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Looking Forward Transdisciplinary Modeling, Environmental Forecasting, and Management

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Looking Forward

Transdisciplinary Modeling, Environmental Forecasting, and Management

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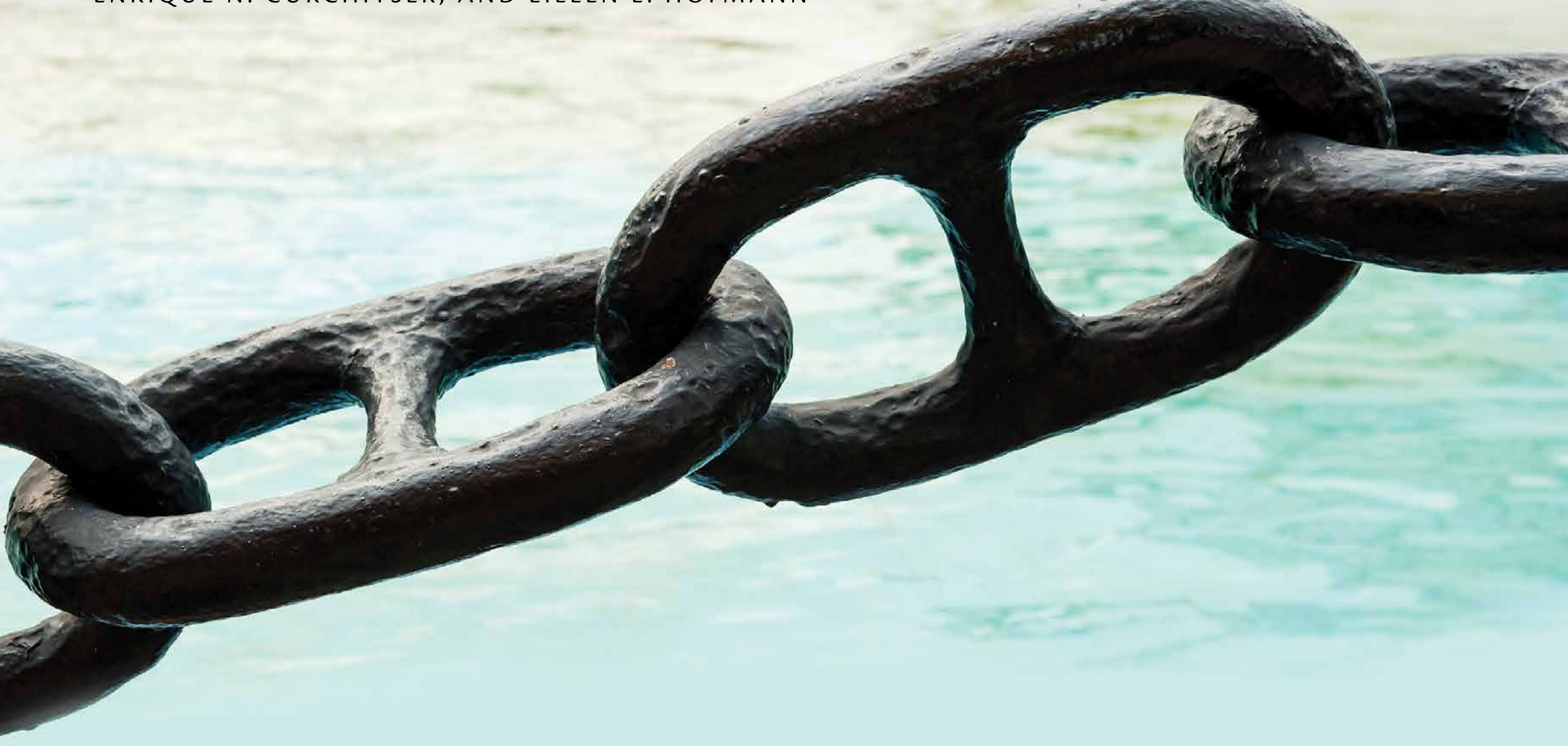

The farther backward you can look,
the farther forward you are likely to see.

—Winston Churchill

In the 1970s, the International Decade of Ocean Exploration (IDOE) set the stage for an era of global ocean research programs (NRC, 1999). Although scientists had long explored the "seven seas," it was only in the late 1960s that observing the ocean at synoptic scales became feasible. This capability, together with the lessons learned from IDOE, allowed for the growth of major oceanographic initiatives. In particular, the late 1980s and the 1990s marked two decades of large oceanographic programs, two of which, the World Ocean Circulation Experiment (WOCE; http://www.nodc.noaa.gov/woce/wdiu/wocedocs/index.htm#design), and the Joint Global Ocean Flux Study (JGOFS; http://www1.whoi.edu), resulted in important advances and transformations in ocean research that fostered the subsequent development of the Global Ocean Ecosystem Dynamics program (GLOBEC; http://www.globec.org).

WOCE was designed to collect a comprehensive data set that could support the development of emerging global eddy-resolving ocean circulation models (Thompson et al., 2001). The program forged international collaborations through the Scientific Committee on Oceanic Research (SCOR), the World Meteorological Organization (WMO), and the International Oceanographic Commission (IOC). WOCE laid the foundation for several large-scale ocean research programs by setting up a steering committee structure, developing science and implementation plans, and creating data management systems. The WOCE data set was unprecedented in scope and scale and is still being used as the basis for scientific studies.

JGOFS focused on fluxes of carbon and biogeochemical cycling in the ocean and sought to develop a capability to understand and model responses of oceanic biogeochemical processes to climate change. The JGOFS science plan included ship-based field programs in a range of oceanic environments, long-term observation sites, and modeling. JGOFS was one of the first programs to integrate satellite observations in its science programs and the first to develop a database structure to handle diverse and disparate data sets. JGOFS was a core project of the International Geosphere-Biosphere Programme (IGBP), which provided an overarching framework for the national programs that implemented the field programs, modeling, and data synthesis. It was also a core program of the US Global Change Research Program (USGCRP). Thus, JGOFS was a direct predecessor to GLOBEC, both in issues addressed and in program structure.

The US GLOBEC program originated in early 1980s scoping workshops that highlighted the gap in understanding of the causes of variability in marine ecosystems (see Turner et al., 2013, in this issue). In the late 1980s and early 1990s, the international community started planning for a program that would address the science underlying marine population variability, with an emphasis on climate change effects. This planning was formalized as part of the international GLOBEC program in the early 1990s when it became a core project of SCOR and IOC, and subsequently of the IGBP. The US GLOBEC program was a national contribution to the international project. Its structure was similar to that of the international GLOBEC and earlier projects, with a science steering committee and a dedicated project office, regional field programs in the four US GLOBEC areas, and focused working groups (e.g., data management, modeling). US GLOBEC also benefited from the data archive structures developed for JGOFS and WOCE, and incorporated data management as a program goal from the outset. Also similar to the earlier programs, US GLOBEC considered modeling a priority and made it an integral part of all field programs and synthesis activities.

LESSONS LEARNED: WHY GLOBEC "WORKED"

GLOBEC benefited from the advances made in ocean sampling and modeling during WOCE and JGOFS, and from advances in instrumentation made possible through these and other large ocean programs. However, in contrast to these earlier programs, GLOBEC sought to advance the study of ocean ecosystems by focusing on individual species and how they are affected by ocean variability and climate change. Field programs were designed to measure species distribution and abundance in relation to oceanographic parameters, and laboratory and shipboard experiments were incorporated to provide understanding of the mechanisms involved. The integration of observing networks, process and survey field studies, and mathematical and numerical modeling into a single program was a key strength of GLOBEC. Another important factor contributing to its success was the synergy provided by the combined national and international program structures; although the International GLOBEC program was composed of national programs, each with its own focus on specific regions and species, the international program provided the broader context and the ability to conduct intercomparisons.

US GLOBEC was the first national GLOBEC program to be funded, and thereafter served as an example to other national GLOBEC programs. Some attributes that contributed to a successful US GLOBEC program have been previously discussed (Turner and Haidvogel, 2009), such as the focus on issues with societal relevance in addition to those at the leading edge of science. Combining societal relevance with cutting-edge science allowed for partnerships both within and across federal agencies to provide long-term funding. Implementation of the program in sequential phases allowed assessment of progress and expertise needs, which guided the science objectives and goals for new competitions and projects. Synthesis phases for the regional programs and a final pan-regional synthesis phase encouraged the interpretation of findings within a larger context and across disciplines. The major advances reported in this issue could not have occurred without specific funding set aside for synthesis.

Perhaps most importantly, GLOBEC underwent long-term strategic research planning both within the US program and in collaboration with the international program. Well-developed science and implementation plans grounded each phase of the program, and regional programs were planned and conducted within overall national program goals. A national program office provided strong leadership and supported a scientific steering committee that oversaw the program as a whole and helped coordinate disparate projects to form a comprehensive program. To make significant progress on complex issues, ocean research in the United States needs strategic multidisciplinary research planning such as that undertaken by GLOBEC, JGOFS, and WOCE. We are encouraged to see this carry on in the international arena through global environmental change programs such as Integrated Marine Biogeochemistry and Ecosystem Research (IMBER, http://www.imber.info). US contributions to strategic research plans now being developed for IMBER and new initiatives through Future Earth (http://www.futureearth.info) are critical and require support from US funding agencies to ensure that these are implemented.

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LOOKING FORWARD: A NEW TRANS-DISCIPLINARY MODELING PARADIGM

The successes of the US GLOBEC program illustrate the advantages of collaborative partnerships among physical scientists, marine biologists, modelers, and mathematicians as well as scientists of other disciplines. In the future, these interdisciplinary science linkages will need to be expanded to encompass interactions with the social sciences.

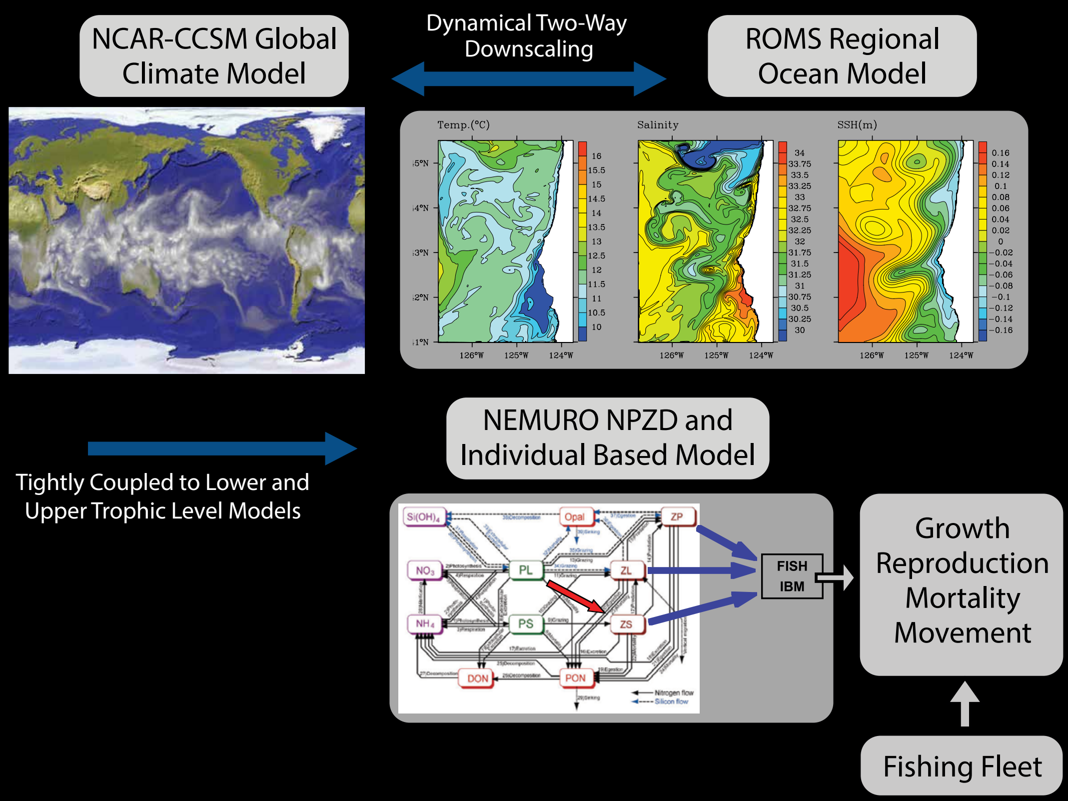
With some notable exceptions (e.g., whales, penguins, seals, and salmon), the US GLOBEC science program focused primarily on the lower trophic levels (nutrients, phytoplankton, zooplankton) and on regional-scale oceanography. Biological variability was attributed primarily to bottom-up effects, in which climate and physics drive the ecosystem. However, in the later years of the program, the evidence for human influences on the marine and climate systems was mounting and resulted in a programmatic shift in GLOBEC science. In particular, humans are now regarded as a critical part of the marine ecosystem, contributing to bottom-up pressures (rising temperatures, ocean acidification) as well as to top-down pressures (increased fishing).

To simultaneously consider both bottom-up and top-down effects, the modeling frameworks that emerged from the GLOBEC program (Curchitser et al., 2013, in this issue) have begun to be extended to include human activities—represented through both economic and human decision-making submodels—as integral components of marine food webs (Box 1). The goals are to test theories of how, in a changing environment, economic and social systems respond to and in turn impact the climate system, and to understand how this information can be used to make resource management decisions by local and regional entities (e.g., municipalities, counties, states). For example, such end-to-end frameworks may be used to understand how climate change will affect energy demand and therefore electricity prices, in turn affecting industrial and household use, and ultimately feeding back onto the climate system through changed emissions and land use.

TRANSITIONING FROM MODELING TO FORECASTING

Several oceanographic models have been operationalized within federal agencies, primarily through the National Oceanic and Atmospheric Administration (NOAA) and the US Navy. They have been physical models transitioned into forecasts of currents, waves, and water levels (e.g., see *Oceanography* special issue on the "Revolution in Global Ocean Forecasting—GODAE: 10 Years of Achievement" at http://www.tos.org/oceanography/archive/22-3.html). Only a very few examples exist of forecasts that incorporate ecology into their predictions. NOAA has operational ecological forecasts for harmful algal blooms (HABs) in some regions, and is supporting efforts to transition HAB forecasts in other regions (http://tidesandcurrents.noaa.gov/hab). There is interest in

BOX 1. END-TO-END MARINE ECOSYSTEM MODELS



In the future, the interactive effects of human activities on global climate and marine ecosystems will need to be taken into account in making projections for purposes of environmental management and decision making. The schematic illustrates the components of an end-to-end (Climate-to-Fish-to-Fishers) model designed to study the combined effects of bottom-up and top-down drivers of an ecosystem. The top-level model is the National Center for Atmospheric Research (NCAR) global climate model (NCAR-CCSM, http://www2.cesm.ucar.edu), which is then regionally downscaled in the California Current System using the Regional Ocean Modeling System (ROMS, http://www.myroms.org), permitting two-way feedbacks. In the high-resolution region, a lower trophic level model (NEMURO; Kishi et al., 2011) is coupled to an individual-based model for several fish species. Top-down effects are represented by a model of a fishing fleet, where individual boat behavior is guided by a bio-economic model for the fishery (from Curchitser et al., 2009). NPZD = Nutrients-Phytoplankton-Zooplankton-Detritus. IBM = Individual Based Model.

operationalizing other types of ecological forecasts such as coastal hypoxia and pathogen occurrence (Brown, 2012; also see http://oceanservice.noaa.gov/ecoforecasting). The National Aeronautics and Space Administration (NASA) also has had an active program in developing ecological forecasting capability for both terrestrial and aquatic ecosystems (http://appliedsciences.nasa.gov/eco-forecasting.html). The types of coupled models developed through GLOBEC provide a rich resource for future ecological forecasting tools.

Models can provide forecast guidance, but are not forecasts in themselves. The transition from models to forecast systems requires software documentation, data storage and assimilation, specification of uncertainties (Beck et al., 2009; Stumpf et al., 2009; Milliff et al., 2013, in this issue), and robust infrastructure for dissemination. Importantly, specifically trained forecast personnel are needed. Often, pre-operational or test forecasts undergo several iterations of feedback between forecasters and the ultimate end users of forecasts. Pathways for transitioning ecological forecasts remain in their infancies, although test bed efforts are underway (http://www.ioos.noaa.gov/modeling/testbed.html).

CONTRIBUTIONS TO ENVIRONMENTAL MANAGEMENT AND PROTECTION

GLOBEC made important contributions to marine ecosystem-based management (mEBM; Fogarty et al., 2013, in this issue) and the candidate areas identified for regional Integrated Ecosystem Assessments by NOAA include the Northwest Atlantic and Northeast Pacific GLOBEC regions. US GLOBEC provided a wealth of data and modeling capacity for these regions, which provide an important baseline for developing, implementing, and evaluating mEBM. Notably, several of the US Integrated Ocean Observing System (IOOS) transects and/or mooring locations are at locations either previously occupied by GLOBEC or identified by GLOBEC as important, such as the Newport Line off Oregon, the Seward Line in the Gulf of Alaska, and the Northeast Channel buoy adjacent to Georges Bank.

The understanding gleaned through US GLOBEC science has been important in guiding approaches for evaluation of environmental change on managed fish populations. Regional fishery management councils in the United States are beginning to grapple with how to implement mEBM, and the insights produced through GLOBEC can identify appropriate (or perhaps more importantly, inappropriate) strategies for harvest (see Ruzicka et al., 2013, and discussion in Fogarty et al., 2013, in this issue).

In addition to monitoring and assessment, US GLOBEC advanced modeling approaches that aid in the development of effective Marine Protected Areas (MPAs). The first US GLOBEC publication helped to identify important regions for protection of spawning biomass of scallops on Georges Bank (Tremblay et al., 1994). Subsequent US GLOBEC work (Botsford et al., 1994; Hill et al., 2002) advanced metapopulation modeling techniques important to MPA design.

FUTURE CHALLENGES

Stable Funding Base in Declining Federal Budgets

The US GLOBEC program sustained a research program for almost two decades, which kept the focus of the science community on a specific set of questions and goals. Without this overarching research agenda, it is unlikely sustained resources and facilities (e.g., ships) would have been directed at the study of the processes underlying marine ecosystem variability. The importance of climate in regulating marine ecosystems and the issues associated with marine resource extraction will only increase in the future. Thus, sustained observations and long-term research efforts will be needed and will be critical to developing policy and mitigation strategies for addressing the impacts on human society.

On July 19, 2010, President Obama issued Executive Order 13547, *Stewardship of the Ocean, Our Coasts, and the Great Lakes* (http://www.presidency.ucsb.edu/ws/index.php?pid=88216), outlining a National Ocean Policy. One key theme was to "Inform Decisions and Improve Understanding," and specifically to support "disciplinary and interdisciplinary science, research, monitoring, mapping, modeling, forecasting, exploration and assessment." The US GLOBEC experience illustrates how these recommendations may be successfully implemented.

Large-scale ocean research programs are difficult to sustain under stable budgets, and are even more so under declining budgets. A national ocean research initiative has been formulated through the Ocean Research Priorities Plan (National Science and Technology Council, 2007, 2013), which highlights themes that were also part of US GLOBEC, such as:

- Monitoring of living resources (at multiple trophic levels)
- Collection of necessary data (observational and experimental) to support robust models
- Process-oriented research to resolve critical functional relationships encoded into models

- Development and validation of ecosystem and species interaction models at appropriate scales that incorporate feedback mechanisms among trophic levels
- Improving ecosystem models to better understand complex ecosystem dynamics and forecast the effects of resource use, exploration, and development on ecosystems and individual components

These ambitions have yet to be fully implemented due to financial constraints, but it is clear that approaches such as those used by US GLOBEC continue to be essential to meeting the nation's ocean research needs.

Importance of Monitoring and Observing Networks

The primary objectives for US GLOBEC's seagoing phases included monitoring to detect change and developing and systematically improving the needed monitoring technologies. Utilizing these new and emerging technologies, long-term observations were set up in each regional study area (see Batchelder et al., 2013, in this issue). Towed packages such as MOCNESS (Multiple Opening Closing Net and Environmental Sensing System), BIOMAPER (Bio-Optical Multifrequency Acoustic and Physical Environmental Recorder), the "Greene Bomber," and SeaSoar were used heavily in these observations (Wiebe et al., 1997, 2002; Batchelder et al., 2002; Hofmann et al., 2002). While these technologies were not exclusively developed through GLOBEC, the GLOBEC program was an early adopter and proponent of technology improvement for these sampling systems (Greene et al., 1998; Harris et al., 2010). Several efforts integrated net sampling with acoustic and optical sampling (Benfield et al., 1996; Broughton and Lough, 2006).

Remote sampling technologies also played a part in US GLOBEC. Satellite observations were incorporated throughout the years in the field (Bisagni et al., 2001; Okkonen et al., 2003; Brickley and Thomas, 2004) and provided data for modeling efforts (Powell et al., 2006) and observational system simulation experiments (McGillicuddy et al., 2001). US GLOBEC was one of the first programs to install, calibrate, and validate HF radar along the California Current (Paduan et al., 2006).

Some of the monitoring work begun under US GLOBEC is being continued beyond the lifetime of the program. Monitoring is an integral component of global- and regional-scale ocean research, as evidenced by the development of IOOS, the Ocean Observing Initiative (OOI), and recent significant investments in observing technology (Argo, gliders). The use of autonomous sensors deployed as part of observing systems will allow sampling the ocean environment at scales not previously possible. However, sensors for biological measurements are limited. Development of autonomous in situ sensors for sustained observing of marine ecosystems must be a high priority. Innovations and advances in genomics, protoeomics, optics, and nanotechnology open a range of opportunities for the development of these sensors. Taking advantage of them requires sustained targeted funding, the development of a community to build, deploy, and maintain the sensors/instruments, and education of a community of researchers who can analyze and use the data.

> "THE IMPORTANCE OF CLIMATE IN REGULATING MARINE ECOSYSTEMS AND THE ISSUES ASSOCIATED WITH MARINE RESOURCE EXTRACTION WILL ONLY INCREASE IN THE FUTURE. THUS, SUSTAINED OBSERVATIONS AND LONG-TERM RESEARCH EFFORTS WILL BE NEEDED AND WILL BE CRITICAL TO DEVELOPING POLICY AND MITIGATION STRATEGIES FOR ADDRESSING THE IMPACTS ON HUMAN SOCIETY."

In addition to autonomous sensors, shipboard expeditions must be continued. Insight derived from net-based monitoring is extremely valuable to both scientific progress and fisheries management advice. Direct ship-based monitoring is needed to evaluate population dynamics, especially in a changing ocean environment, as evidenced by, for example, regime shifts in the Pacific and the recently documented shelf warming in the Atlantic. These shipboard surveys can feed directly into ecosystem information used by NOAA (e.g., see National Marine Fisheries Service ecosystem advisory, http://nefsc.noaa.gov/ecosys/

advisory/current and salmon return forecast, and http://www.nwfsc.noaa.gov/research/divisions/fe/estuarine/oeip/g-forecast.cfm).

Modeling the Responses of Marine Food Webs to Global Climate Fluctuations

Improving the skill and robustness of marine ecosystem projections requires advances beyond increasing the number of model components and their complexity. A fundamental challenge remains in representing the wide range of scales in the ocean—from tens of thousands of kilometers needed to represent global climate fluctuations to the submeter scales of (even) the higher trophic levels. As a consequence, the current generation of "high-resolution" ocean circulation models cannot adequately represent many of the physical phenomena believed to be significant for many organisms, such as submesoscale processes.

Linkages and interactions that interconnect this wide range of scales enhance the difficulty. For example, a warming of the surface ocean, due to a warmer atmosphere, will change the ocean stratification, which in turn affects the generation, scale, and structure of ocean eddies. As eddies are known to play a significant role in ocean productivity, projections of future ecosystem states require projection of large-scale temperature changes as well as how these changes cascade down to the scales that influence the biology. Furthermore, in many locations, ocean turbulence is responsible for the redistribution of temperature, salt, and nutrients. Thus, changes in ocean mixing states may contribute back to large-scale circulation.

As computer power increases, the resolution of global climate models continues to be enhanced. However, with the current technological development rate, it will be, optimistically, many decades before organismal-to-global scales can be resolved for climate simulations. Nevertheless, progress can be made with some of the techniques developed during US GLOBEC, such as unstructured meshes and nesting. Current development of multiscale models that permit scale interactions (two-way feedbacks) are at the leading edge of research on the co-evolution of climate and regional ecosystems.

Integration Among Disciplines

The focus in US GLOBEC on a limited number of key species clearly showed important linkages and interconnectivity in marine ecosystems. However, the species-specific approach limited the scope of the science program, which was addressed somewhat through the development of end-to-end food web models (Steele et al., 2007). An additional limitation was the lack of explicit study of human effects on marine food webs. The importance of this effect was acknowledged in the latter part of the research program and in the synthesis phase, motivating US GLOBEC to evolve its research agenda to include human, social, and economic components. The inclusion of these components was important, but it came after the implementation of the field programs and, as a result, was not an integral part of the science questions and approaches that were developed for them.

Recognition of these limitations has stimulated subsequent research programs to include scientists with social, economic, and policy backgrounds as collaborators from the start. Current global environmental change programs strive to integrate environmental, biogeochemical, food web, socio-economic, and policy interactions from the outset. This inclusiveness represents a fundamental change in the study of marine ecosystems and also offers exciting research opportunities that are focused at the interface of human-natural science. A legacy of US GLOBEC is the demonstrated need to take a whole ecosystem approach that links across all trophic levels and encompasses studies and models at regional, basin, and global scales. GLOBEC provided many exciting and new approaches for linking across these scales, approaches that are now being further advanced through community modeling efforts and through international programs such as IMBER. However, challenges will come from the need to include methodologies that integrate natural, social, economic, and policy research, particularly as mEBM approaches are implemented.

This is US GLOBEC contribution 746.

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