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US GLOBEC
Program Goals, Approaches, and Advances

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This special issue summarizes the major achievements of the US Global Ocean Ecosystem Dynamics (GLOBEC) program and celebrates its accomplishments. The articles grew out of a final symposium held in October 2009 under the auspices of the National Academy of Sciences Ocean Studies Board (http://usglobec.org/Symposium). This special issue updates the US GLOBEC "mid-life" *Oceanography* issue (Vol. 15, No. 2, 2002, http://tos.org/oceanography/archive/15-2.html), which put forward many of the goals and activities of the program, but was published while field work was still being conducted and results had yet to be synthesized across regional programs. The present special issue highlights the advances in understanding achieved through the synthesis of regional studies and pan-regional comparisons.

US GLOBEC: MOTIVATION AND GOALS

Questions about marine population variability have been a focus for biological oceanography and fisheries science since the early development of the disciplines: What regulates the distribution and abundance of zooplankton and fish populations? Why do marine populations exhibit wide interannual variability? What are the relative roles of physical forcing vs. biological processes in determining marine recruitment? How can we use knowledge of past and current conditions to predict future recruitment and population size? US GLOBEC was designed around these and similar questions to provide understanding of how physical variability and change in the ocean will influence future marine populations and to translate that understanding into predictive capability for climate impacts on marine ecosystems. This focus is reflected in the overall goal articulated for the US GLOBEC program in its Initial Science Plan (1991):

> *To understand how physical processes, both directly and indirectly, influence the success of individual animals in the sea, their feeding, growth, reproduction, and survivorship. From this information can be derived the consequences of changing physical processes on animal populations and ecosystems. Models of global climate can then be used to relate global change to changes in regional ocean physics and, subsequently, changes in regional physics to shifts at the scales of events that influence the individual organism.*

The goal of the US GLOBEC program was subsequently refined as the program evolved to explicitly include prediction of future states of the marine ecosystem as an objective in its long-range science plan (US GLOBEC, 1995):

> *US GLOBEC's goal is to understand how physical processes influence marine ecosystem dynamics in order to predict the response of the ecosystem and the stability of its food web to climate change.*

Accompanying this long-term goal was an enhanced emphasis on modeling studies and observing networks that together link physics and ecosystems:

> *The vision of US GLOBEC is that the models and scientific insights that arise from these field studies will ground an ecosystem monitoring program to predict variability in living marine resources.*

This re-statement of the program goal also introduces the concept of food web stability, discussed in more detail in **Ruzicka et al.** (2013, in this issue), and the identification of variables that will become important to monitoring for ecosystem-based management, discussed in **Fogarty et al.** (2013, in this issue).

Finally, the synthesis and integration phase of US GLOBEC (US GLOBEC, 2009) extended the program to explicitly address the important issue of fishery production:

> *The objective of US 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,*

thereby reflecting the increased emphasis across US science programs on connecting research with outcomes to benefit society at large. Prediction depends on a clear understanding of processes (e.g., **Batchelder et al.**, 2013; **Di Lorenzo et al.**, 2013a,b; **Ruzicka et al.**, 2013, all in this issue), integrated modeling (**Curchitser et al.**, 2013, in this issue), and identification of uncertainties in both measurements and model results (**Milliff et al.**, 2013, in this issue; Lynch et al., 2009).

DEVELOPMENT OF THE "GLOBEC APPROACH"

The community planning that resulted in the US GLOBEC program (Fogarty and Powell, 2002) began in the early 1980s when the Biological Oceanography Program of the National Science Foundation sponsored a series of three workshops that came to be known as Fish Ecology I, II, and III. These workshops occurred at about the same time that a relevant National Academy of Sciences report entitled *Recruitment Processes and Ecosystem Structure in the Sea* (NRC, 1987) was published. In April 1988, a group of zooplankton ecologists met to identify new directions emerging in marine zooplankton research, including several themes that became incorporated into US GLOBEC planning, such as the importance of larval stages and the physical-biological processes surrounding them. At the same time, physical oceanographers were also recognizing the importance of interdisciplinary approaches to pressing problems in coastal oceanography (Brink, 1988).

As the planning process continued, it became clear that advances in understanding would progress most rapidly with a research program focused on climate impacts on a select group of target organisms in contrasting environmental regions. The overarching GLOBEC strategy of interrelated long-term observational programs, retrospective analysis, technological innovation, process-oriented studies, and model development provided a common framework for implementation within each region. The partnership between the National Science Foundation and the National Oceanic and Atmospheric Administration in establishing and supporting the program signaled both a strong commitment to basic science and recognition that fundamental progress at the interface between oceanography, climate research, and fisheries science would ultimately be necessary to inform effective and adaptive ocean management strategies in a changing world.

To reflect these early considerations, the "GLOBEC Approach" was envisioned to emphasize:

1. The connection between physics and biology, argued to be especially important for planktonic animals
2. A focus on selected target species in each region of interest
3. Moving beyond correlation to the development of a mechanistic understanding based on fundamental processes of growth, reproduction, and recruitment in the target species
4. The integration of models with process studies of organisms and populations
5. Down-scaling of global circulation models to regional physics and organism responses

These elements were integral to each of the US GLOBEC regional programs and to the programmatic synthesis and integration studies that are the subject of the papers in this special issue.

MAKING THE CLIMATE CONNECTION

From its outset, GLOBEC was designed to understand the likely consequences of changes in global climate and physics on animal production in the sea (US GLOBEC, 1991). Climate change and variability have many effects on marine ecosystems (Stenseth et al., 2004; Drinkwater et al., 2010). Climate can directly alter environmental temperature and thus, given the overriding importance of temperature in regulating physiological processes, can have large impacts on both lower and upper trophic level species. Habitability of the marine environment can also be altered directly by other climate-related factors, including vertical stratification (stability) of the water column and altered transport pathways. Indirect effects of climate on population dynamics can occur through trophic interactions between a species and its prey, predators, and/or competitors. Perhaps the best documented indirect effect of climate on marine populations is phenology shifts that create mismatches in timing between prey and consumers and impacts foraging success, growth, and survival (Cushing, 1990; Ji et al., 2010).

The US GLOBEC program adopted a broad approach to examining climate variability, defined here as variation in the environment at multiyear and longer time scales. Time series programs that extend over multiple decades are clearly required to directly address these climate issues, an approach that was not feasible to complete within the duration of the GLOBEC program. Because the GLOBEC regional investigations were expected to span only about five to eight years at most in each study region, the program targeted sites that had preexisting historical sampling that would allow comparisons of the GLOBEC sampling period with earlier periods for at least some variables.

Large-scale climate variability can be characterized by changes in indices related to (regional) atmospheric pressure patterns such as the El Niño-Southern Oscillation (ENSO; equatorial Pacific), North Atlantic Oscillation (NAO), North Pacific Index (NPI), and Southern Annual Mode (SAM).

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Other indices are based on patterns of sea surface temperatures, such as the Pacific Decadal Oscillation (PDO) or the Atlantic Multidecadal Oscillation (AMO). As the time scales of the environmental variability lengthen from a few years (ENSO) to decadal and longer (PDO, NAO, AMO), the responses of marine populations/ecosystems may be analogous to the changes that could occur in response to secular climate change. Some US GLOBEC studies were done in regions and during time periods characterized by dramatic interannual and longer period changes in wind forcing and temperature ("regime shifts"), allowing the potential effects of long-term climate change to be inferred from observations and documentation of population and community responses to shorter term variability. Coupled physical-biological modeling was used to examine links between atmospheric forcing and population dynamic responses, and to integrate multiple, diverse data sets in the analysis of physical and ecological patterns and processes (*sensu* Runge et al., 2010; **Curchitser et al.**, 2013, in this issue).

IMPLEMENTATION OF THE US GLOBEC APPROACH

The planning and evolution of US GLOBEC reflected and benefited from several ongoing trends in ocean science. New remote-sensing technologies were developing (e.g., Bisagni, 2001; Carr et al., 2002; Brickley and Thomas, 2004) that enabled synoptic observations of ocean phenomena. New systems that allowed physics and biology to be sampled simultaneously were being developed (Benfield et al., 1996, 1998; Greene et al., 1998; Lawson et al., 2004). Ocean modeling was making great leaps forward (**Curchitser et al.**, 2013, in this issue) that paralleled developments in computer technology and informed field sampling strategies (McGillicuddy et al., 2001). At the same time, long time series that would enable retrospective analysis had been obtained in many locations in the coastal ocean (e.g., Bisagni et al., 1996; Meise and O'Reilly, 1996; Conversi et al., 2001; Pierce et al., 2006; Huyer et al., 2007). These longer-term observations were complemented by retrospective reconstructions of past ecosystem states and their changes over long time scales, including proxy-based paleo-reconstructions (Finney et al., 2000, 2002; Field et al., 2006).

US GLOBEC fused these developments into a common program (Figure 1). Technological innovation facilitated process studies on target species, which led to new mechanistic understanding. New technologies also drove the collection of long-term observations that put the process studies into a longer-term context. Retrospective analysis of historical observations extended the comparative time scales. Results of process studies, long-term observations, and retrospective results were used to develop conceptual and dynamic models that provided frameworks for synthesis of new understanding and identification of key parameters linking physical forcing to ecosystem processes.

The regions chosen for US GLOBEC studies had common characteristics, such as the likelihood of climate impacts within the region, the availability of prior studies to provide time-series data, and the potential to encompass a variety of physical forcings (Table 1, Figure 2). In the Northwest Atlantic, Georges Bank is situated at a biogeographic boundary, influenced by both the Gulf Stream and the Labrador Current. It offers a bank system with retentive circulation and a wealth of prior work (see references in Wiebe et al., 2002). It also supports important fisheries with regional and national importance.

The Northeast Pacific provided two contrasting systems, the upwelling eastern boundary current system in the Northern California Current and the seasonal downwelling system in the coastal Gulf of Alaska. These systems

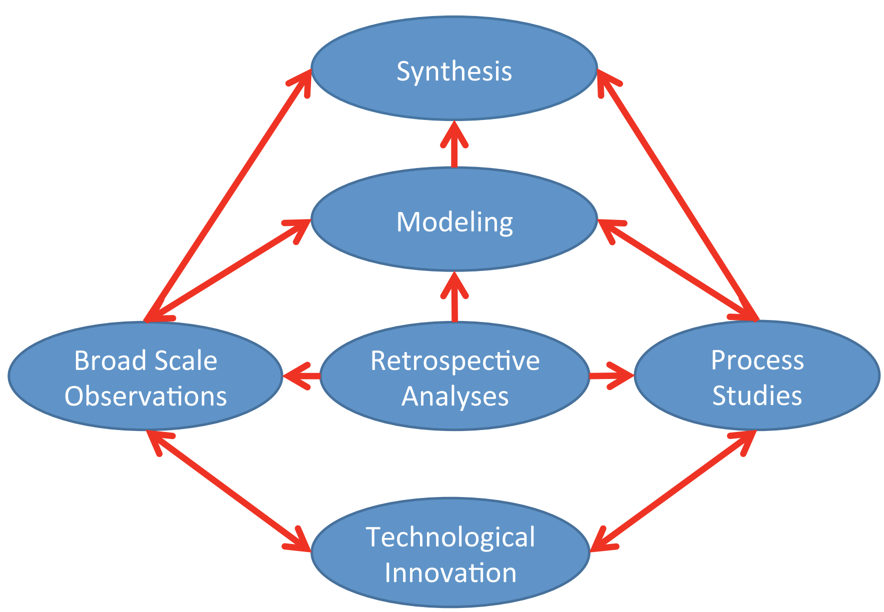

Figure 1. The GLOBEC research strategy.

showed intriguing patterns of zooplankton (Brodeur et al., 1996) and fish (Hare et al., 1999) populations that covaried out of phase with each other, and they provided a way to compare and contrast the controlling mechanisms at work (Worden et al., 2010; **Batchelder et al.**, 2013, in this issue).

The Southern Ocean was an active site for GLOBEC because of its strong linkage to climate and the importance of the region's natural resources to international regulatory organizations, such as the Convention for the Conservation of Antarctic Marine Living Resources and the International Whaling Commission. Ice dynamics play an important role in physical forcing of the Antarctic system, but there are also parallels to cross-shelf transport and retentive features seen in other US GLOBEC regions.

Target species were chosen in each US GLOBEC region for their ecological and (in some cases) commercial importance (Table 2), and that selection drove the process studies focusing on particular species' vital rates and predator/prey interactions. In the Northwest Atlantic, larval cod and haddock served as the target fish species, while their primary prey, calanoid copepods, were the target zooplankton species. In the Northeast Pacific, salmon species were chosen due to their regional importance and apparent response to regime shifts, while copepods and krill were the zooplankton target species. In the Southern Ocean, krill was the central species, along with its main predators, such as penguins, seals, and cetaceans. The Southern Ocean was the only US GLOBEC program that included marine mammals as target species. While the target species were emphasized in each regional program, other zooplankton taxa, including

Table 1. Characteristics of US GLOBEC study regions.

	Region			
	NW Atlantic/ Georges Bank	**Southern Ocean: West Antarctic Peninsula**	**NE Pacific: California Current System (CCS)**	**NE Pacific: Coastal Gulf of Alaska (CGOA)**
System Type	» Bank	» Ice-dominated	» Eastern boundary current	» Buoyancy-driven flow
Area	» 42,000 km^2	» 89,000 km^2	» 34,000 km^2	» 291,840 km^2
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
Atmospheric Climatic Indicators	» North Atlantic Oscillation	» El Niño-Southern Oscillation » Southern Annual Mode	» El Niño-Southern Oscillation » Pacific Decadal Oscillation	» El Niño-Southern Oscillation » Pacific Decadal Oscillation
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 contribute 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 Upper Circumpolar Deep Water supply heat, salt, and nutrients that affect ice properties and enhance biological production » Antarctic krill employ a range of overwintering strategies	» Local wind forcing and basin-scale currents affect spatial and temporal variability in mesoscale circulation » Mesoscale features impact zooplankton biomass, production, distribution, retention, and loss » Variations in the intensity of cross-shelf transport and the levels of primary and secondary production control juvenile coho and chinook salmon growth » High and variable predation mortality of juvenile coho and chinook salmon in the coastal CCS affects population variation	» Local wind forcing and basin-scale currents affect spatial and temporal variability in mesoscale circulation » Mesoscale features impact zooplankton biomass, production, distribution, retention, and loss » Rapid growth and high survival of pink salmon depend on cross-shelf import of large zooplankton from offshore to nearshore waters » High and variable predation mortality of juvenile pink salmon affects population variation

microzooplankton in some regions, were investigated as well.

Having regions with some common, as well as differing, features allowed US GLOBEC to compare the systems in relation to specific physical processes (including stratification, mechanisms of retention and loss, upwelling and downwelling, and cross-front exchange). Regions with closely related target species allowed species comparisons across systems (US GLOBEC, 2009).

CONSIDERATIONS OF MANAGING AND CONDUCTING A LARGE MARINE RESEARCH PROGRAM

The research questions undertaken by US GLOBEC could not be addressed without a large-scale effort over a considerable time period (Turner and Haidvogel, 2009). Large oceanographic research programs require a major commitment of funding, ship availability, science investigator time, and multiple generations of technicians and graduate students. One of the primary aspects of US GLOBEC that contributed to its success was development of partnerships that helped to support the program. Partnerships between the National Science Foundation and the National Oceanic and Atmospheric Administration provided science support and ship time. Partnerships among scientific disciplines pushed the boundaries of traditional fields and widened both the interpretation and the applicability of the scientific results. Partnerships across academic and federal science institutions nurtured important collaborations that continue beyond the end of the GLOBEC program. International partnerships, importantly with the GLOBEC international program, but also through the International Council for the Exploration of the Seas (ICES) and the North Pacific Marine Science Organization (PICES), provided international context for the US regional programs, and were integral for cross-regional comparisons. Many of the ideas and approaches that characterized GLOBEC science have been carried forward and helped shape the science agenda for current international global environmental change programs, such as the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) Project.

Infrastructure also needed to be developed to deal with scientific, logistical, and technical challenges. The program benefitted from outstanding scientific leadership through the scientific steering committee (SSC), which met twice per year during the course of the entire program. The SSC provided general scientific oversight, tracked programmatic progress, developed implementation plans for regional programs and pan-regional synthesis, and liaised with funding agency representatives. Active engagement by the SSC stitched the regional programs together into a national program. It also allowed the program to adapt to financial setbacks, challenges in ship schedules, regional programs staggered in time, and a multitude of other trials. A central planning office for the US GLOBEC program provided strategic planning and program coordination, maintained records of publications, and supported a number of special reports and symposia (see http://www.usglobec.org). The existence of a dedicated planning office

Figure 2. US GLOBEC study regions.

is central to the success of a large interdisciplinary program like US GLOBEC.

Communications to the scientific, governmental, and lay communities were sustained through articles in peer-reviewed scientific journals (over 700 to date), newsletters, dedicated issues of national journals, and numerous special sessions at national and international meetings. Data management needs had to be addressed to allow integration of disparate disciplines through common access to data sets. The GLOBEC data management office, established in the mold of the Joint Global Ocean Flux Study data management effort, has evolved into the Biological and Chemical Oceanographic Data Management Office (BCO-DMO; Baker and Chandler, 2009; Chandler et al., 2012), which now serves the entire oceanographic community.

PROGRAM LEGACIES

The extensive data sets obtained from the US GLOBEC regional program field and synthesis studies provide an important scientific legacy of the program. Field sampling during US GLOBEC included long-term observations as part of the research program, with the intent that aspects of these would be maintained beyond the end of the US GLOBEC program. As an example, the Seward Line in the Gulf of Alaska, initiated by US GLOBEC, has proven to be an important component of monitoring Gulf of Alaska oceanography (http://www.sfos.uaf.edu/sewardline). Monitoring of biology and physics along a cross-shelf transect off central Oregon has been continued, but on a less frequent basis, since US GLOBEC concluded. The Southern Ocean program was groundbreaking as it collected the first austral winter coupled physical-biological measurements (Hofmann et al., 2004). These significant data will "live on" in future scientific analyses and through BCO-DMO, and they will provide foundations for regional Integrated Ecosystem Assessments (**Fogarty et al.**, 2013, in this issue).

US GLOBEC studies led to the recognition of the importance of physical transport in all regions (**Di Lorenzo et al.**, 2013a, b, in this issue). Anomalies and episodic events are now acknowledged as driving forces in marine ecosystem dynamics. These include interactions of the Labrador Current and Scotian shelf waters reacting to the North Atlantic Oscillation and the Arctic Oscillation (Pershing et al., 2005; Greene et al., 2008, 2012), "minty" water events on the Oregon shelf (Huyer, 2003), upwelling-induced hypoxia (Grantham et al., 2004; Chan et al., 2008), transport of different zooplankton populations in different upwelling conditions (Keister and Peterson, 2003; Hooff and Peterson, 2006), and the importance of remote and local connectivity in Southern Ocean krill populations (Piñones et al., 2011, 2013). Marine populations were shown to be sensitive to environmental variability at many different scales (Botsford et al., 1994; Fogarty and Murawski, 1998; Worden et al., 2010). Long-term variability was recognized as an important influence on food web structure and dynamics (Hofmann and Powell, 1998; **Di Lorenzo et al.**, 2013b, in this issue; **Fogarty et al.**, 2013, in this issue).

US GLOBEC made essential contributions to the evolution of numerical modeling as a tool for interdisciplinary understanding and prediction of coupled physical/biological response in the marine environment (**Curchitser et al.**, 2013, in this issue). Modeling was a central tool used by US GLOBEC to integrate process studies, long-term observations, and retrospective studies, as well as to bridge spatial and temporal scales through nesting of model domains. By utilizing many different kinds of models (fully coupled dynamical models, end-to-end food web models, Bayesian hierarchical models, and others), GLOBEC researchers were able to test hypotheses and synthesize understanding in an ecosystem context. As examples, great strides were made in the development of alternative strategies for coupled physical-biological models (Powell et al.,

Table 2. Target species for US GLOBEC process studies.

	Region			
	NW Atlantic/ Georges Bank	Southern Ocean: West Antarctic Peninsula	NE Pacific: California Current System	NE Pacific: Coastal Gulf of Alaska
Target Organisms	*Gadus morhua* *Melanogrammus aeglefinus* *Calanus finmarchicus* *Pseudocalanus* spp.	*Euphausia superba* Penguin spp. Seal spp. Whale spp.	*Oncorhynchus kisutch* *Oncorhynchus tshawytscha* *Calanus* spp. *Euphausia pacifica* *Thysanoessa spinifera*	*Oncorhynchus gorbuscha* *Neocalanus* spp. *Euphausia pacifica* *Thysanoessa spinifera* *Thysanoessa inermis* *Thysanoessa raschii*

2006; Ji et al., 2008a,b; Hermann et al., 2009) and in quantifying uncertainties in them (Lynch et al., 2009; **Milliff et al.**, 2013, in this issue). There were also pioneering approaches to the application of data assimilation in US GLOBEC (McGillicuddy et al., 1998, 2001; Lynch et al., 2001; Fiechter et al., 2011).

Finally, US GLOBEC made enormous advances in linking global climate and regional ocean models, one of the original goals of the program. GLOBEC researchers were the first to run regional models to explore climate variability of the ocean on a regional scale and to investigate the implications to populations (**Curchitser et al.**, 2013, in this issue; **Di Lorenzo et al.**, 2013a,b, in this issue). US GLOBEC investigators significantly advanced the practice of dynamical synthesis and hindcasting in all of the study regions. A new multiscale paradigm was demonstrated for coupling global climate models with regional models at higher resolution (**Curchitser et al.**, 2013, in this issue). Now there is a community actively working on regional climate variability and its impacts on marine animals.

US GLOBEC was able to provide a broader perspective than fisheries science, climate science, or oceanography alone, thereby contributing the basis to move forward into more ecosystem-based approaches to management (Turner and Haidvogel, 2009; **Fogarty et al.**, 2013, in this issue). The many advances highlighted in this issue could not have been made without national support for large integrative ocean science programs. Even in times of shrinking research budgets, there is a vital need for these cross-disciplinary, long-term research programs. Future large ocean research programs will need to incorporate human dimension research from the outset, and build a new community for "transdisciplinary" science (**Haidvogel et al.**, 2013, in this issue). The National Science Foundation has begun to address this through the recent SEES program (Science, Engineering, and Education for Sustainability), and we applaud these types of initiatives. We are proud of what US GLOBEC was able to accomplish, and fully expect that future research programs will benefit from, and build upon, the US GLOBEC legacy to understand climate impacts on ocean ecosystems, and to protect and sustain marine populations.

This is US GLOBEC contribution 737.

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