded improved understanding, such as (a) more consistent and reliable predictions or forecasts, (b) increased confidence in our ability to simulate and predict climate change and variability, and (c) broadly accepted conclusions about key issues or relationships.

4. Research results have been transitioned to operational use.

5. Institutions and human capacity have been created that can better address a range of related problems and issues.

6. The measurements, analysis, and results are being used (a) to answer the high-priority climate questions that motivated them, (b) to address objectives outside the program plan, or (c) to support beneficial applications and decision making, such as forecasting, cost-benefit analysis, or improved assessment and management of risk.

Elements 1 and 2 of this component are now underway in U.S. GLOBEC; elements 3-6 should again be viewed as guides to action as the synthesis effort proceeds.

Finally, the societal relevance of the U.S. GLOBEC program will ultimately be judged by the CMGCR Impact Metrics (measures of the long-term societal, economic, or environmental consequences of an outcome):

1. The results of the program have informed policy and improved decision making.

2. The program has benefited society in terms of enhancing economic vitality, promoting environmental stewardship, protecting life and property, and reducing vulnerability to the impacts of climate change.

3. Public understanding of climate issues has increased.

The GLOBEC synthesis effort should be constructed to allow for an evaluation of these different classes of performance metrics.

6.0 Contributions to Ecosystem-Based Management

The focal point for societal relevance in U.S. GLOBEC research rests in its importance to the development of strategies for Ecosystem-Based Management. An important motivation for the U.S. GLOBEC program from its inception has been to understand how fishery productivity may be altered by climate change and variability. Fishing accounts for 40 billion dollars per annum in the U.S. economy (National Research Council 1998) and the social and economic impacts of changes in the productivity of fish stocks in response to climate change are potentially large. The factors affecting the productivity of marine resources and ecosystem structure must be directly accounted for in any fishery management strategy. Levels of sustainable yield and optimal levels of exploitation are both directly tied to the state of the environment and its effects on productivity of marine populations. The effects of exploitation and environmental change can be synergistic. In particular, environmental changes that result in an overall reduction in the productivity of a marine resource can result in the decline or collapse of a population under levels of exploitation that are sustainable under more favorable environmental conditions. Persistent shifts in productivity levels on longer time scales in particular must be taken into consideration in the development of management approaches. The multidecadal shifts in productivity in the Pacific provide an important indication of the types of changes that can occur and their effects on fishery yields.

In general, the yield from a fishery will be highest at some intermediate level of fishing pressure for populations governed by some form of compensatory response. Environmental conditions will affect both population levels and the resulting yields. If persistent shifts in environmental conditions occur on decadal time scales, we can envision a family of production curves. If the changes in production characteristics change in a way that is independent of population density, relationships such as those depicted in Figure 6 will hold. Notice that not only is the expected yield reduced under less favorable environmental conditions, the level of fishing pressure that can be sustained by the population is lower. The peak of the lower curve occurs at a lower level of fishing pressure and the population will collapse at fishing intensities that are sustainable under more favorable environmental conditions. It is clear that we must consider concepts such as maximum sustainable yield as being directly linked to prevailing environmental conditions.

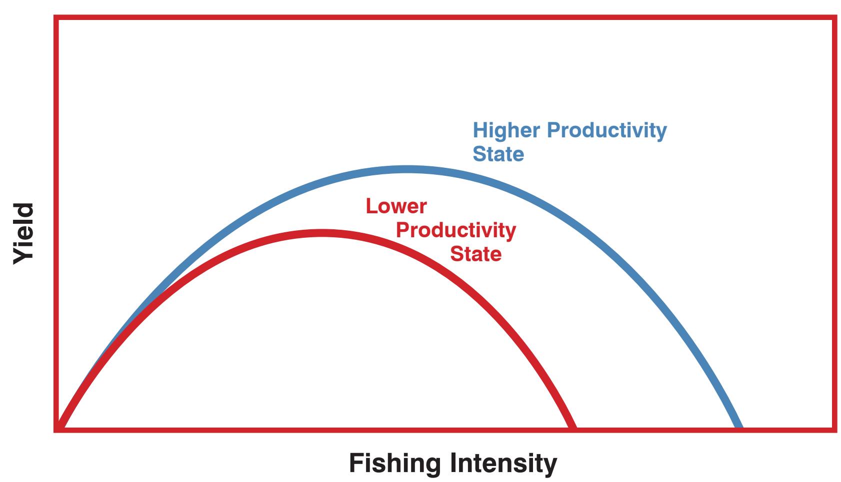

Figure 6. Shift in fishery production domains under two environmental regimes. A shift to a lower productivity state lowers the expected yield and the level of fishing resulting in maximum yield. Levels of fishing sustainable under the higher productivity regime are not necessarily sustainable under the lower level.

Ecosystem-Based Management encompasses a much broader set of considerations, however, than fishery-related objectives. Climate-related changes in productivity affecting lower trophic levels can have direct effects on trophodynamic pathways affecting a broad spectrum of marine organisms, including threatened and endangered species. For example, climate-induced changes in copepod abundance have been linked to calving success in the critically endangered Northern Right Whale (Kenney *et al.* 2001.). GLOBEC research is directly relevant to management concerns for protected resource species.

The call for ecosystem-based approaches to fishery management includes consideration of climate forcing on the dynamics of exploited marine populations. The research conducted under U.S. GLOBEC is directly relevant to these considerations. GLOBEC results can be transferred to managers through several mechanisms. The first and most direct involves the role of NOAA scientists in GLOBEC research and the provision of results relevant to management. As the synthesis phase of GLOBEC proceeds, results directly relevant to management will become available. GLOBEC researchers can identify pathways for the incorporation of climate considerations in ecosystem-based management. In particular, documentation of the role of climate change on the productivity characteristics of exploited marine ecosystems will permit an analysis of the implications of bottom-up forcing in these systems. Clear evidence of low-frequency environmental forcing in marine systems studied by U.S. GLOBEC will provide important insights into appropriate adjustments to management targets in these systems. Recently, the U.S. Oceans Commission report called for the establishment of Ecosystem Councils to facilitate the development of integrated ocean management policies. Should such councils be formed, U.S. GLOBEC should explore avenues for the transmission of GLOBEC results to the Commission.

7.0 Facilitating Synthesis

The preceding sections outline the issues involved in overall synthesis of the U.S. GLOBEC program with a focus on analytical issues. Possible pathways to regional and pan-regional synthesis are described and approaches defined. The mechanics of facilitating synthesis activities in U.S. GLOBEC however involve an additional set of considerations. To meet this goal, we suggest the following:

- Adoption of calls for synthesis in U.S. GLOBEC to allow for adjustment in relation to progress and perceived needs,

- Annual data and synthesis workshops for GLOBEC investigators with goal of linking observations to models,

- Examination of all GLOBEC-funded projects in relation to requirements for modeling and synthesis to ensure full utilization,

- Assembling teams of modelers and field researchers to address requirements for model development,

- Continued development of special journal issues devoted to U.S. GLOBEC,

- Continued convening of Special Sessions at national and international meetings devoted to U.S. GLOBEC results, and

- Organization of Special Symposia devoted to U.S. GLOBEC results.

A proposed timeline for many of these activities is provided in Figure 7. The specific products for the synthesis activities include the following:

- Special issues of journals devoted to U.S. GLOBEC. In the past, GLOBEC results have been presented as special volumes in Deep Sea Research, (Part II), Progress in Oceanography, and Oceanography.

- Multiauthored books for each region with chapters aimed at broad synthesis in identified topic areas. A book devoted to pan-regional synthesis in U.S. GLOBEC would complete the series.

- Contributions to the development of ecosystem-based management based on GLOBEC findings.

To implement this strategy and to provide guidance as the synthesis effort unfolds, we propose to establish a Standing Committee for Synthesis (SCS) comprising selected members of the SSC. The Standing Committee will oversee the synthesis phase under the direction of the Chair of the SSC. Senior-level personnel supported within the U.S. GLOBEC National Office will have the responsibility of ensuring that the outreach and ecosystem-based management activities identified by the SCS are implemented.. The over-riding importance of synthesis to the overall success of U.S. GLOBEC mandates a dedicated commitment to these goals.

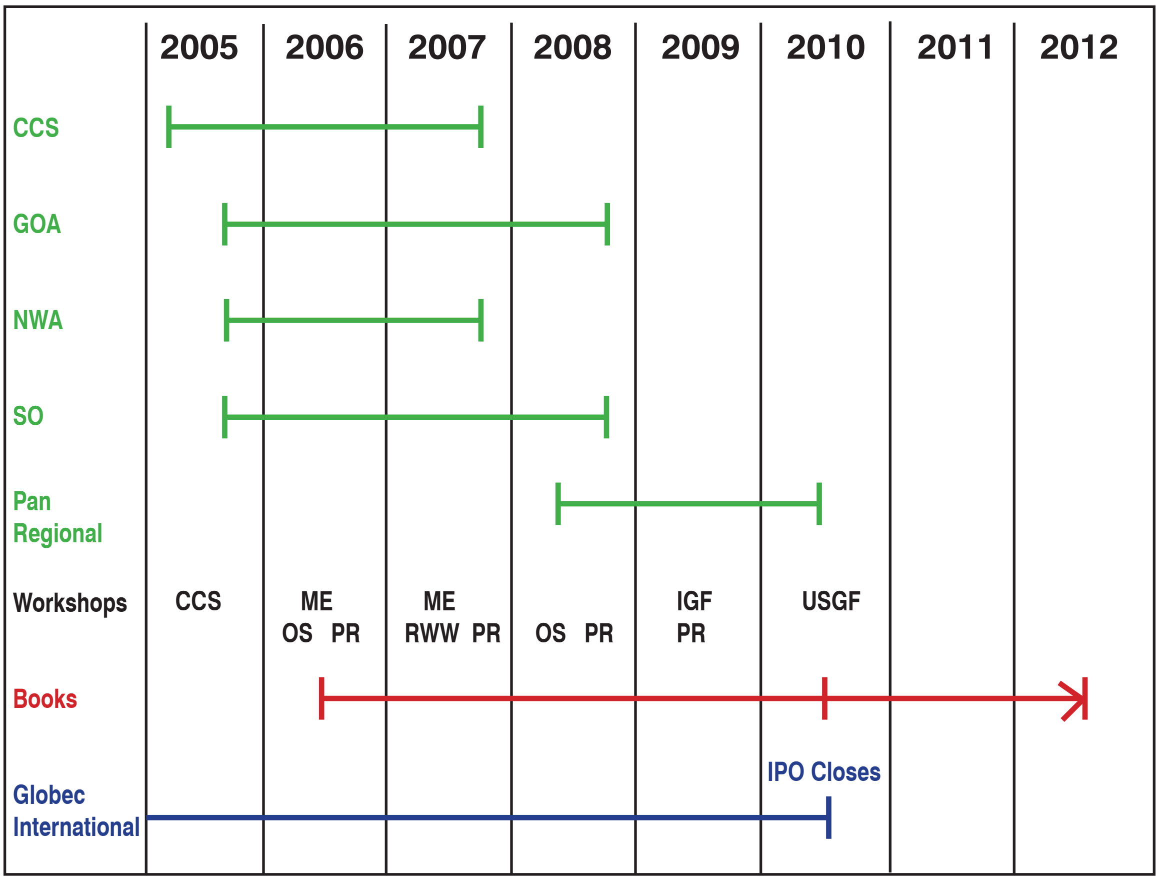

Figure 7. Proposed timeline for workshops, and special sessions to facilitate GLOBEC synthesis. **IGF:** International GLOBEC Final Symposium; **ME**: Model Evaluation Workshop, **OS:** Ocean Sciences; **PR:** Pan Regional Workshop; **RWW:** Regional (GB, SO, NEP) Workshops; **USGF:** U.S. GLOBEC Final Symposium.

8.0 Data Access and Management

Access to data collected during the U.S. GLOBEC Program is a central requirement for effective synthesis. The U.S. GLOBEC Coordinating Office has assumed responsibility for serving data for each of the three regional GLOBEC programs. The centralized data hub and distributed data servers are intended to facilitate cross-comparison of data derived from the regional programs by providing a unified framework for serving the data using the JGOFS data management system initially adopted for use in the Georges Bank GLOBEC program. Cruise reports, event logs, and data objects are now accessible via our on-line data and information server,[http://globec.whoi.edu/]. These data are stored either locally or remotely at one of half a dozen servers at other researchers' sites. By the end of 2004, we had 186 cruises reflected in the inventory, from the three U.S. GLOBEC study regions. Cruise and meeting reports, event logs, and 1105 data sets are accessible via our on-line data and information server.

The data management function involves maintenance of data inventories and metadata, documentation and dissemination of changes in data set inventories, final submission of data sets to NODC and other data centers as appropriate, participation in data exchange with other programs as appropriate, and development or application of new software tools for data management. Software tools for data analysis specifically developed for U.S. GLOBEC are available at the data hub for functions such as developing gridded data sets based on spatial analysis of GLOBEC data. A highly interactive 3D visualization system has also been developed in conjunction with researchers at the University of New Hampshire. The Silhouette Digitizer program is a MATLAB-based computer program for measuring the lengths of marine organisms in the macrozooplankton size range. The program allows one to identify and measure the organisms from a plankton sample that has been photographed and scanned.

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Table 1: Overview of U.S. GLOBEC system types, target organisms, physical processes, and key hypotheses for each regional study.

U.S. GLOBEC Program - Overview				
	Region			
	NW Atlantic / Georges Bank	**Southern Ocean: West Antarctic Peninsula**	**NE Pacific: California Current**	**NE Pacific: Coastal Gulf of Alaska**
System Type	Bank	Ice-dominated	Eastern boundary current	Buoyancy-driven flow
Target Organisms	*Gadus morhua* *Melanogrammus aeglefinus* *Calanus finmarchicus* *Pseudocalanus spp.*	*Euphausia superba* *Penguins* *Seals* *Whales*	*Oncorhynchus kisutch* *Oncorhynchus tshawytscha* *Calanus spp.* *Euphausia pacifica* *Thysanoessa spinifera*	*Oncorhynchus gorbuscha* *Neocalanus spp.* *Euphausia pacifica* *Thysanoessa spinifera* *Thysanoessa inermis* *Thysanoessa raschii*
Physical Processes	Stratification Transport/Retention Cross-Frontal-Exchange	Stratification Cross-shelf transport Transport/Retention Mesoscale circulation Sea Ice Dynamics	Stratification Cross-Shelf-Transport Mesoscale Circulation Upwelling	Stratification Cross-Shelf-Transport Mesoscale Circulation Downwelling

Key Hypotheses and Issues	Retention and in situ growth are more important than lateral exchange processes Stratification results in prey aggregation and increased predator survival Variation in mixing and stratification affects phytoplankton production and food web dynamics Large episodic water mass exchanges contributes to population variability Stratification and turbulent mixing affects predator-prey encounter rates Predation is dominant source of mortality	Shelf circulation in the vicinity of Marguerite Bay retains the krill population in a favorable environment Persistent winter ice cover provides dependable food and protection for larval krill to grow and survive over winter On-shelf intrusions of the Upper Circumpolar Deep Water supplies heat, salt, and nutrients that affect ice properties and enhance biological production Antarctic krill employ a range of over-wintering strategies	Local wind forcing and basin-scale currents affects spatial and temporal variability in mesoscale circulation in the CCS Mesoscale features in the CCS impact zooplankton biomass, production, and distribution and retention and loss of zooplankton Variation in the intensity of cross-shelf transport and the levels of primary and secondary production control juvenile coho and chinook salmon growth in the CCS High and variable predation mortality on juvenile coho and chinook salmon in the coastal CCS affects population variation	Local wind forcing and basin-scale currents affects spatial and temporal variability in mesoscale circulation in the CGOA Mesoscale features in the CGOA impact zooplankton biomass, production, and distribution and retention and loss of zooplankton Rapid growth and high survival of pink salmon depends on cross-shelf import of large zooplankton from offshore to nearshore waters High and variable predation mortality on juvenile pink salmon in the CGOA affects population variation

Table 2: Model types currently employed in U.S. GLOBEC regional studies including physical models and biological models. Coupled models combine most of the biological and physical models identified.

Model Type	**Region**			
	Georges Bank/ NW Atlantic	Southern Ocean	Northeast Pacific California Current	Northeast Pacific Coastal Gulf of Alaska
Physical Models	Quoddy FVCOM ROMS (in progress)	ROMS with dynamic sea ice processes	ROMS	ROMS
Biological Models	NPZD IBM (Copepod) IBM (Gadoids) Mass Balance Energy Flow Multispecies Fishery	IBM (Krill) Bioenergetic Krill Model Top predator bio-energetics models Top predator population models	NPZD IBM (Copepod) IBM (Salmon) Size Spectrum	NPZ IBM (Copepod) IBM (Salmon)

Table 3. The dynamics of target taxa in U.S. GLOBEC studies with respect to key physical processes can be compared in one or more GLOBEC regional programs : Georges Bank (GB), California Current System (CCS), Coastal Gulf of Alaska (CGOA) and Southern Ocean (SO). Regional program sites marked by an asterisk afford opportunities for comparisons among the principal target taxa within the region.

	Physical Process			
Taxa	Stratification	Retention/Loss	Upwelling/ Downwelling	Cross-Shelf Transport
Calanoid Copepods	GB/CCS/CGOA/SO	GB/CCS/CGOA/SO	CCS/CGOA	CCS/CGOA/GB/SO
Euphausiids	CCS/CGOA/SO	CCS/CGOA/SO	CCS/CGOA	CCS/CGOA/SO
Gadoids	GB	GB		
Salmonids	CCS/CGOA		CCS/CGOA	CCS/CGOA

Appendix

Table I. Instrumentation employed in U.S. GLOBEC regional studies

	Region			
Instrumentation	NW Atlantic Georges Bank	Southern Ocean	NE Pacific California Current	NE Pacific Coastal Gulf of Alaska
Physical Measurements	CTD Bosette (1.4 & 5 l) BDCP (Shipboard and Moored) Brifters (GPS & ARGOS) BET Package Booring (C/T, ADCP, BioOptics)	CTD Rosette (1.4 & 5 l) BDCP (Shipboard and Moored) Brifters (GPS & ARGOS) BET Package Boring (C/T, ADCP) Microstructure profiler	CTD Rosette (1.4 & 5 l) ADCP (Shipboard and Moored) Drifters (GPS & ARGOS) MET Package Mooring (C/T, ADCP)	CTD Rosette (1.4 & 5 l) ADCP (Shipboard and Moored) Drifters (GPS & ARGOS) MET Package Mooring (C/T, ADCP)
Biological Measurements	1m^2 MOCNESS (150 & 335 :m mesh) 10m^2 MOCNESS (3 mm mesh) 60 cm Bongo (335:m mesh) Plankton Pump Acoustics (120 & 420 kHz) Video Plankton Rec. Fluorometer	1m^2 MOCNESS (335:m mesh) 10m^2 MOCNESS (3 mm mesh) 1m Reeve Net (333:m mesh) 1m ring net (333:m mesh) Acoustics Split Beam 38,/120 & 43/120/200/420/1000 kHz) Video Plankton Rec. 1.5 m^2 Tucker Trawl (1/4 in mesh graded to 707:m mesh) Fluorometer Remotely Operated Vehicle Divers	70 cm Bongo (505:m mesh) 57 cm WP-2 Net (202:m mesh) Neuston Net (505:m mesh) Mid-Water Trawl Fluorometer	1m2 MOCNESS (500:m mesh) 70cm Bongo (500:m mesh) 25cm CalVet (0.16mm mesh) 10l Nisken Bottle Acoustics XSplit Beam 38/120/200 kHz XSingle Beam 420 kHz Mid-Water Trawl Fluorometer
Remote Sensing	AVHRR Topex-Poseidon SeaWifs Air-borne laser	AVHRR Topex-Poseidon SeaWifs	AVHRR Topex-Poseidon SeaWifs Synthetic Aperture Radar	AVHRR Topex-Poseidon SeaWifs

Table II. Variables directly measured in U.S. GLOBEC regional studies

	Region			
Direct Measurements	NW Atlantic Georges Bank	Southern Ocean Western coast of the Antarctic Peninsula	NE Pacific California Current	NE Pacific Coastal Gulf of Alaska
Physical/ Chemical Measurements	Water Temperature Salinity Currents Dissolved Oxygen NO_3, SiO_4, NH_4 Oxygen Isotopes Air Temperature Wind Speed & Dir. Barometric Pressure	Water Temperature Salinity Currents Dissolved Oxygen NO_3, SiO_4, NH_4 Air Temperature Wind Speed & Dir. Barometric Pressure	Water Temperature Salinity Currents Dissolved Oxygen NO_3, SiO_4, NH_4 Air Temperature Wind Speed & Dir. Barometric Pressure	Water Temperature Salinity Currents Dissolved Oxygen NO_3, SiO_4, NH_4 Air Temperature Wind Speed & Dir. Barometric Pressure
Biological Measurements	Chlorophyll Zooplankton Species Composition Distribution Biomass Counts Size/Stage Condition -Gut Fullness -Gut Content -Lipid Content -Gut Fluorescence Microzooplankton Abundance Fish Eggs/Larvae Counts Size Condition -Gut Fullness & Content Volume Backscatter (Acoustics)	Chlorophyll Primary production Particulate organic matter (POC/N) Zooplankton Species Composition Distribution Biomass Counts Size/Stage Condition -Gut Fullness -Gut Content Lipid Microzooplankton Abundance Fish Eggs/Larvae * Counts Size Volume backscatter (Acoustics) *Nontarget Spp. +Anticipated	Chlorophyll Zooplankton Species Composition Distribution Biomass Counts Size/Stage Condition -Gut Fullness -Gut Content Microzooplankton Abundance Fish Eggs/Larvae * Counts Size Juvenile Salmon+ Biomass Counts Size *Nontarget Spp. +Anticipated	Chlorophyll Zooplankton Species Composition Distribution Biomass Counts Size/Stage Condition -Gut Fullness -Gut Content Microzooplankton Abundance Fish Eggs/Larvae* Counts Size Juvenile Salmon Biomass Counts Size Volume Backscatter (Acoustics) *Nontarget Spp.
Remote Sensing	Brightness Temperature* Altimetry** Fluorescence*** *AVHRR/SeaWifs **TOPEX/Poseidon ***Air-borne laser	Brightness Temperature* Altimetry** Backscatter Sea ice extent and thickness *AVHRR/SeaWifs **TOPEX/Poseidon	Brightness Temperature* Altimetry** Backscatter Brightness*** *AVHRR/SeaWifs **TOPEX/Poseidon ***SAR	Surface Pigment Brightness Temperature* Altimetry** Backscatter Brightness*** *AVHRR/SeaWifs **TOPEX/Poseidon ***SAR

Table III. Derived measurements obtained during U.S. GLOBEC regional studies

	Region			
Derived Measurements	NW Atlantic Georges Bank	Southern Ocean	NE Pacific California Current	NE Pacific Coastal Gulf of Alaska
Physical/ Chemical Measurements	Seawater Density Stratification Turbulence (Energy Dissipation) Heat Flux (Air/Sea Exchange) 18O/16O	Seawater Density Stratification Turbulence (Energy Dissipation) Microstructure	Seawater Density Stratification Turbulence (Energy Dissipation)	Seawater Density Stratification Turbulence (Energy Dissipation)
Biological Measurements	Zooplankton XDensity Condition -RNA/DNA -Cell Growth Potential Genetic Structure Rate Processes -Feeding -Egg Production -Growth/Molting Rate Fish Eggs/Larvae Condition -RNA/DNA	Zooplankton Density Condition -RNA/DNA Genetic Structure Rate Processes -Feeding -Growth/Molting Rate Stable isotopes Fatty acid composition	Zooplankton Density Condition -RNA/DNA Genetic Structure Rate Processes -Feeding -Egg Production -Growth/Molting Juvenile Salmon* Rate Processes -Growth -Mortality *Anticipated	Zooplankton Density Condition -RNA/DNA Genetic Structure Rate Processes -Feeding -Egg Production -Growth/Molting Rate Juvenile Salmon Rate Processes -Growth -Mortality
Remote Sensing	Chlorophyll* Sea Surface Temperature* Sea Surface Height** Wind Speed** Wave Height** *AVHRR/SeaWifs/ Laser ** TOPEX/Poseidon	Chlorophyll* Sea Surface Temperature* Sea Surface Height** Wind Speed**BWave Height** *AVHRR/SeaWifs/ Laser ** TOPEX/Poseidon	Chlorophyll* Sea Surface Temperature* Sea Surface Height** Wind Speed** Wave Height** Wave Spectra*** *AVHRR/SeaWifs ** TOPEX/Poseidon ***SAR	Chlorophyll* Sea Surface Temperature** Sea Surface Height** Wind Speed** Wave Height** Surface Roughness *AVHRR/SeaWifs ** TOPEX/Poseidon ***SAR