THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

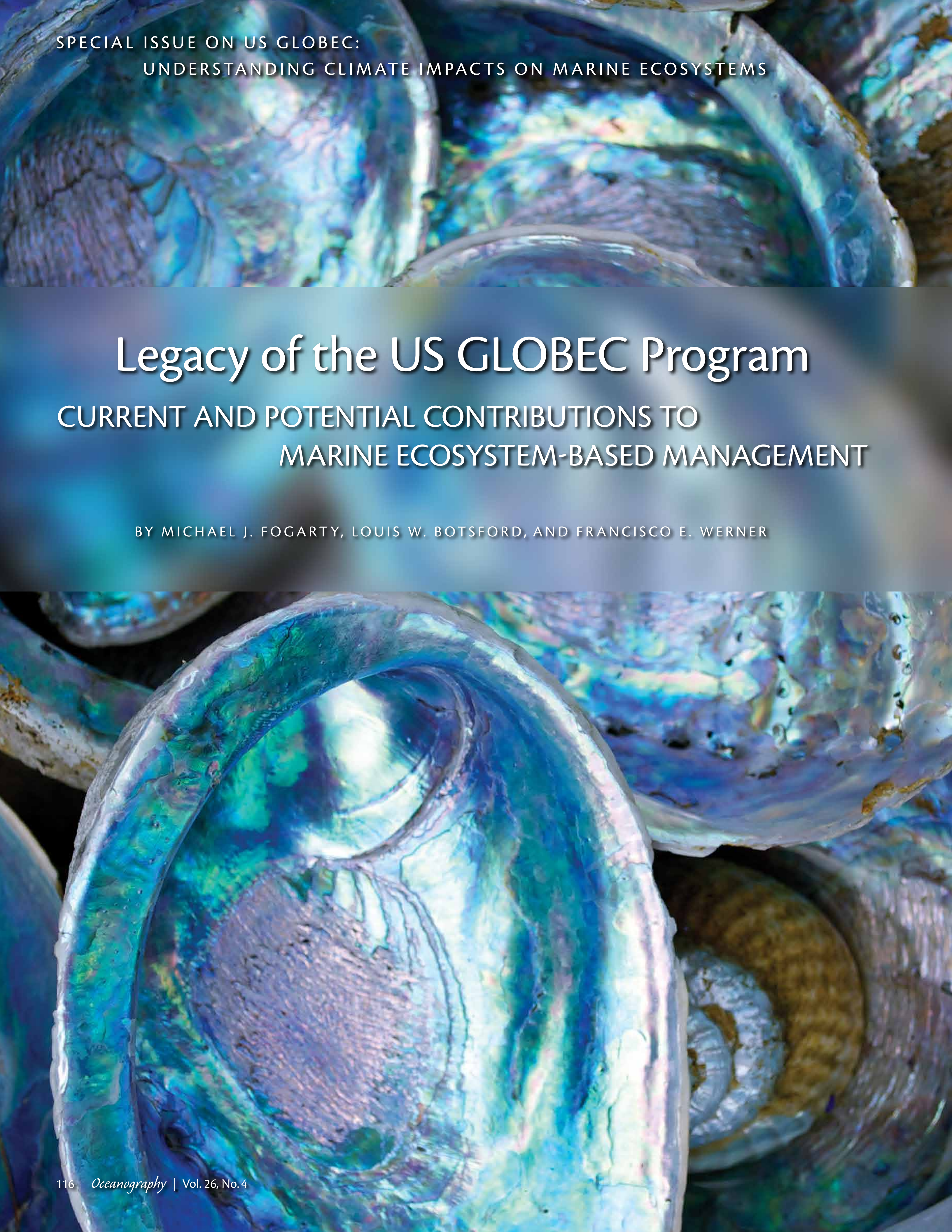
Oceanography

CITATION

Fogarty, M.J., L.W. Botsford, and F.E. Werner. 2013. Legacy of the US GLOBEC program: Current and potential contributions to marine ecosystem-based management. *Oceanography* 26(4):116–127, http://dx.doi.org/10.5670/oceanog.2013.79.

DOI

http://dx.doi.org/10.5670/oceanog.2013.79



Legacy of the US GLOBEC Program

CURRENT AND POTENTIAL CONTRIBUTIONS TO MARINE ECOSYSTEM-BASED MANAGEMENT

BY MICHAEL J. FOGARTY, LOUIS W. BOTSFORD, AND FRANCISCO E. WERNER

ABSTRACT. Management of living marine resources is undergoing a profound transition toward a more holistic, ecosystem-based paradigm. The interplay of climate and environmental forcing, ecosystem structure and function, and human influences and requirements shape the dynamics of these systems in complex ways. The US Global Ocean Ecosystem Dynamics (GLOBEC) program was designed to unravel the elements of this complexity and to forge the tools needed to explore the scope for predictability of ecosystem change in a rapidly changing ocean. As a basic science program, US GLOBEC established new standards in ecological monitoring, technological development, and coupled bio-physical modeling of marine systems. Its legacy goes beyond these fundamental achievements, however, through the realized and potential importance of the GLOBEC approach and findings in resource management. Development of the US GLOBEC program considerably predated the formal adoption of strategies for ecosystem-based management of coastal and marine systems in the United States under the aegis of the National Ocean Policy. The GLOBEC strategy and its resulting products and tools have nonetheless proven extremely valuable in moving toward the goal of operational marine ecosystem-based management. The GLOBEC selection of target species of direct relevance to management (including economically important species and those with special conservation status) underscored the recognized need to provide results of the highest scientific caliber while also meeting broader societal needs and objectives for sustainable resource management. Here, we trace some of the current applications of GLOBEC science in resource management (including the extension of single species management strategies to incorporate climate forcing and the use of broader ecosystem models) and point to its potential to further shape the evolution of marine ecosystem-based management.

INTRODUCTION

The developmental arc of the US Global Ocean Ecosystem Dynamics (GLOBEC) program from conception to implementation strongly reflected a rapidly evolving set of questions and issues at the intersection of basic oceanography, climate science, ecology, and resource management. The genesis of the US GLOBEC program can be traced to a series of fish ecology workshops held from 1980–1983 and a series of subsequent workshops and meetings over the following decade (Fogarty and Powell, 2002; Turner et al., 2013, in this issue). The quest to understand the determinants of recruitment variability of marine organisms in relation to oceanographic processes and environmental forcing mechanisms provided the impetus for these workshops, and this focus ultimately emerged as a core element of GLOBEC research. The difficulty in predicting recruitment had long been recognized as an important impediment to effective fisheries management (e.g., Fogarty et al., 1991). Although this issue was initially framed in the context of traditional single-species management, recognition that the broader dimensions of ecological research in oceanography and fisheries science must be integrated into resource management was also gaining traction. The ecosystem-based perspective and its implications for management was beginning to be incorporated in basic textbooks in oceanography, coastal ecology, and fisheries science (e.g., Pitcher and Hart, 1982; Parsons et al., 1984; Mann, 2000), influencing a new generation of marine scientists and shaping the career paths of many. The focus of research planning for GLOBEC expanded accordingly, ultimately to encompass a strong emphasis on climate processes and their effects on marine populations, communities, and ecosystems.

The establishment of a sequence of important national-level panels concerned with ocean resource management in the United States, including the Pew Oceans Commission (2003) and the US Commission on Ocean Policy (2004), solidified the view that consideration of the interplay of environmental forcing and ecosystem structure and function is essential to both understanding ecosystem dynamics and devising effective management strategies. The US Commission on Ocean Policy (2004) noted that:

> *US ocean and coastal resources should be managed to reflect the relationships among all ecosystem components, including human and nonhuman species and the environments in which they live. Applying this principle will require defining relevant geographic management areas based on ecosystem, rather than political, boundaries.*

McLeod et al. (2005) defined marine ecosystem-based management (mEBM) as:

> *an integrated approach to management that considers the entire ecosystem, including humans. The goal of ecosystem-based management is to maintain an ecosystem in a healthy, productive, and resilient condition so it can provide the services humans want and need. Ecosystem-based management differs from current approaches that usually focus on a single species, sector, activity, or concern; it considers the cumulative impact of different sectors.*

In July 2010, the move toward mEBM in the United States was revitalized with the signing of an executive order establishing a new National Ocean Policy (WHCEQ, 2010). This policy document designated EBM as the cornerstone for coastal ocean management in the United States. Under the National Ocean Policy, management authority resides with the existing management institutions while providing a vehicle for coordination and resolution of tradeoffs among different ocean use sectors. It recognizes that the prospect of climate change is among the major challenges facing society today. Insights derived from the US GLOBEC program in understanding the implications of climate change and variability for ecosystem productivity and resilience provide an important foundation for informing management decisions and designing strategies for mitigation and adaptation. Managers need tools to understand how climate effects influence their ability to frame and to achieve goals and objectives for sustainable resource use. Although US GLOBEC research was centered on selected target species in relation to climate change, the broader ecological dimensions and management implications of the problem were recognized and ultimately incorporated into the program (e.g., Steele et al., 2007; Ruzicka et al., 2013, in this issue).

GLOBEC AND mEBM: MAKING THE CONNECTION

Because EBM goes beyond single species population management to include interactions among species and physical influences on production (Botsford et al., 1997), GLOBEC products ranging from legacy monitoring programs to indicator variables, technological advances, and coupled bio-physical models are well suited to support further development of EBM in marine systems (see Barange et al., 2010) and to assess human impacts on marine ecosystems (Brander et al., 2010).

mEBM establishes an integrated framework for sustainable delivery of ecosystem services from the sea (Fogarty and McCarthy, 2014). Ecosystem services are the benefits humans derive from our connection to the ocean and coasts, including sustenance—one of the long-term (although often unstated) foci for GLOBEC research. A principal goal of mEBM is to protect ecosystem structure and function to ensure continued flow of these benefits. mEBM entails the development of integrated management strategies for defined ecological units. There is a natural connection between this place-based approach and the research strategies established by US GLOBEC, which clearly identified ecological regions with distinct physiographic, oceanographic, ecological, and environmental characteristics as units of study. Figure 1 shows the close relationship of GLOBEC study areas and designated Large Marine Ecosystems (LMEs) within US waters and in the Southern Ocean. These LMEs have been proposed as possible starting points for the delineation of management units for implementation of mEBM in the United States. The overall place-based strategy at the heart of mEBM encompasses not only management units and boundaries but also the application of spatially explicit management strategies, including the establishment of Marine Protected Areas (MPAs) nested within these designated units (see below).

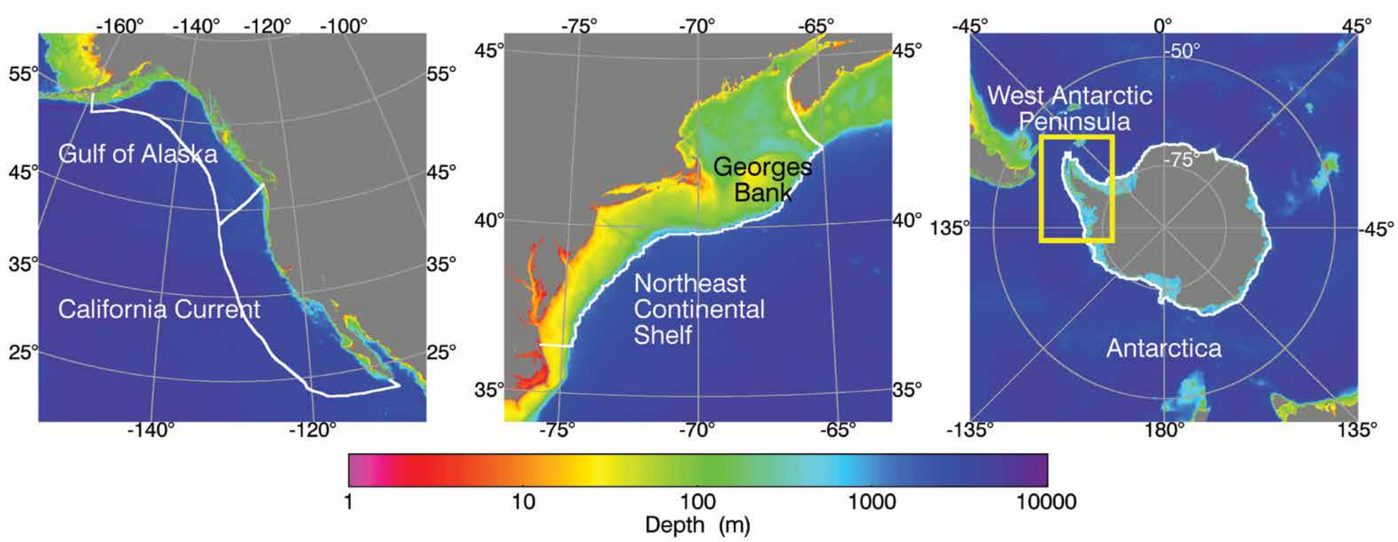


Figure 1. Location of US GLOBEC study areas in relation to boundaries of designated Large Marine Ecosystems (delineated in white). *Maps courtesy of Kimberly Hyde, Northeast Fisheries Science Center*

The focus on understanding connections and interrelationships in mEBM also finds clear resonance in GLOBEC research. GLOBEC target species were selected as dominant components of marine food webs whose connection with environmental drivers are key determinants of change at population, community, and ecosystem levels. In each GLOBEC study area, some of the target species were chosen for both their ecological and economic importance, while others were selected for their critical roles in ecosystem structure and function. For example, GLOBEC zooplankton target species occupy central positions in the food webs in each region, and understanding their dynamics emerges as a critical element in predicting ecosystem change in response to climate forcing.

Implementation of mEBM will require establishment of appropriate governance structures, clearly specified goals and objectives, identification of targets that will serve as guideposts for management, and development of methods for assessment of ecosystem status in relation to specified targets and limits (Levin et al., 2009). The GLOBEC strategy of establishing or supplementing effective monitoring programs in each study region and developing coupled physical-biological models to integrate observations and process studies is particularly relevant to the assessment requirements for mEBM as described below.

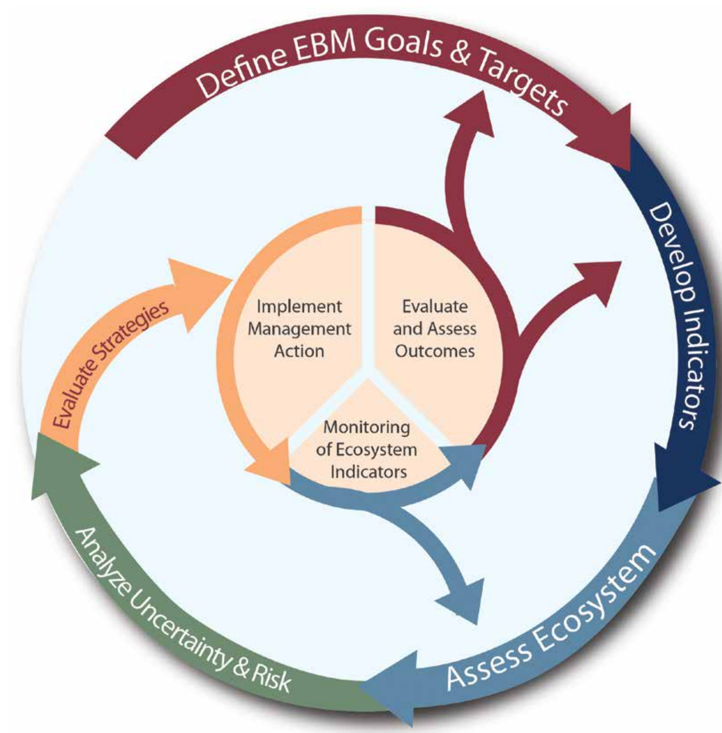


Figure 2. Elements of an Integrated Ecosystem Assessment. This basic framework is now being implemented nationally on the Northeast Continental Shelf (including Georges Bank), in the US portions of the California Current System, in the Gulf of Alaska-Bering Sea, in the Gulf of Mexico, and in the Pacific Islands. The US GLOBEC program has contributed to indicator development and coupled models that can be used for ecosystem assessment, risk analysis, and management strategy evaluation. *Figure courtesy of NOAA Integrated Ecosystem Assessment Program Office*

PUTTING THE PIECES TOGETHER: INTEGRATED ECOSYSTEM ASSESSMENTS

Once objectives are specified for ecosystem-based management in a defined ecological region, the current state of the ecosystem needs to be assessed (including its human and nonhuman dimensions), and the implications of alternative management decisions along with associated risks need to be evaluated. Management decisions impact the broad spectrum of services provided by ecosystems in diverse ways. GLOBEC research products can contribute substantially to the scientific understanding required to inform these decisions.

Integrated Ecosystem Assessments (IEAs) are intended to provide a formalized structure to assess ecosystem status relative to specified objectives and related management targets. IEAs provide "a quantitative synthesis and integration of information on relevant physical, chemical, ecological, and human processes in relation to specified management objectives" (Levin et al., 2008, 2009). Ecosystem models provide the principal synthetic tool for IEAs. The IEA process (Figure 2) iteratively steps through several well-defined stages, including (1) adoption of objectives based on extensive stakeholder engagement, (2) specification of a set of informative indicators that track changes in system dynamics in response to natural and anthropogenic pressures, (3) assessment of the status of the ecosystem in

Michael J. Fogarty *(michael.fogarty@noaa.gov) is Chief, Ecosystems Assessment Program, National Oceanic and Atmospheric Administration (NOAA), Northeast Fisheries Science Center, Woods Hole, MA, USA.* **Louis W. Botsford** *is Professor, Department of Fish, Wildlife, and Conservation Biology, University of California, Davis, CA, USA.* **Francisco E. Werner** *is Director, Southwest Fisheries Science Center, NOAA, La Jolla, CA, USA.*

relation to stated objectives and reference points, (4) analysis of uncertainty and risk, and (5) rigorous simulation testing of proposed management processes (or management strategy evaluations, MSEs). Following this "outer" cycle, management actions with the highest support from the MSEs can be selected for implementation. Continued monitoring and refinement of selected indicators, and routine evaluation of the performance of management strategies then follow (e.g., see inner cycle in Figure 2). Depending on circumstances, some parts of this cycle may be altered and some elements may proceed concurrently rather than sequentially. Many GLOBEC-supported researchers have contributed to the development of the IEA paradigm.

GLOBEC research products can contribute to this process in several key ways. First, careful attention to the development of broad-scale observation programs in each of the GLOBEC regions and the selection of the critical variables to measure provide an important foundation for the choice of indicators to be used in IEAs in each region. Indeed, these indicator variables are now being used to inform management decisions in several GLOBEC study areas. For example, indicators tracking climate factors in the California Current (using the Pacific Decadal Oscillation Index), its copepod community composition, and indicators for Pacific salmon species are now being used to assess status of this important assemblage of pelagic species. The salmon indicators are being used further to develop forecasts of the run size of these species in selected rivers as the fish return to their natal streams to spawn (see http://www.nwfsc.noaa.gov/research/hottopics/salmon_forecasts.cfm).

Second, models developed under US GLOBEC can play an essential role in IEAs as tools for synthesis and integration. They can be used to evaluate the status and condition of marine ecosystems, for forecasting, and for evaluating different management options. Coupled physical-biological models, one of the signature GLOBEC accomplishments (deYoung et al., 2004, 2010; Curchitser et al., 2013, in this issue), can help meet each of these needs. At its core, an IEA involves one or more models that are designed to serve several purposes. Operational ecosystem models can, for example, provide a virtual world within which to: (1) test the outcomes of alternative management strategies, (2) test the performance of potentially simpler models for such management needs as setting fish quotas in a multispecies context, and (3) evaluate the status of protected species under changing climatic conditions and other stressors.

GLOBEC coupled physical-biological models culminated in several endpoints with potential relevance to management. These models ranged from nutrient-phytoplankton-zooplankton-detritus (NPZD) models (see Batchelder et al., 2013, in this issue), including those coupled to higher trophic levels through to fish populations (e.g., Megrey et al., 2007), to full ecosystem models. In general, NPZD models can be connected to upper trophic levels, including managed fish, mammal, seabird, and other species in one of three ways: (1) end-to-end models (E2Es), which can be any model that links ocean physics to an upper trophic level, (2) individual-based models (IBMs) in which each individual is simulated and tracked, and (3) stochastic age structured models, which reflect the dynamic effects of time-lagged responses due to age. Each of these are briefly described in sequence below and more detailed accounts can be found in Batchelder et al. (2013, in this issue), Curchitser et al. (2013, in this issue), and Ruzicka et al. (2013, in this issue).

End-to-End Models

Insights gained from GLOBEC modeling efforts have helped frame the set of expectations for mEBM in GLOBEC study areas. For example, Steele et al. (2007) used an E2E food web model to explore the implications of changing nutrient and environmental regimes on Georges Bank (Figure 3). The analysis entailed evaluation of production and potential yield for fish communities on the bank in relation to climate forcing. Steele et al. (2011) found that sustainable yield levels based on food web considerations were approximately one-third lower for cod and nearly 50% lower for haddock (Steele et al., 2011) relative to single species models. Mountain et al. (2008) reported inverse recruitment patterns for cod and haddock stocks on Georges Bank based on information derived from the Georges Bank broad-scale monitoring program. This result is consistent with the more general inference drawn by Steele et al. (2011) that limiting resources on the bank set overall constraints on the production capacity of fish communities under a given set of environmental conditions. These insights indicate that management plans that do not account for fundamental ecological properties of the system run the risk of providing overly optimistic projections of sustainable yield from these systems, potentially leading to over-exploitation of the resource(s).

Individual-Based Models

IBMs for target fish species in GLOBEC were most often used to represent the individual larvae and juvenile stages (e.g., Lough et al., 2005; Huret et al., 2007). Because the fate of each individual is tracked in these simulations, they can be treated as particles in coupled physical-biological models with unique trajectories and characteristics. The advent of realistic circulation models allowed use of IBMs to determine spawning areas with back-tracking approaches and larval retention/dispersion mechanisms as well as the effect of active swimming behaviors (e.g., Werner et al., 2007; Curchitser et al., 2013, in this issue).

Stochastic Age-Structured Models

Stochastic age-structured models link lower trophic level production to upper trophic level species of interest to management by translating the effects of any changes in upper trophic level vital rates (survival, growth, fecundity) to the population level. Age-structured populations are known to be most sensitive to variability on long time scales, and to generational time scales, an effect termed "cohort resonance" (Bjørnstad et al., 2004). GLOBEC scientists showed that fishing or other long-term changes in survival (e.g., the decline in survival of juvenile salmon in the 1990s) intensified this sensitivity, increasing total population variance (Worden et al., 2010). Increasing sensitivity to slow time scales associated with fishing-induced change confounds detection of climate-induced slow changes in population parameters. These results address the important issue of the synergistic effects of fishing and climate change in marine ecosystems (Planque et al., 2010).

Figure 4 is an example of how species with very different life-history strategies respond to climate-scale forcing by the Pacific Decadal Oscillation (PDO). The dynamical response of a species with a relatively short life span and semelparous (breeding once in a lifetime) history such as Pacific salmon is contrasted with that of a longer-lived iteroparous (repeated reproduction) species such as cod in this analysis. This demonstration of cohort resonance contributes to the initial GLOBEC goal of a better understanding of the factors causing variability in recruitment.

TOOLS FOR MANAGEMENT: GLOBEC RESEARCH AND MARINE PROTECTED AREAS

Spatial management strategies are a critical component in the mEBM toolkit. The use of MPAs in particular to achieve broad ecosystem objectives has received wide attention. MPAs can address multiple objectives, ranging from protection of biodiversity and habitat, to providing refuges from fishing. They arguably hold the potential to meet a broader array of management objectives in an ecosystem context than any other single management tool (Fogarty, 1999; Fogarty et al., 2000).

Over the last decade, California has implemented one of the largest systems of MPAs in the world (http://www.dfg.ca.gov/marine/mpa). GLOBEC researchers were instrumental in many aspects of this initiative. An early focus of GLOBEC modeling centered on the dynamics of marine metapopulations and the potential efficacy of MPAs as a management tool. Metapopulations comprise separate subpopulations distributed over space, linked by dispersing larvae (Botsford et al., 1994).

GLOBEC researchers developed detailed models to assess the effects of proposed MPAs on yield and sustainability for the decision making involved in implementation of California's Marine Life Protection Act (MLPA) (e.g., White et al., 2010, 2011). Protecting ecosystems by controlling fishing using MPAs protects some species more than others,

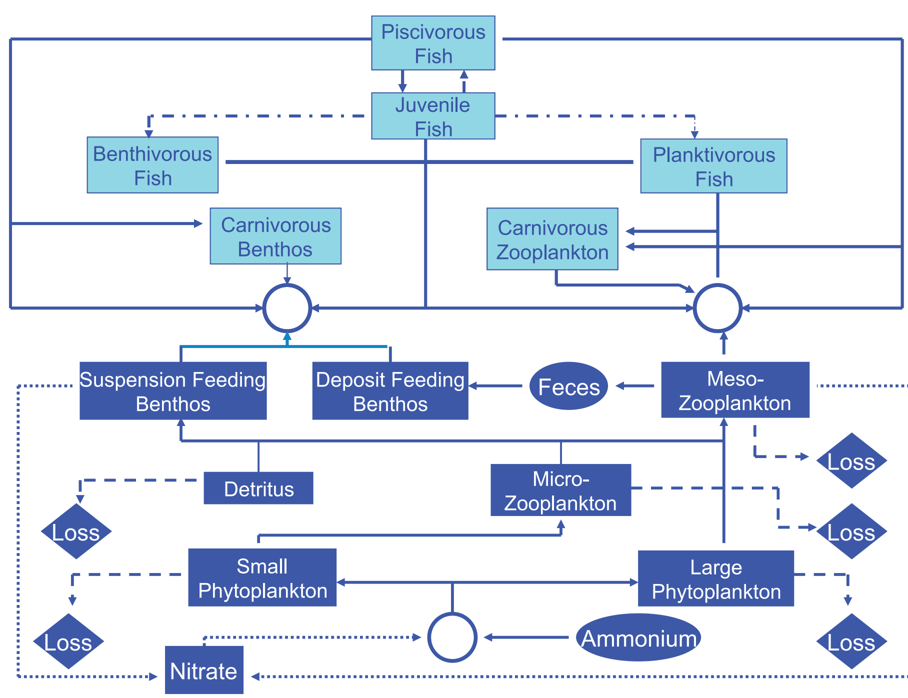


Figure 3. End-to-end food web model for Georges Bank. Rectangles represent elements of the food web. Solid arrows are fluxes. Dashed lines represent recycling. Dash-dot lines represent fish recruitment. Physical losses are shown by dotted lines connecting to arrows. Ovals are inputs (NO_3) and outputs (feces). *Figure adapted from Steele et al. (2007)*

depending on their movement rates and the conventional fisheries management being applied outside the MPAs. As the area protected by MPAs increases, species with shorter larval dispersal and less adult movement (e.g., red abalone, *Haliotis rufescens)* respond more than species with longer larval movement and no adult movement (e.g., cabezon, *Scorpaenichthys marmoratus*) or species with long larval dispersal and large home ranges (e.g., black rockfish, *Sebastes melanops*) (Figure 5; Botsford et al., 2001). However, it also shows that short-distance dispersers (e.g., abalone) predictably contribute less to fisheries outside the reserve (Figure 5b). If fisheries are already sustainably managed, adding MPAs can actually cause fishery yield to decline (Hastings and Botsford, 1999; Figure 5d). Empirical evidence of the effects of differences in species' mobility, fishing patterns, and species interactions on the performance of MPAs was also addressed as an extension of this earlier GLOBEC work (Micheli et al., 2004).

The GLOBEC program on Georges Bank explored the theme of spatial management, with consideration of the importance of larval dispersal of sea scallops (*Placopectin magellanicus*). A finite-element hydrodynamic model coupled with a dispersal submodel incorporating larval behavior was used (Tremblay et al., 1994). The characteristic anticyclonic gyre on Georges Bank, an important focus of GLOBEC physical oceanographic studies, plays a key role in retention of larvae on the bank, with important implications for both self-seeding of areas closed to fishing and provision of larval subsidies to open areas (Fogarty and Botsford, 2007). Subsequent work on the efficacy of the closed areas for an assemblage of fish species, including cod and haddock, revealed interesting differences in both spill-over benefits and biomass accumulation from the closed areas related to the movement patterns and home range of these species (Murawski et al., 2004, 2005; Fogarty and Murawski, 2005).

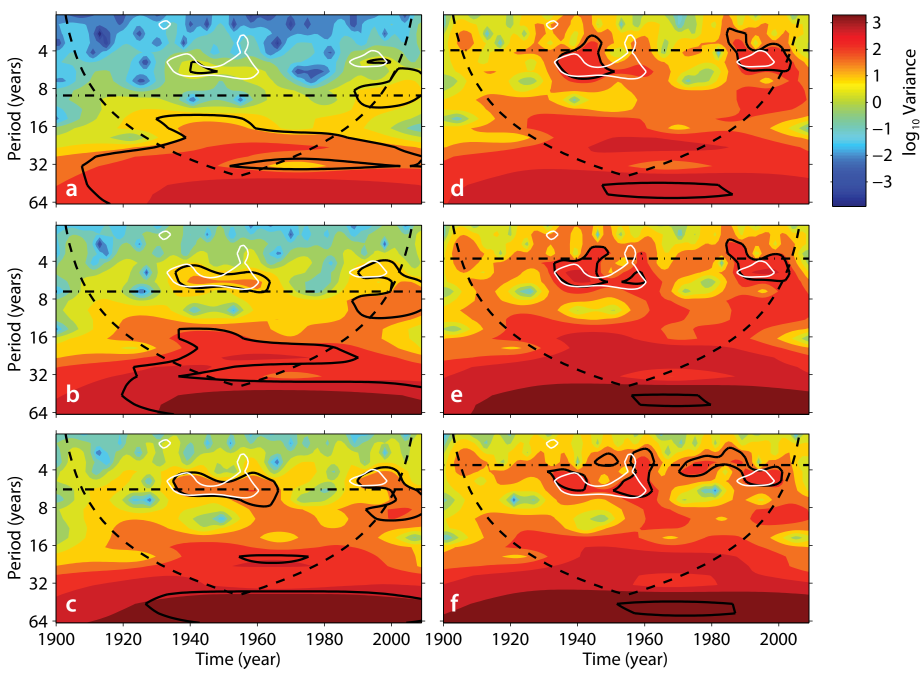


Figure 4. An illustration of how cod (on left) and salmon (on right) would respond to the different time scales of variability in the Pacific Decadal Oscillation (PDO; white outlines) as fishing increases from no fishing (at top) to higher levels (lower). Wavelet spectra for the recruitment of the generic cod species (a, b, and c) and generic salmon (d, e, and f) time series forced by PDO. The three levels of fishing are unfished (a,d), fished to Fraction of Lifetime Egg Production (FLEP) = 0.5 (b, e) and fished to FLEP = 0.3 (c, f). Heavy black contours enclose regions with variance significantly greater than a red-noise process autocorrelation. White contours indicate regions of significant variability in the spectrum of the PDO forcing signal. The horizontal dash-dot line in each panel is the mean age of reproduction (T) for each case. The dashed line is the cone within which results are significant. *Reprinted with permission from Botsford et al. (2011)*

STATUS OF IMPLEMENTATION OF mEBM IN US GLOBEC STUDY AREAS

US GLOBEC research on Georges Bank, the California Current, and the Gulf of Alaska has substantially increased our direct knowledge of major components of three Large Marine Ecosystems in US waters and in an important domain within the broader Antarctic LME (the western Antarctic Peninsula region).

As noted above, the transition to full multisector mEBM has now been initiated in the United States under the provisions of the National Ocean Policy. Regional planning bodies formed under the National Ocean Policy are responsible for developing management strategies within each of nine designated management regions. These regional planning bodies directly consider competing uses of the ocean and associated trade-offs by different sectors (e.g., fisheries, aquaculture, transportation and shipping, energy). Activities of different sectors that entail the pre-emptive use of space (e.g., fishing vs. renewable energy installations) must be reconciled and dealt with using some form of spatial management strategy. Integrated Ecosystem Assessments are now underway in each of the three LMEs off the continental United States where GLOBEC study sites exist (see http://www.noaa.gov/iea).

In the Southern Ocean, one of the first formal mEBM strategies was formulated and implemented. In the following, we provide a brief overview of the state of play in implementing mEBM in the US GLOBEC study areas and how GLOBEC research can help further support these efforts.

Southern Ocean

The Southern Ocean ecosystem is currently managed under the umbrella of the Antarctic Treaty System, which establishes protocols for international cooperation and scientific investigation within the convention area. The treaty sets conservation objectives and strategies for seals and birds, provides a vehicle for coordination with the International Whaling Commission (which is responsible for management of large mammals within the region), and supports research and management of other human impacts, including pollution, shipping, and tourism.

Southern Ocean fisheries are managed through the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR), under the Antarctic Treaty System. Management of krill (*Euphausia superba*) is central to the overall CCAMLR ecosystem-based approach. Krill are recognized as a keystone species in the Antarctic food web (Figure 6). The Antarctic Treaty nations developed and subsequently established CCAMLR in recognition of the threat of unconstrained krill harvest throughout the Southern Ocean ecosystem. Coupled physical-biological models and E2E models for the western Antarctic Peninsula region (incorporating krill and upper trophic level predators) that were developed during the GLOBEC program (see Hofmann et al., 2011; Murphy and Hofmann, 2012) are well suited to contribute to assessment and management of this critically important species. Further work with important potential management applications include demographic models designed to assess the decline of penguin populations in response to predicted climate change (Jenouvrier et al., 2009). Spectral analysis has also been used to evaluate changes in the dynamics of seabird populations in the region in response to climate change (Jenouvrier et al., 2005), again providing important insights into variability of key species in the food web.

Georges Bank

The Northeast Regional Planning Body was the first in the nation to set overall objectives for mEBM under the provisions of the National Ocean Policy and to initiate multisectoral management planning processes. Ecosystem-based fishery management (EBFM), a critical component of the broader mEBM, has a longer developmental history in the region. Fisheries management authority in the region rests with the New England Fishery Management Council (NEFMC). NEFMC has developed a strategy document outlining options for the transition to EBFM within their jurisdiction (O'Boyle et al., 2012). Among the options under consideration is the specification of management targets and limits, with direct consideration of both interspecific interactions and environmental/climate forcing based on multispecies and ecosystem models.

Management of the target GLOBEC fish species, cod and haddock, currently falls under the purview of the NEFMC

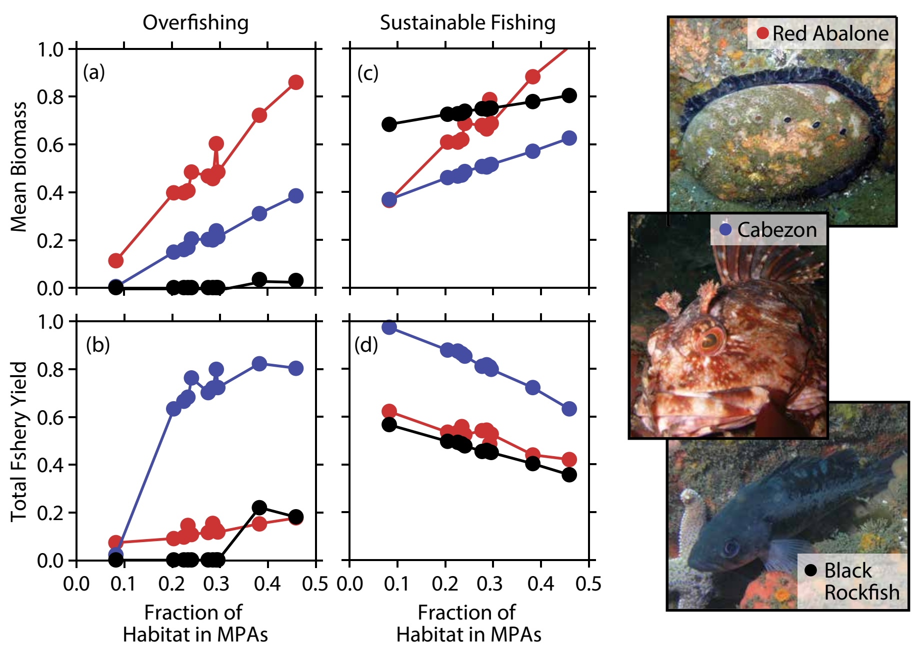


Figure 5. Comparison of the responses to increasing coverage by Marine Protected Areas (MPAs) for three species with different degrees of adult and larval movement, in terms of biomass and fishery yield, when populations are overfished prior to MPAs or are sustainably managed. Each dot represents performance of a specific proposed MPA network in the North Central Region of California's MPAs. Red abalone (*Haliotis rufescens*) have minimal larval dispersal and adult movement. Cabezon (*Scorpaenichthys marmoratus*) have long larval dispersal distance but sedentary adults. Black rockfish (*Sebastes melanops*) have long larval dispersal distance and large home range. *Figure courtesy of Will White, University of North Carolina, Wilmington; photos by S. Halewood (abalone), J. Freiwald (cabezon), and J. Figurski (black rockfish)*

Northeast Multispecies Groundfish Management Plan. As noted above, evidence based on GLOBEC studies suggests that single-species management strategies that ignore ecosystem structure can lead to risk-prone management strategies for these species. The NEFMC EBFM transition strategy entails an assessment of interdependencies among existing plans (including technical [bycatch] interactions and biological interactions among species) and development of a strategy to account for these interactions. These transitional plans are to be ultimately replaced by fully integrated plans within defined ecological management units.

Ecosystem Status Reports are currently produced to document changes in system condition using an ecosystem indicator framework (see http://www.nefsc.noaa.gov/ecosys) as one element of an IEA for the region including Georges Bank. These status reports are routinely provided to the fishery management councils and other interested stakeholder groups to provide an overall context for management decisions based on ecosystem principles.

A number of NPZD models have been developed for Georges Bank, and they have been linked to several IBM models of cod larvae and juveniles (Runge et al., 2010). An ongoing GLOBEC effort is describing the differences in the sensitivity of cod stocks to fishing due to the different temperatures of their local environments (H.-Y. Wang, National Taiwan University, and colleagues, *pers. comm.*, 2013).

California Current

The West Coast Governors Alliance has provided the principal vehicle for coordination and development of mEBM for the states of Washington, Oregon, and California. Again, the most direct connection to GLOBEC research is through fishery and protected species management. The Pacific Fishery Management Council (PFMC) is responsible for fishery management in US federal waters in the California Current LME (CCLME). The PFMC has developed a Fishery Ecosystem Plan (FEP) designed to build on the Council's four existing fishery management plans (PFMC, 2012). The FEP enhances the Council's species-specific management programs with more ecosystem science, broader ecosystem considerations, and management policies that coordinate Council management across its Fishery Management Plans (FMPs).

Development of an IEA for the California Current to support mEBM is now well advanced (Levin and Schwing, 2011; http://www.noaa.gov/iea/CCIEA-Report). This region was selected to be the nation's first full IEA. The PFMC has called for the development of annual State of the Ecosystem Reports for the CCLME to inform ongoing management decisions. The FEP notes the importance of the ongoing effort to develop an IEA for the California Current to inform policy choices (see below). In addition to consideration of the ecosystem requirements established under the Sustainable Fisheries Act, PFMC has instituted requirements to protect forage species of the CCLME food web. For example, in recognition of the role krill play as key forage for many fishery and protected species, PFMC preemptively closed any possibility of developing a krill fishery in the US portion of the CCLME in 2006.

In both the Gulf of Alaska and the California Current, there is considerable interest in the spatial covariability among salmon populations because of the portfolio effect—greater persistence

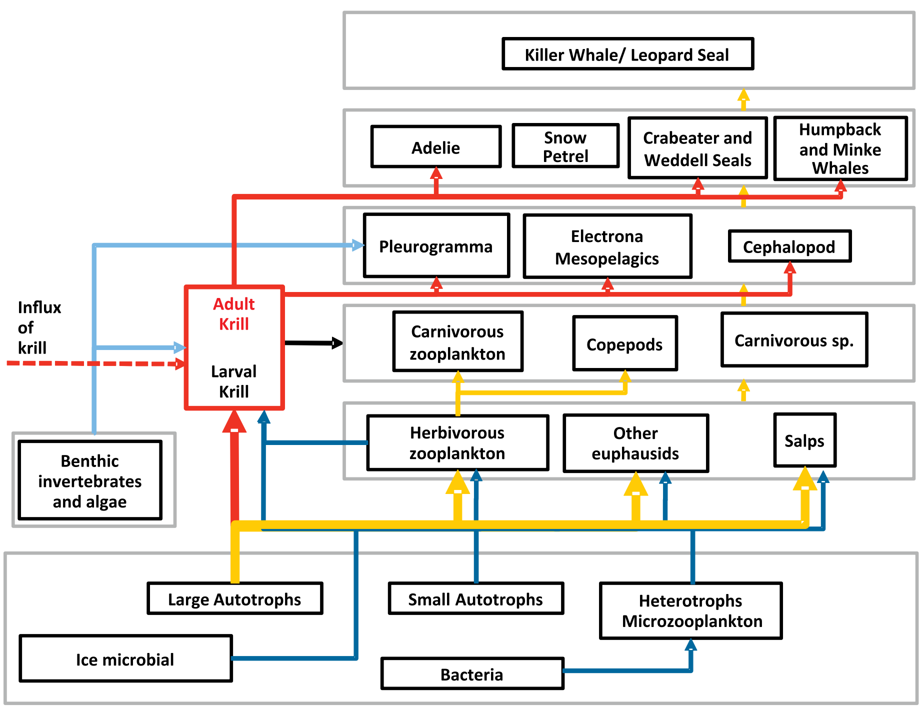


Figure 6. Generic model of Southern Ocean food web structure applied to the West Antarctic Peninsula based on knowledge of the summer food web operation. Red arrows indicate the main Antarctic krill trophic pathways. Yellow arrows are the main non-krill pathways involving the large autotrophs and dark blue arrows the main non-krill links associated flows from other components of the microbial system. Lighter blue arrows indicate the main benthic-pelagic connections. *Figure from Murphy et al. (2013)*

of aggregates of separate salmon stocks when there is lower covariability among stocks (e.g., Schindler et al., 2010). Ongoing GLOBEC research indicates increasing alongshore covariability in ocean survivals of Chinook salmon (Kilduff et al., in press). Also, in collaboration with NOAA, GLOBEC researchers are investigating the degree to which increasing covariability among the Chinook salmon stocks in the tributaries of the Sacramento River (Carlson and Satterthwaite, 2011) may have contributed to the recent collapse of the central California fishery in 2007 and 2008 (Lindley et al., 2009).

Gulf of Alaska

The Alaska Marine Ecosystem Forum (AMEF) provides cross-sectoral coordination and collaboration for mEBM in Alaska. The AMEF includes representatives of the North Pacific Fisheries Management Council (NPFMC), four state agencies, and 10 federal agencies, providing a mechanism for collaboration and coordination (Alaska Marine Ecosystem Forum, 2006). The NPFMC, the State of Alaska, and the International Pacific Halibut Commission coordinate with one another in the management of fishery resources. The Alaska region has a highly developed ecosystem-based fishery management system that incorporates large fishery closed areas to protect habitat and vulnerable species (Witherell et al., 2000). Conservative caps on total fishery removals have been implemented in the Gulf of Alaska and the Bering Sea-Aleutian Islands systems. These caps are 20–30% lower on average than the sum of individual species allocations derived from single-species analyses (D. Witherell, NPFMC, *pers. comm*., 2013).

The NPFMC recently developed an Aleutian Islands Fishery Ecosystem Plan (AIFEP) to specify strategies for EBFM in the region (AIFEP Team, 2007). The AIFEP incorporates an EBM-based risk assessment approach by addressing sectors beyond fishing (e.g., shipping), and serves as advisory document to the NPFMC. Fisheries in the Aleutian Islands are now managed under the Bering Sea Aleutian Islands Fishery Management Plan, and the AIFEP is again intended to provide a broader ecosystem context. An Ecosystem Considerations Report has been prepared annually since 1995, providing indicators focused on productivity (Zador and Gaichas, 2010). Models currently being used to support the IEA process in the gulf draw on information from a number of research programs, including some initiated under GLOBEC. Monitoring lines established in the Gulf of Alaska and enhanced with GLOBEC funding serve to track key indicators in the region.

Both the NPFMC and the PFMC are gradually adding considerations from ecosystem indicators and ecosystem models to their decision-making processes with single species, age-structured models (Livingston et al., 2005). The well-known cycles in sockeye salmon abundance and catch in Bristol Bay, Alaska, and the Fraser River in British Columbia have recently been described by GLOBEC researchers as being an extreme case of the cohort resonance seen in stochastic age-structured models (White et al., in press).

FUTURE DEVELOPMENTS AND NEEDS

The development of mEBM in the United States has just been initiated under the impetus of the National Ocean Policy. The analytical framework required to support mEBM through the development of IEAs is also now being developed and refined. The GLOBEC legacy of model development, monitoring, indicator development, and advanced instrumentation can contribute to the evolution of mEBM and associated IEAs in critical ways. The GLOBEC commitment and investment in human capital through the training of students and postdocs now in academic and decision-making positions is also a critically important element of the GLOBEC legacy (see also Turner and Haidvogel, 2009).

IEAs are now being developed in a phased implementation strategy (not unlike that employed in the GLOBEC program itself) in the California Current, Gulf of Mexico, Northeast Continental Shelf (including Georges Bank), the Gulf of Alaska, and the Pacific Islands. US GLOBEC program products can thus contribute materially to three of the five IEA initiatives underway in the country, and can provide insights into best practices in the remainder. The realization of the nature and magnitude of the impacts to the Southern Ocean due to a changing climate will undoubtedly result in further need and application of GLOBEC results from both US work in the western Antarctic Peninsula region and the complementary work of other international GLOBEC countries in the broader domain of the Southern Ocean. This work will assist in implementation of the Convention for the Conservation of Antarctic Marine Living Resources and the Antarctic Treaty System in general. A concerted effort to fully integrate GLOBEC products and knowledge into these efforts in US waters and the Southern Ocean will pay important dividends in the future and will improve the sustainability of living marine resources in these regions.

ACKNOWLEDGMENTS

We are grateful for the many helpful comments and criticisms of Ian Perry, Claudia Mengelt, and Steven Murawski. Bill Peterson and Eileen Hofmann kindly provided information for the California Current and Southern Ocean programs. This is US GLOBEC contribution 745.

REFERENCES

AIFEP (Aleutian Islands Fishery Ecosystem Plan) Team. 2007. *Aleutian Islands Fishery Ecosystem Plan*. North Pacific Fishery Management Council, Anchorage, AK, 190 pp. Available online at: http://www.npfmc.org/wp-content/PDFdocuments/conservation_issues/AIFEP/AIFEP12_07.pdf (accessed January 4, 2014).

Alaska Marine Ecosystem Forum. 2006. Alaska Marine Ecosystem Forum Memorandum of Understanding. Available online at: http://www.npfmc.org/wp-content/PDFdocuments/conservation_issues/AIFEP/AMEF_MOU.pdf (accessed January 4, 2014).

Barange, M., R. O'Boyle, K.L. Cochrane, M.J. Fogarty, A. Jarre, L.T. Kell, F.W. Köster, J.R. King, C.L. de Moor, K. Reid, M. Sinclair, and A. Yatsu. 2010. Marine resource management in the face of change: From ecosystem science to ecosystem management. Pp. 253–283 in *Marine Ecosystems and Global Change*. M. Barange, J. Field, R. Harris, E. Hofmann, I. Perry, and F. Werner, eds, Oxford University Press.

Batchelder, H.P., K.L. Daly, C.S. Davis, R. Ji, M.D. Ohman, W.T. Peterson, and J.A. Runge. 2013. Climate impacts on zooplankton population dynamics in coastal marine ecosystems. *Oceanography* 26(4):34–51, http://dx.doi.org/10.5670/oceanog.2013.74.

Bjørnstad, O.N., R.M. Nisbet, and J.-M. Fromentin. 2004. Trends and cohort resonant effects in age-structured populations. *Journal of Animal Ecology* 73:1,157–1,167, http://dx.doi.org/10.1111/j.0021-8790.2004.00888.x.

Botsford, L.W., J.C. Castilla, and C.H. Peterson. 1997. The management of fisheries and marine ecosystems. *Science* 277:509–515, http://dx.doi.org/10.1126/science.277.5325.509.

Botsford, L.W., A. Hastings, and S.D. Gaines. 2001. Dependence of sustainability on the configuration of marine reserves and larval dispersal distance. *Ecology Letters* 4:144–150, http://dx.doi.org/10.1046/j.1461-0248.2001.00208.x.

Botsford, L.W., M.D. Holland, J.F. Samhouri, J.W. White, and A. Hastings. 2011. Importance of age structure in models of the response of upper trophic levels to fishing and climate change. *ICES Journal of Marine Science* 68:1,270–1,283, http://dx.doi.org/10.1093/icesjms/fsr042.

Botsford, L.W, C.L. Moloney, A. Hastings, J.L. Largier, T.M. Powell, K. Higgins, and J.F. Quinn. 1994. The influence of spatially and temporally varying oceanographic conditions on meroplanktonic metapopulations. *Deep-Sea Research Part II* 41:107–145, http://dx.doi.org/10.1016/0967-0645(94)90064-7.

Brander, K., L.W. Botsford, L. Ciannelli, M.J. Fogarty, M. Heath, B. Planque, L.J. Shannon, and K. Wieland. 2010. Human impacts on marine ecosystems. Pp. 41–71 in *Marine Ecosystems and Global Change*. M. Barange, J. Field, R. Harris, E. Hofmann, I. Perry, and F. Werner, eds, Oxford University Press.

Carlson, S.M., and W.H. Satterthwaite. 2011. Weakened portfolio effect in a collapsed salmon population complex. *Canadian Journal of Fisheries and Aquatic Sciences* 68:1,579–1,589, http://dx.doi.org/10.1139/f2011-084.

Curchitser, E.N., H.P. Batchelder, D.B. Haidvogel, J. Fiechter, and J. Runge. 2013. Advances in physical, biological, and coupled ocean models during the US GLOBEC program. *Oceanography* 26(4):52–67, http://dx.doi.org/10.5670/oceanog.2013.75.

deYoung, B., M. Heath, F. Werner, F. Chai, B. Megrey, and P. Monfray. 2004. Challenges of modeling decadal variability in ocean basin ecosystems. *Science* 304:1,463–1,466, http://dx.doi.org/10.1126/science.1094858.

deYoung, B., F. Werner, H. Batchelder, F. Carlotti, Ø. Fiksen, E.E. Hofmann, S. Kim, H. Yamazaki, and M. Kishi. 2010. Dynamics of marine ecosystems: Integration through models of physical-biological interactions. Pp. 89–128 in *Marine Ecosystems and Global Change*. M. Barange, J. Field, R. Harris, E. Hofmann, I. Perry, and F. Werner, eds, Oxford University Press.

Fogarty, M.J. 1999. Essential habitat, marine reserves, and fishery management. *Trends in Ecology and Evolution* 14:133–134, http://dx.doi.org/10.1016/S0169-5347(98)01579-1.

Fogarty, M.J., J. Bohnsack, and P. Dayton. 2000. Marine reserves and resource management. Pp. 283–300 in *Seas at the Millennium: An Environmental Evaluation*. C. Sheppard, ed, Elsevier.

Fogarty, M.J., and L.W. Botsford. 2007. Population connectivity and spatial management of marine fisheries. *Oceanography* 20(3):112–123, http://dx.doi.org/10.5670/oceanog.2007.34.

Fogarty, M.J., and J.M. McCarthy, eds. 2014. *The Sea, Volume 16: Marine Ecosystem-Based Management*. Harvard University Press, Cambridge, MA, 568 pp.

Fogarty, M.J., and S.A. Murawski. 2005. Do marine protected areas really work? *Oceanus* 43:42–44. Available online at: http://www.whoi.edu/oceanus/feature/do-marine-protected-areas-really-work (accessed January 3, 2014).

Fogarty, M.J., and T.M. Powell. 2002. An Overview of the US GLOBEC program. *Oceanography* 15(2):4–12, http://dx.doi.org/10.5670/oceanog.2002.17.

Fogarty, M.J., M.P. Sissenwine, and E.B. Cohen. 1991. Recruitment variability and the dynamics of exploited marine populations. *Trends in Ecology and Evolution*. 6:241–246, http://dx.doi.org/10.1016/0169-5347(91)90069-A.

Hastings, A., and L.W. Botsford. 1999. Equivalence in yield from marine reserves and traditional fisheries management. *Science* 284:1,537-1,538, http://dx.doi.org/10.1126/science.284.5419.1537.

Hofmann, E.E., P.H. Wiebe, D.P. Costa, and J.J. Torres. 2011, eds. Understanding the linkages between Antarctic food webs and the environment: A synthesis of Southern Ocean GLOBEC studies. Special issue *Deep Sea Research Part II* 58(13–16):1,505–1,507.

Huret, M., J.A. Runge, C. Chen, G. Cowles, Q. Xu, and J.M. Pringle. 2007. Dispersal modeling of fish early life stages: Sensitivity with application to Atlantic cod in the western Gulf of Maine. *Marine Ecology Progress Series* 347:261–274, http://dx.doi.org/10.3354/meps06983.

Jenouvrier, S., H. Caswell, C. Barbraud, M. Holland J. Stroeve, and H. Weimerskirch. 2009. Demographic models and IPCC climate projections predict the decline of an emperor penguin population. *Proceedings of the National Academy of Sciences of the United States of America* 106:1,844–1,847, http://dx.doi.org/10.1073/pnas.0806638106.

Jenouvrier, S., H. Weimerskirch, C. Barbraud, Y.-H. Park, and B. Cazelles. 2005. Evidence of a shift in the cyclicity of Antarctic seabird dynamics linked to climate. *Proceedings of the Royal Society B* 272:887–895.

Kilduff, D.P., L.W. Botsford, and S.L.H. Teo. In press. Spatial and temporal covariability in early ocean survival of Chinook salmon (*Oncorhynchus tshawytscha*) along the west coast of North America. *ICES Journal of Marine Science*.

Levin, P.S., M.J. Fogarty, G.C. Matlock, and M. Ernst. 2008. *Integrated Ecosystem Assessments*. US Department of Commerce, NOAA Technical Memorandum NMFS-NWFSC-92, 20 pp. Available online at: http://www.st.nmfs.noaa.gov/iea/documents/IEA_TM92Final.pdf (accessed January 3, 2014).

Levin, P.S, M.J. Fogarty, S.A. Murawski, and D. Fluharty. 2009. Integrated ecosystem assessments: Developing the scientific basis for ecosystem-based management of the ocean. *PLoS Biology* 7(1):e1000014, http://dx.doi.org/10.1371/journal.pbio.1000014.

Levin, P.S., and F.B. Schwing, eds. 2011. *Technical Background for an Integrated Ecosystem Assessment of the California Current: Groundfish, Salmon, Green Sturgeon, and Ecosystem Health*. US Department of Commerce, NOAA Technical Memorandum, NMFS-NWFSC-109, 330 pp. Available online at: http://www.nwfsc.noaa.gov/assets/25/1618_07122011_125959_CalCurrentIEATM109WebFinal.pdf (accessed January 3, 2014).

Lindley, S.T., C.B. Grimes, M.S. Mohr, W. Peterson, J. Stein, J.T. Anderson, L.W. Botsford, D.L. Bottom, C.A. Busack, T.K. Collier, and others. 2009. *What Caused the Sacramento River*

Fall Chinook Stock Collapse? US Department of Commerce, NOAA Technical Memorandum. NOAA-TM-NMFS-SWFSC-447, 61 pp. Available online at http://swfsc.noaa.gov/publications/TM/SWFSC/NOAA-TM-NMFS-SWFSC-447.PDF (accessed January 3, 2014).

Livingston, P.A., K. Aydin, J. Boldt, J. Ianelli, and J. Jurado-Molina. 2005. A framework for ecosystem impacts assessment using an indicator approach. *ICES Journal of Marine Science* 62:592–597, http://dx.doi.org/10.1016/j.icesjms.2004.12.016.

Lough, R.G., L.J. Buckley, F.E. Werner, J.A. Quinlan, and K. Pehrson Edwards. 2005. A general biophysical model of larval cod (*Gadus morhua*) growth applied to populations on Georges Bank. *Fisheries Oceanography* 14:241–262, http://dx.doi.org/10.1111/j.1365-2419.2005.00330.x.

Mann, K. 2000. *Ecology of Coastal Waters with Implications for Management.* J. Wiley and Sons, Hoboken, 404 pp.

McLeod, K.L., J. Lubchenco, S.R. Palumbi, and A.A. Rosenberg. 2005. Scientific consensus statement on marine ecosystem-based management. Communication Partnership for Science and the Sea. Available online at: http://doc.nprb.org/web/BSIERP/EBM scientific statement.pdf (accessed January 3, 2014).

Megrey, B.A., K.A. Rose, R. Klumb, D. Hay, F.E. Werner, D.L. Eslinger, and S.L. Smith. 2007. A bioenergetics-based population dynamics model of Pacific herring (*Clupea harengus pallasii*) coupled to a lower trophic level nutrient-phytoplankton-zooplankton model: Description, calibration and sensitivity analysis. *Ecological Modelling* 202:144–164, http://dx.doi.org/10.1016/j.ecolmodel.2006.08.020.

Micheli, F., B.S. Halpern, L.W. Botsford, and R.R.Warner. 2004. Trajectories and correlates of community change in no-take marine reserves. *Ecological Applications* 14:1,799–1,723, http://dx.doi.org/10.1890/03-5260.

Mountain, D., J. Green, J. Sibunka, and D. Johnson. 2008. Growth and mortality of Atlantic cod *Gadus morhua* and haddock *Melanogrammus aeglefinus* eggs and larvae on Georges Bank, 1995–1999. *Marine Ecology Progress Series* 353:225–242, http://dx.doi.org/10.3354/meps07176.

Murawski, S.A., P. Rago, and M. Fogarty. 2004. Spillover effects from temperate marine protected areas. *American Fisheries Society Symposium* 42:167–184.

Murawski, S.A., S.E. Wigley, M.J. Fogarty, P.J. Rago, and D.G. Mountain. 2005. Effort distribution and catch patterns adjacent to temperate MPAs. *ICES Journal of Marine Science* 62:1,150–1,167, http://dx.doi.org/10.1016/j.icesjms.2005.04.005.

Murphy, E.J., and E.E. Hofmann. 2012. End-to-end in Southern Ocean ecosystems. *Current Opinion in Environmental Sustainability* 4:264–271, http://dx.doi.org/10.1016/j.cosust.2012.05.005.

Murphy, E.J., E.E. Hofmann, J.L. Watkins, N.M. Johnston, A. Piñones, T. Ballerini, S.L. Hill, P.N. Trathan, G.A. Tarling, R.A. Cavanagh, and others. 2013. Comparison of the structure and function of Southern Ocean regional ecosystems: The Antarctic Peninsula and South Georgia. *Journal of Marine Systems* 109–110:22–42, http://dx.doi.org/10.1016/j.jmarsys.2012.03.011.

O'Boyle, B., S. Cadrin, D. Georgianna, J. Kritzer, M. Sissenwine, M. Fogarty, C. Kellogg, and P. Fiorelli. 2012. Ecosystem-based fishery management for the New England Fishery Management Council. Paper presented at the Wakefield Symposium on Ecosystem-Based Fisheries Management. Available online at: http://seagrant.uaf.edu/conferences/2010/wakefield-ecosystems/presentations/o'boyle-new-england-fishery.pdf (accessed January 4, 2014).

Parsons, T.R., M. Takahashi, and B. Hargrave. 1984. *Biological Oceanographic Processes*, 3rd ed. Pergamon Press, 344 pp.

Pew Oceans Commission. 2003. *America's Living Oceans: Charting a Course for a Sea Change, A Report to the Nation.* Pew Charitable Trusts, Washington, DC, 144 pp. Available online at: http://www.pewtrusts.org/our_work_report_detail.aspx?id=30009 (accessed January 4, 2014).

PFMC (Pacific Fishery Management Council). 2012. *Pacific Coast Fishery Ecosystem Plan for the US Portion of the California Current Large Marine Ecosystem.* Pacific Fishery Management Council, Portland, OR, 83 pp.

Pitcher, T.J., and P.J.B. Hart. 1982. *Fisheries Ecology*. Kluwer Academic Publishers, Norwell, MA, 414 pp.

Planque, B., J.-M. Fromentin, P. Cury, K.F. Drinkwater, S. Jennings, R.I. Perry, and S. Kifani. 2010. How does fishing alter marine populations and ecosystems sensitivity to climate? *Journal of Marine Systems* 79:403–417, http://dx.doi.org/10.1016/j.jmarsys.2008.12.018.

Ruzicka, J.J., J.H. Steele, S.K. Gaichas, T. Ballerini, D.J. Gifford, R.D. Brodeur, and E.E. Hofmann. 2013. Analysis of energy flow in US GLOBEC ecosystems using end-to-end models. *Oceanography* 26(4):82–97, http://dx.doi.org/10.5670/oceanog.2013.77.

Schindler, D.E., R. Hilborn, B. Chasco, C.P. Boatright, T.P. Quinn, L.A. Rogers, and M.S. Webster. 2010. Population diversity and the portfolio effect in an exploited species. *Nature* 465:609–613, http://dx.doi.org/10.1038/nature09060.

Steele, J.H., J. Bisagni, J. Collie, M. Fogarty, D. Gifford, J. Link, M. Sieracki, B. Sullivan, and A. Beet. 2007. Balancing end-to-end budgets of the Georges Bank ecosystem. *Progress in Oceanography* 74:423–448, http://dx.doi.org/10.1016/j.pocean.2007.05.003.

Steele, J.H, D.J., Gifford, and J.S. Collie. 2011. Comparing species and ecosystem-based estimates of fisheries yield. *Fisheries Research* 111:139–144, http://dx.doi.org/10.1016/j.fishres.2011.07.009.

Tremblay, M.J., J.W. Loder, F.E. Werner, C. Naimie, F.H. Page, and M.M. Sinclair. 1994. Drift of scallop larvae on Georges Bank: A model study of the roles of mean advection, larval behavior and larval origin. *Deep Sea Research Part II*, 41:7–49, http://dx.doi.org/10.1016/0967-0645(94)90061-2.

Turner, E., and D.B. Haidvogel. 2009. Taking ocean research results to applications: Examples and lessons learned from US GLOBEC. *Oceanography* 22(4):232–241, http://dx.doi.org/10.5670/oceanog.2009.111.

Turner, E., D.B. Haidvogel, E.E. Hofmann, H.P. Batchelder, M.J. Fogarty, and T. Powell. 2013. US GLOBEC: Program goals, approaches, and advances. *Oceanography* 26(4):12–21, http://dx.doi.org/10.5670/oceanog.2013.72.

US Commission on Ocean Policy. 2004. *An Ocean Blueprint for the 21st Century*. Final report. Washington, DC, 522 pp. plus appendices. Available online at: http://govinfo.library.unt.edu/oceancommission/documents/full_color_rpt/welcome.html (accessed January 4, 2014).

Werner, F.E., R.K. Cowen, and C.B. Paris. 2007. Coupled biological and physical models: Present capabilities and necessary developments for future studies of population connectivity. *Oceanography* 20(3):54–69, http://dx.doi.org/10.5670/oceanog.2007.29.

WHCEQ (White House Council on Environmental Quality). 2010. *Final Recommendations of the Interagency Ocean Policy Task Force*. Washington, DC, 77 pp. plus appendices. Available online at: http://www.whitehouse.gov/files/documents/OPTF_FinalRecs.pdf (accessed January 4, 2014).

White, J.W., L.W. Botsford, M.L. Baskett, L.A.K. Barnett, R.J. Barr, and A. Hastings. 2011. Linking models and data in assessment of no-take reserves. *Frontiers in Ecology and the Environment* 9:390–399, http://dx.doi.org/10.1890/100138.

White, J.W., L.W. Botsford, A. Hastings, and M.D. Holland. In press. Stochastic models reveal conditions for cyclic dominance in sockeye salmon populations. *Ecological Monographs*, http://dx.doi.org/10.1890/12-1796.1.

White, J.W., L.W. Botsford, E.A. Moffitt, and D.T. Fischer. 2010. Decision analysis for designing marine protected areas for multiple species with uncertain fishery status. *Ecological Applications* 20:1,523–1,541.

Worden, L., L.W. Botsford, A. Hastings, and M.D. Holland. 2010. Frequency responses of age structured populations: Pacific salmon as an example. *Theoretical Population Biology* 78:239–249, http://dx.doi.org/10.1016/j.tpb.2010.07.004.

Witherell, D., C. Pautzke, and D. Fluharty. 2000. An ecosystem-based approach for Alaska groundfish fisheries. *ICES Journal of Marine Science*. 57:771–777, http://dx.doi.org/10.1006/jmsc.2000.0719.

Zador, S., and S. Gaichas, eds. 2010. *Ecosystem Considerations for 2011.* North Pacific Fishery Management Council, Anchorage, AK, 242 pp. Available online at: http://access.afsc.noaa.gov/reem/ecoweb/Eco2010.pdf (accessed January 4, 2014).