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ICES and PICES Strategies for Coordinating Research on the Impacts of Climate Change on Marine Ecosystems

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ABSTRACT. The social, economic, and ecological consequences of projected climate change on fish and fisheries are issues of global concern. In 2012, the International Council for the Exploration of the Sea (ICES) and the North Pacific Marine Science Organization (PICES) established a Strategic Initiative on Climate Change Effects on Marine Ecosystems (SICCME) to synthesize and to promote innovative, credible, and objective science-based advice on the impacts of climate change on marine ecosystems in the Northern Hemisphere. SICCME takes advantage of the unique and complementary strengths of the two organizations to develop a research initiative that focuses on their shared interests. A phased implementation will ensure that SICCME will be responsive to a rapidly evolving research area while delivering ongoing syntheses of existing knowledge, thereby advancing new science and methodologies and communicating new insights at each phase.

INTRODUCTION

A century ago, the pioneering fisheries biologist Johan Hjort introduced the "critical period" and the "larval advection" hypotheses to explain how variation in the environment could be responsible for variability in the recruitment of marine fish populations (Hjort, 1914). Since then, oceanography has been considered an essential determinant of fish production. The study of the direct and indirect relationships between ocean conditions and fish production (growth and survival) is termed fisheries oceanography (Wooster, 1961; Kendall et al., 1996). The physical properties of the ocean are influenced by weather and climate. In this regard, linking climate variability, through its influence on seawater properties, and ocean processes to explain trends in the spatial distribution and abundance of marine fish is a key element of fisheries oceanography. Considering the economic importance of commercial fisheries and the ecological impacts of a rapidly changing climate (IPCC, 2013), there is a compelling need to expand fisheries oceanographic research programs to provide the knowledge necessary to understand and predict the implications of climate change on global fisheries.

The International Council on Exploration of the Sea (ICES) and the North Pacific Marine Science Organization (PICES) recognize that providing science-based knowledge and advice to management and policy decision makers is essential for the protection of marine fish and crustacean populations, the identification of effective and sustainable management strategies, and the conservation of essential habitats into the future. Providing science-based knowledge and advice during a period of rapidly changing climate presents new challenges for both organizations.

MOTIVATION FOR THE STRATEGIC INITIATIVE ON CLIMATE CHANGE EFFECTS ON MARINE ECOSYSTEMS (SICCME)

Throughout the last decade, compelling evidence has been gathered that humans are contributing to atmospheric and oceanic warming (IPCC, 2013). At regional or basin scales, long-term increases in ocean temperature are observed within systems influenced by interannual and decadal-scale climate variability (IPCC, 2007; Di Lorenzo et al., 2010). Decadal shifts in ocean conditions have been linked to structural shifts in marine ecosystems (also called regime shifts; Ebbesmeyer et al., 1991; Mantua et al., 1997; Wooster and Zhang, 2004; Overland et al., 2008). Comparative studies have identified synchrony in the timing of substantial changes in climate state and ocean conditions across large geographical areas (Chavez et al., 2003; Drinkwater et al., 2010). Climate variability and change in marine environments are often accompanied by changes in the production of some salmon and groundfish stocks, although recent retrospective studies have found weaker evidence for these linkages in groundfish (Mueter et al., 2011; Stachura et al., 2014). Climate shifts have also been linked to shifts in spatial distributions of marine species (Nye et al., 2009; Kotwicki and Lauth, 2013). Numerous lines of evidence demonstrate ecosystem responses to climate shifts in the North Pacific and North Atlantic Oceans (Francis and Hare, 1994; Francis et al., 1998; Seo et al., 2006; Greene and Pershing, 2007; Di Lorenzo et al., 2008; Overland et al., 2008; Alheit and Bakun, 2010; Bakun, 2010).

Climate and marine ecosystems vary on many spatial and temporal scales (IGBP, 1999; Ottersen et al., 2010). Proposed mechanisms for how the effects of climate variability could be transmitted to marine biota include such interacting ecological processes as match-mismatch, connectivity, and ocean triads (Bakun, 2010). Some marine populations elicit different responses (e.g., direct/indirect or unlagged/lagged) to climate signals (Ottersen et al., 2010). Many studies reveal that the relationships between climate forcing and biological responses are unresolved due to the complexity of the pathways involved (Bakun, 2010; Drinkwater et al., 2010). Understanding the primary mechanisms through which climate and physical forcing affects ecosystems from region to region was a focus of the International Global Ocean Ecosystem Dynamics (GLOBEC) program, a SCOR-IGBP-IOC initiative of 29 countries (Barange et al., 2010). The formation of integrated interdisciplinary research teams, such as GLOBEC and Integrated Marine Biogeochemistry and Ecosystem Research (IMBER), to conduct comparative ecosystem studies has helped to reveal the commonalities in complicated ocean processes. ICES and PICES have facilitated this integration by sponsoring regional programs, workshops, and symposia that provide a venue for scientists from other regions to share results and ideas; SICCME is the newest example of a PICES/ICES interdisciplinary research team.

Upon completion of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4; IPCC, 2007), the marine science community

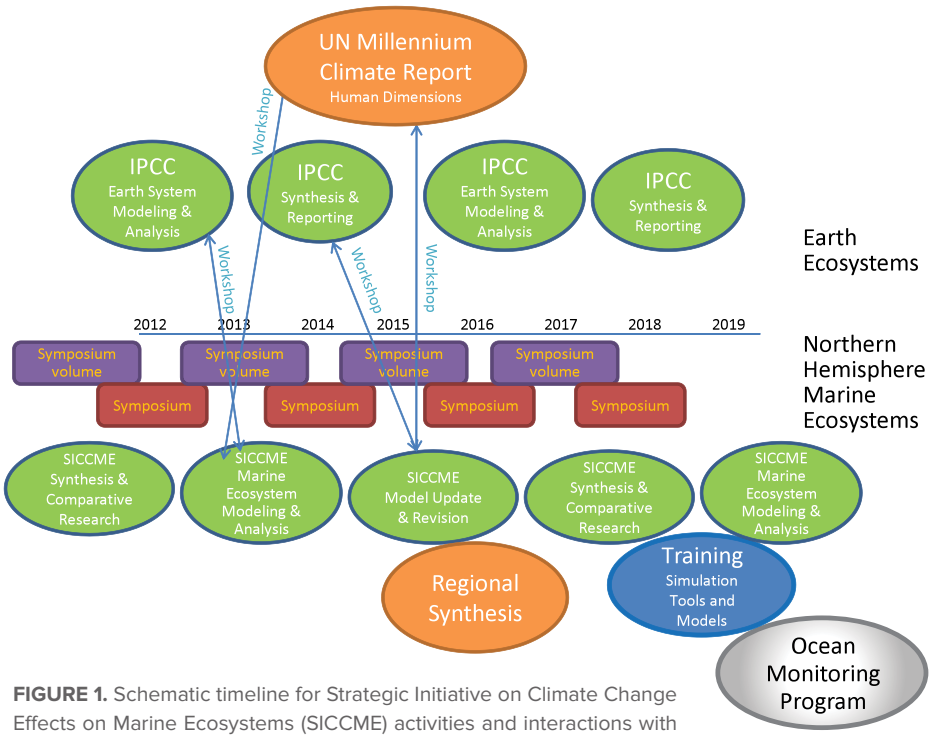

FIGURE 1. Schematic timeline for Strategic Initiative on Climate Change Effects on Marine Ecosystems (SICCME) activities and interactions with Earth system research organizations.

recognized the paucity of quantitative information on the effects of future climate change on marine ecosystems, and endeavored to rectify this limitation in time for the IPCC's Fifth Assessment Report (AR5; Richardson and Poloczanska, 2008). Later studies showed that climate change could impact the productivity of some marine ecosystems and the quality and quantity of habitat (Arrigo et al., 2008; Cheung et al., 2009). These changes could affect biodiversity, phenology, spatial distribution, interaction, and vital rates of marine biota, resulting in changes in the quantity and quality of some marine resources available for human use (Blanchard et al., 2012; Poloczanska et al., 2013; Ruckelshaus et al., 2013). The effect of these changes is expected to impact some seafood markets world-wide (Barange et al., 2011). Projecting marine ecosystem states for the next century requires development of mechanistic links between biology and physics combined with scenarios for future anthropogenic uses of marine resources that consider changes in fishing technology, markets, demand, and consumption, all within a diverse marine policy framework (Kim, 2010; Merino et al., 2012; Barange et al., 2014).

Although the IPCC has provided assessments of the evidence for, and projections of, climate change impacts on the planet, ICES and PICES recognize that their regional organizations play a critical role in the process by delivering information on the expected impacts of changing climate on living marine ecosystems to the communities and industries that depend on them. Until the early 2000s, ICES and PICES independently initiated efforts to develop frameworks for assessing and projecting climate change impacts on marine resources and the ecosystems that support those resources (Beamish, 2008; Foreman and Yamanaka, 2011; Reid and Valdés, 2011). Growing interest in understanding climate change impacts on fish and fisheries at the global scale caused the marine science community to initiate new ways to collaborate and plan for ways to conduct regional comparisons in support of a global synthesis. As the leading marine science organizations in the Northern Hemisphere, ICES and PICES were the logical choices to lead this effort; in 2008, the two organizations, together with the International Oceanographic Commission (IOC), convened in Gijón, Spain, the first international symposium on the effects of climate change on the world ocean (Valdés et al., 2009). To promote greater collaboration, PICES and ICES formed their first joint working group (the Working Group on Forecasting Climate Change Impacts on Fish and Shellfish, WG-FCCIFS). A primary objective of WG-FCCIFS was to convene an international symposium on climate impacts on fish and fisheries. It was brought to fruition in Sendai, Japan, in 2010 (Hollowed et al., 2011). Recognizing the ongoing nature of climate change research and its global importance, the work started by WG-FCCIFS evolved to become the Section on Climate Change Effects on Marine Ecosystems (S-CCME) within PICES, and the Strategic Initiative on Climate Change and Marine Ecosystem (SICCME) within ICES. For convenience, the new group was referred to as SICCME.

GOALS AND OBJECTIVES

SICCME was tasked with engaging the Northern Hemisphere marine science community in a coordinated fashion to enhance our ability to project the impact of climate change on marine ecosystems and to use this information to develop strategies for managing living marine resources under a changing climate. SICCME facilitates and accelerates the acquisition of new knowledge and ensures that it is communicated and published on a schedule useful to

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scientific organizations such as the IPCC and the United Nations Environment Programme, which are responsible for providing advice on climate change. To be responsive to the international bodies likely to use its research, SICCME will be implemented in three-year phases (Figure 1). While specific activities may change over time, three elements of the SICCME implementation plan were always present: synthesis of existing knowledge, advancement of new science and methodology, and communication of research findings.

The specific goals of SICCME, first published in Hollowed et al. (2013), are:

- Identify techniques for projecting climate change impacts in systems impacted by decadal variability
- Define the vulnerability of commercial species to climate change and identify which species would be most likely to experience shifts in spatial distributions
- Engage the global Earth system modeling community in modeling climate change effects on marine ecosystems and identifying opportunities for collaborations
- Build response scenarios for how the human community will respond to climate changes as an extension (added dimension) of Representative Concentration Pathways (RCP) scenarios of the IPCC AR5.

SICCME facilitates new interest and thinking about all ecosystem levels, from physics to fish and fish to markets. It was designed to work effectively within the existing structural frameworks of ICES and PICES to engage and to inspire the scientific community to direct attention toward its goals and to communicate their results to decision makers to improve the performance of management strategies under a changing climate (Figure 2). SICCME identifies approaches and operational practices that will facilitate and encourage the development of integrated scenarios of climate impacts on marine systems by engaging scientists from diverse backgrounds, including climatology, oceanography, ecology, fisheries, technology, and the social and economic sciences. SICCME members include representatives with expertise in each of these areas.

SICCME results are reported in phases to coincide with the expected timing of a regular series of international symposia on the effects of climate change on the world ocean. This schedule enables scientists to plan for collaborative research that will take advantage of the opportunity to meet. The schedule for the symposia is designed to be responsive to the IPCC's assessment reporting schedule. During intervening years, SICCME members often serve as co-conveners of workshops or theme sessions at ICES and PICES annual meetings. Intersessional workshops and formal scientific sessions provide venues to plan, discuss, and coordinate international collaborative research. In principle, SICCME strives to alternate the locations of its sponsored scientific sessions between the PICES Annual Meeting and the ICES Annual Science Conference.

SCIENTIFIC CONTRIBUTIONS: 2012–2014

During Phase 1, SICCME members focused on synthesizing existing information presented at the 2010 symposium in Sendai, Japan. They tested modeling techniques based on the IPCC AR4 and facilitated new interdisciplinary research within ICES and PICES. A series of international symposia, workshops, and theme sessions were held through the end of the Phase 1 period (Table 1). Two symposium volumes were published in the *ICES Journal of Marine Science* during this period. They included selected papers from the Sendai (Vol. 68, 2011) and Yeosu (Vol. 70, 2013) symposia. Drawing on these results, SICCME members synthesized the current knowledge of how climate change might impact marine ecosystems (Hollowed et al., 2013).

In 2012/2013, SICCME activities focused on the role climate change plays in the spatial distribution of marine fish and crustaceans. At the Yeosu, Korea, symposium in 2012, Session S4 (Climate change effects on living marine resources: From physics to fish, marine mammals, and seabirds, to fishermen and fishery-dependent communities) focused on climate-induced changes in the medium to high trophic levels of the marine ecosystem biological components, which includes fish, marine mammals, seabirds, and humans. A wide range of analytical methods was discussed, revealing the need for inter-regional comparisons of projected responses of fish and invertebrates to changing ocean conditions. In response, SICCME convened an international workshop in St. Petersburg, Russia (May 2013), to discuss observed shifts in spatial distributions of marine species

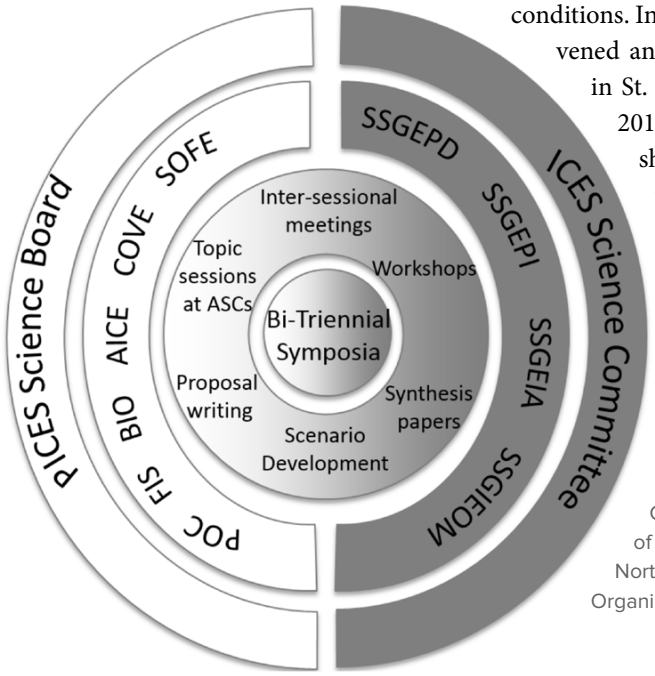

FIGURE 2. A conceptual model of SICCME with concentric circles that represent how members of the initiative will conduct their research and report to the International Council for the Exploration of the Sea (ICES) and the North Pacific Marine Science Organization (PICES).

TABLE 1. List of International science symposia and intersessional workshops convened by Strategic Initiative on Climate Change Effects on Marine Ecosystems (SICCME) members since 2010.

Activity	Topic	Date	Location
International Science Symposium	Climate change effects on fish and fisheries	2010	Sendai, Japan
Workshop	Biological consequences of a decrease in sea ice in Arctic and sub-Arctic seas	2011	Seattle, WA, USA
International Science Symposium	Climate change effects on living marine resources: from physics to fish, marine mammals, and seabirds, to fishermen and fishery-dependent communities	2012	Yeosu, Korea
Workshop	Global assessment of the implications of climate change on the spatial distribution of fish and fisheries	2013	St. Petersburg, Russia
Workshop	Comparison of projected impacts of climate change on marine ecosystems based on different modeling approaches	2013; 2014	Nanaimo, BC, Canada; Hawaii, USA
Workshop	Climate change and ecosystem-based management of living resources: appraising and advancing key modeling tools	2014	Hawaii, USA

(Poloczanska et al., 2013; Engelhard et al., 2014) and to foster the development and testing of analytical methods for (1) detecting changes in distribution (Pinsky et al., 2013; Lynch et al., 2014), (2) assessing the skill of different modeling approaches, and (3) quantifying uncertainty in projected climate-driven changes and methods to extend projections to quantify impacts on markets and communities (Jones et al., 2014). At this workshop, it was clear that a framework was needed to link projections from global ocean models to regional ocean ecosystems in a way that would capture the sophisticated responses to the dual pressures of climate change and market forces on the quality, quantity, and access to marine resources.

The human dimension of the impact of climate change on the ocean is very often overlooked. As a result, information available to the general public about climate change is incomplete and often biased to the terrestrial experience. To bridge the gap between what the scientific community understands about marine climate change impacts and what the public knows and cares about, the gap must first be identified. Research teams were formed to tackle these difficult issues, and their recent papers are providing new insights (Kim, 2010; Barange et al., 2011; Merino et al., 2012; Barange et al., 2014). SICCME members are facilitating continued dialog on this subject by organizing workshops and scientific sessions on the issue of communicating science at the upcoming Third International Symposium on Climate Change Effects on the World's Oceans to be held in March 2015 in Santos, Brazil (hereafter referred to as the Brazil Symposium 2015).

SICCME APPROACH: 2015–2017

It is increasingly clear that a global network of models is needed for a worldwide synthesis of climate change effects on marine ecosystems and on the global food supply. A necessary first step toward this goal is assessing the relationships between model complexity, efficiency, predictive skill, and the computational costs of increased ecological realism in models in order to identify the suite of candidate models for the global network (Planque et al., 2011; Link et al., 2012; Brander et al., 2013). PICES has long maintained the Marine Ecosystem Model Inter-Comparison Project (MEMIP) toward developing the appropriate models. One of key outcomes of these comparisons will be to identify early warning indicators of large-scale ecosystem change. ICES and PICES are not alone in their recognition of the importance of conducting model intercomparisons, although in most cases, existing groups involved in model intercomparisons focus on spatial scales and trophic levels that differ from those targeted by SICCME. SICCME's activities are most closely aligned with the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) and the MARine Ecosystem Model Intercomparison Project (MAREMIP). SICCME's efforts fill a unique niche through its focus on improving the quality of projected impacts analyses for commercially exploited fish and crustaceans and providing guidance to the fishing communities that depend on them regarding the trade-offs of using different harvest strategies under changing ocean conditions. Several marine ecosystem modeling approaches have been advanced to project the impacts of climate-driven changes on marine ecosystems and to identify sustainable harvest practices for ecosystems impacted by climate change (Plagányi et al., 2011; Stock et al., 2011).

New science published in SICCME symposium volumes was cited in the IPCC AR5 (Hoegh-Guldberg et al., 2014; Larsen et al., 2014; Pörtner et al., 2014), and new scenarios provided by the IPCC AR5 are already being used by SICCME members to force regional ocean circulation models. SICCME plans to compare projections from a variety of modeling approaches with the initial effort comparing different scenarios for the future of fish and fisheries under changing climate conditions. Successful implementation of this activity will require coordination with ongoing model intercomparison projects (Figure 3).

In 2014, SICCME members met to discuss options for interfacing fisheries and ecosystem models with next generation Earth system models (ESMs). The meeting brought together Earth system modelers, oceanographers, fisheries

stock assessment scientists, and ecosystem modelers to discuss the current and near-term future status of ESMs and their potential contributions to projecting climate change impacts on living marine resources, providing much-needed information to ensure sustainable fisheries management in the future. Following discussions of the strengths and weaknesses of different projection modeling approaches, participants agreed that it would be informative to examine projections from multiple models of different complexity.

The Brazil Symposium 2015 will cover the latest developments in predicting changes in biodiversity, phenology, fisheries, and ecosystems as well as in physical systems. Several SICCME-related workshop and sessions will be organized, including topics such as "addressing uncertainty in projecting climate change impacts in marine ecosystems," "forecasting climate change impacts on fish populations and fisheries," and "impacts of climate change on ecosystem carrying capacity via food-web spatial relocations." The symposium will also highlight knowledge gaps to stimulate the development of the new generation of science that studies the impact of climate change on our ocean.

SICCME will convene its next international workshop in the United States in August 2015 to develop scenarios for quantitative projections of climate change impacts on major commercially important fish stocks. The workshop is being planned with a focus on commercially important species and their prey. In coordination with Fish Model Intercomparison (FISH-MIP), the specific terms of reference for this workshop are to:

- Resolve which physical global climate or Earth system models should be used for the projections
- Compare attributes and performance of regional ocean circulation models
- Identify suites of projection models for key species (e.g., single-species climate-enhanced projections,

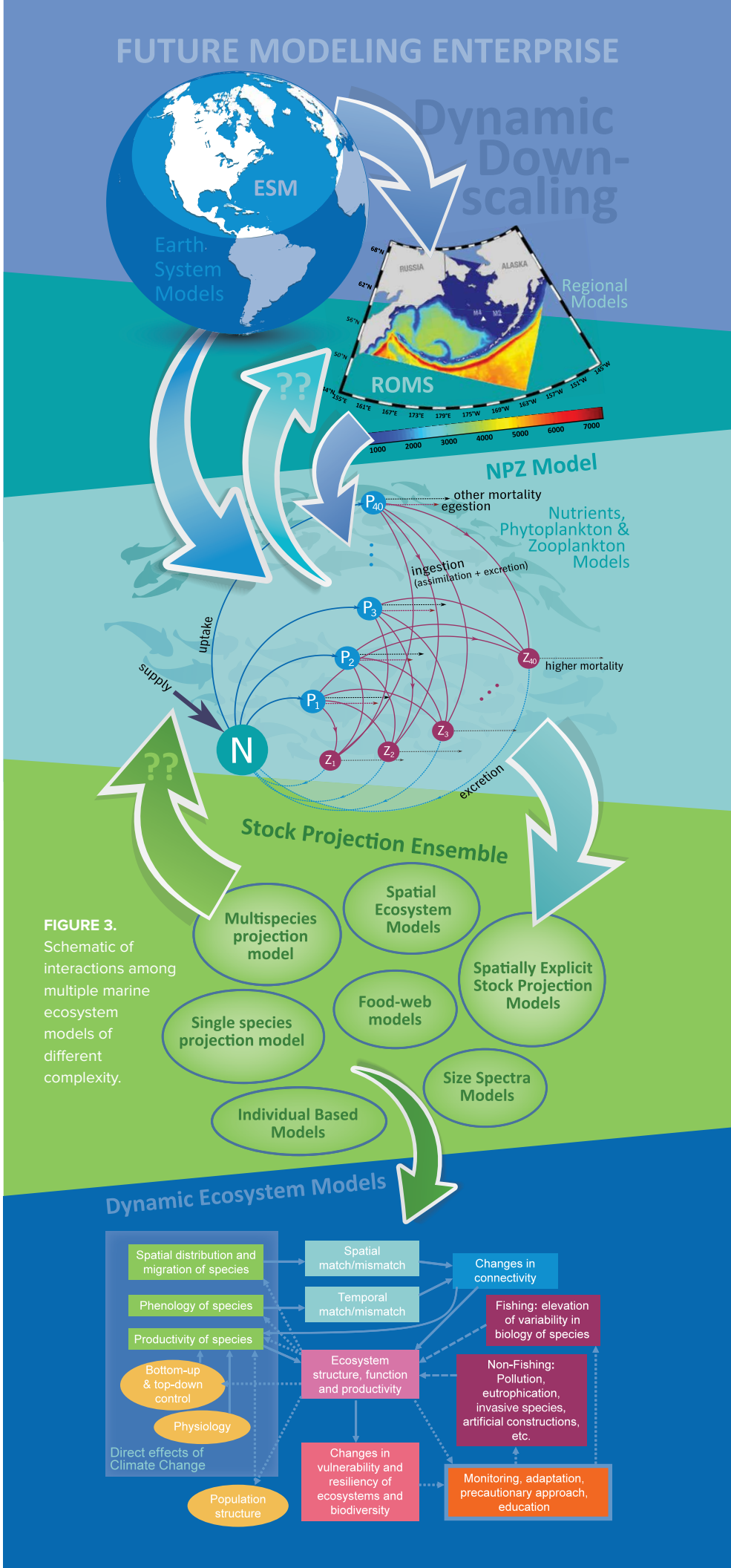

FIGURE 3. Schematic of interactions among multiple marine ecosystem models of different complexity.

individual-based projections, full end-to-end models) and compare their attributes and performance

SUMMARY

The SICCME partnership between ICES and PICES has been successful in many of its core missions, including synthesizing existing knowledge, advancing science and methodology, and fostering communication and integration of science through peer-reviewed publications, symposia, workshops, and science sessions. It also demonstrates how in times of limited funding for international science coordination, existing regional structures can be used to effectively address global concerns. The benefits of such collaborations include: increased understanding of physical, chemical, and biological linkages and ecosystem responses to anthropogenic and climate forcing; coordinated monitoring and descriptions of the current state of ecosystems; provision of a range of robust projections of future states of Northern Hemisphere marine ecosystems and their associated uncertainties; full consideration of human activities that may accelerate or decelerate the impacts of climate change on marine resources, such as over-exploitation practices, global market pressures, eutrophication, and adaptations to change at local and regional levels; provision of information to the IPCC Assessment Report on responses of Northern Hemisphere marine ecosystems to climate change; quantification of the benefits and risks associated with different management strategies; and increased marine science capabilities in ICES and PICES member countries in the disciplines relevant to SICCME.

These benefits are also evident in PICES and ICES scientific programs that establish the vision and the plans for a climate change research program. SICCME provides a foundation for working scientists that will ensure that work is completed and delivered in a manner consistent with the goals and objectives of the ICES Science Committee (SCICOM) and the PICES Science Board. The SICCME collaboration will accelerate the pace of discovery, innovation, and progress by facilitating rapid exchange of information between ICES and PICES scientists. SICCME will expand opportunities for the use of the comparative approach by extending our partnerships to other regions in the Northern Hemisphere and will ensure that PICES and ICES are at the forefront of climate change research in the world's oceans.

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