A 2-day workshop on “Modeling Ecosystems and Ocean Processes: The GLOBEC Perspective of the Past, Present, and Future”, co-convened by the authors of this article, was held at the 2009 GLOBEC Open Science Meeting (June 22–23). It attracted a considerable interest, with approximately 50 attendees over both days. The general goals of the workshop were to summarize the physical and biological modeling activities during the GLOBEC years and discuss future directions. The workshop was divided into four sub-topics: (1) Physical and biological modeling, (2) Biological and advanced ecosystem models, (3) Frontiers in ecosystem modeling, and (4) Climate change in regional marine ecosystems, although there was some unavoidable overlap between these. Workshop activities included five invited (review) talks (by Francisco Werner, Raghu Murtugudde, Jerome Fiechter, Michael Follows and Kenneth Drinkwater), which introduced individual sub-topics, and over 35 submitted talks, in addition to six posters and a final discussion session. Some of the common themes that emerged from the discussions and some of the presentations focused on (1) end-to-end models, (2) agent-based models, (3) complex food-webs, (4) simple vs. complex ecosystem models, and (5) evolutionary models.

The traditional (“classical” or more “advanced”) physical–biological coupled models, especially NPZD models coupled with three-dimensional physical models, have achieved considerable progress in the study of marine ecosystems. For long-term predictions, like the ecosystem response to climate change, traditional methods using physical–biological coupled models are still useful. Since the 1990’s, IBM (Individual Based Models) have been successfully employed to capture much of the physical–biological interaction in marine ecosystems. The IBM approach has also been widely used in modeling zooplankton or larval fish behavior. However, as it was pointed out during the discussions, the more complex models need more data to assess the degree of realism and more parameters need to be specified. There is ample space for discussion on this matter, but we must recognize that, although advances in computing technology allow us to increase the number of biological compartments or refine the grid in our models, ecosystem models are just “models”, i.e., representations of nature. Nevertheless, as the impacts of climate change become manifest in all components of the Earth System, the need for high resolution (meter scale) multi-compartment modeling frameworks for policy and decision-making and adaptive management is very clear. The IPCC-class models continue to enhance their spatial resolutions but participatory decision-making on the ground will always require further improvements in the resolution at which Earth System information is provided with its irreducible uncertainties, and will require dynamic and statistical downscaling.

A prototype implementation of a regional Earth System prediction framework was illustrated for Chesapeake Bay by Raghu Murtugudde (Fig. 1). This forecasting system uses the WRF (Weather Research and Forecasting) regional atmosphere model, NOAH land model, ROMS (Regional Ocean Modeling System) ocean model and the SWAT (Soil and Water Assessment Tool) watershed model to generate seasonal predictions and decadal projections for not only meteorological and climatic variables but also for nutrient and sediment loading of streams, pathogens, harmful algal blooms, fisheries, dissolved oxygen, and other ecosystem parameters. An important aspect of this type of regional Earth System prediction approach is to recruit users such as city water supply managers, parks and river keepers, and watermen so that the model forecasts are employed in decision-making. This allows quantitative feedbacks from the users that are important to validate, optimize, provide uncertainties, and improve skills and products of the Earth System prediction. In the case of the Chesapeake Bay system, an interactive decision-making tool has been developed such that users can change land use types, crops, urban sprawl, emissions, population, and other variables of interest to track the impacts on air and water quality, health of the coast–estuarine ecosystems, pathogen levels, and other critical system indicators. While the task of validating the output of these systems with data remains an important issue to address, the philosophy is to demonstrate the feasibility of regional Earth System prediction and its usefulness in determining the observational data needs.
Other topics of discussion about future progress and model applications included the use of modeling tools to describe species migrations (in regional models), including the spread of “invasive” species or, in terms of methodology, allowing for shifting parameters/distributions to describe entropy maximization. An interesting approach based on the self-organizing principle of marine ecosystems was presented by Michael Follows, where the marine ecosystems are organized by the relative fitness of the myriad of potentially viable phenotypes in a given environment. With this guiding principle an ocean model is seeded with many tens or hundreds of plausible phytoplankton physiologies, which are then allowed to “self-organize”. Using this approach, a familiar pattern of biogeographical provinces naturally emerge in the model, with a subset of the initialized organisms ultimately dominating the population of each province. The emergent biogeography is broadly plausible, with pleasing correspondence between observed and model-analog ecotypes of the cyanobacterium Prochlorococcus (Fig. 2). These types of complex model solutions can be understood using established ecological concepts; in particular, it was found that resource competition theory accurately anticipates the characteristics of the modeled subtropical ecosystems. Based on these results, it was suggested that such “self-assembling” ecosystem approaches are particularly suitable for modeling the broader food web and will provide preliminary illustrations incorporating heterotrophic microbes and predators in a similar manner.

Fig. 2 Observed and modeled properties along the AMT13 cruise track. Left column shows observations, right column shows results from a single model integration. (A and B) Nitrate (µmol kg⁻¹); (C and D) total Prochlorococcus abundance [log (cells ml⁻¹)]; (E, G, I) distributions of the three most abundant Prochlorococcus ecotypes [log (cells ml⁻¹)] ranked vertically; (F, H, and J) the three emergent model ecotypes ranked vertically by abundance. Model Prochlorococcus biomass was converted to cell density assuming a quota of 1 fg P cell⁻¹. Black lines indicate isotherms. Source: Follows et al., Science 315, 1843–1846 (2007).

Another interesting avenue for future ecosystem modeling was discussed by Jerome Fiechter. The approach involves combining existing ecosystem models with Bayesian Hierarchical Models (BHM). BHM is a unified probabilistic modeling methodology that updates uncertain distributional knowledge about process models and parameters in the presence of multi-platform observations. Summary measures of the resulting “posterior” distributions provide realistic quantitative estimates of central tendencies and uncertainties. Process model distributions are based on NPZD-type lower trophic level ecosystem models, including NEMURO (North Pacific Ecosystem Model for Understanding Regional Oceanography) specifically developed and parameterized for the North Pacific Ocean. A significant outcome of BHMs will be a quantitative understanding and comparisons of the relative uncertainties of modeled state variables and
parameters (e.g., from NPZD or NEMURO), region-by-region across different oceanic ecosystems.

As a general observation, the ROMS emerged as the most widely used physical model for coastal and shelf applications, although results using other physical models were also presented. In the case of NPZD models, there was a wide degree of “regional variability”. The size of NPZD models averages around ten compartments. In most of these models, each phytoplankton and zooplankton is divided into two to four compartments. The NEMURO model, which was developed by the PICES CCC (Climate Change and Carrying Capacity) Program’s MODEL Task Team, was one of the more popular NPZD models. One of the topics that came out in the discussion period was that the number of compartments in a biological model is not necessarily a measure of its complexity. A four-compartment model may have more parameters to tune, thus making it more complex than a ten-compartment model which has simple feedbacks. The question of what is the appropriate level of complexity was widely discussed and, in the mind of the organizers, will continue to be an important topic in the near future. The workshop was a fitting final presentation of GLOBEC modeling work. We thank the OSM organizers and all workshop attendees and participants and, in particular, we appreciate the interaction with so many GLOBEC friends through these last ten years. The organizers would also like to thank Ivonne Ortiz and Jerome Fiechter for helping with running the workshop.

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