OSM Workshop on an *"Ecosystem projection model inter-comparison and assessment of climate change impacts on global fish and fisheries"*

By Anne B. Hollowed, Kirstin Holsman and Kerim Aydin

Introduction

Climate change is a global issue affecting marine ecosystems and species that span multiple international boundaries, and is one of the most universal challenges facing fisheries scientists and managers around the world. To address these challenges scientists have developed modeling approaches and management tools to project future impacts. This task mandates international collaboration to develop approaches that can be implemented across multiple, large marine ecosystems worldwide. Keeping pace with a rapidly changing climate also requires fisheries management tools that can accurately and efficiently inform best solutions in an uncertain future and evaluate tradeoffs associated with alternative carbon management strategies, yet implementation of such management lags behind climate-driven changes to species and ecosystems. As part of the on-going activities of the PICES/ICES Section on *Climate Change Effects on Marine Ecosystems* (S-CCME, also known as the Strategic Initiative on Climate Change Effects on Marine Ecosystems), Anne B. Hollowed (AFSC NOAA), Kerim Aydin (AFSC NOAA), and Kirstin Holsman (JISAO/AFSC) co-convened a workshop on April 12–13, 2014, at the FUTURE Open Science Meeting (OSM). The workshop was funded by the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) as a project within its International Science Program. Twenty nine scientists, representing seven nations, participated in the meeting.

The goal of this workshop was to discuss options for interfacing fisheries and ecosystem models with next generation Earth System Models (ESMs). 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[1][2]. Each of these approaches has inherent strengths and weaknesses, depending on which fisheries management questions are being considered[3]. Increasingly, fishery and ecosystem modelers recognize that a global network of models is needed for a world-wide synthesis of climate change effects on marine ecosystems and the global food supply. A necessary first step towards this goal is an assessment of the relationship between model complexity, efficiency, predictive skill, and the computational costs of increased ecological realism in models, which can be used to identify the suite of candidate models for the global network [4][5]. This assessment requires guidance on how the fisheries science community and the global climate modeling community interface their models and exchange data.

The workshop 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 for sustainable fisheries management in the future. Increases in computing power and storage have facilitated refinements in the spatial and temporal scale of climate models[6] and ESMs have been developed that incorporate terrestrial and oceanic biosphere processes. Conceivably, ESM outputs could be used to project climate change impacts on the distribution and abundance of phytoplankton and zooplankton in marine systems[7], eliminating the need for dynamic downscaling of global climate projections to regional circulation models. However, because ESMs may not appropriately capture important oceanographic features (*e.g.*, regional upwelling zones, coastal eddies, or benthic processes) the appeal of such a unified, global approach must be weighed carefully against the advantages of regionally tailored marine ecosystem modeling frameworks.

Specific objectives for the workshop included:

Obj. 1 Identify the optimal means of combining global ESMs, high resolution regional modeling frameworks (RMFs), and ecosystem models of varying complexity to provide robust assessments of climate change impacts on living marine resources and their habitat.

Obj. 2 Coordinate international efforts to assess biological and societal impacts of climate-driven changes to future marine resources.

The 1½ day workshop (W4) consisted of a mix of oral presentations and group discussions. On day 1, Anne Hollowed gave a brief opening address and described the expectations for the workshop. She explained that participants would focus on three tasks: (1) review the current state of climate and ecosystem models for each region; (2) identify inter- and intra-region comparisons and objective questions, specifically, identify focal regions/ marine systems, available data, and a subset of existing models for initial analyses; and (3) identify a list of collaborators, individual tasks relative to comparative analyses phase A or B (see Fig. 1), specific timelines and benchmarks, and budgetary/funding requirements for completing model inter-comparisons.

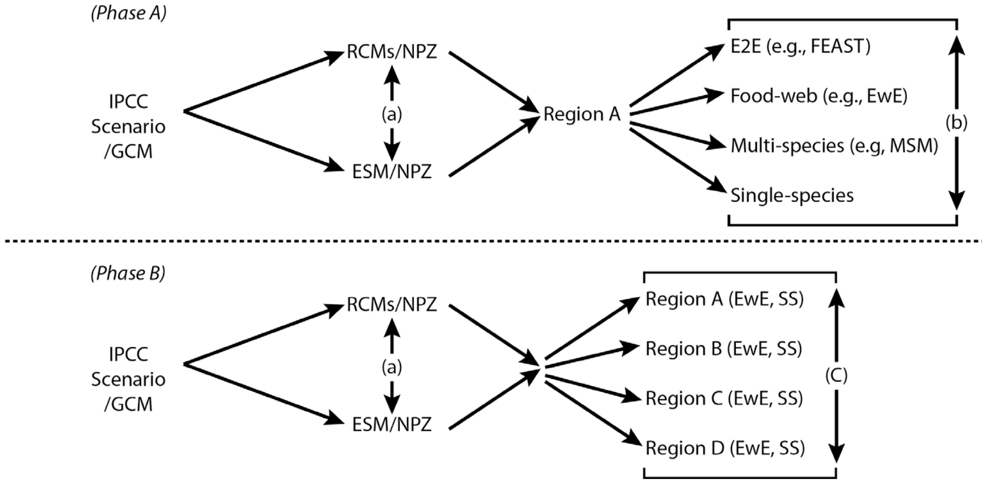

Fig. 1 Two-phase framework for model inter-comparisons (order of phases depends on available models and data), using the eastern Bering Sea (AK, USA) as an example. a) Comparative results from coupled regional climate models and nutrient phytoplankton zooplankton models (RCMs/NPZ) and Earth System Models (ESM); b) intra-regional comparison of model results to identify best models for application in c) inter-regional comparisons. Proposed regional models are for illustrative purposes only and will depend on existing models for each region. E2E: end-to-end models; EWE: Ecopath with Ecosim; MSM: multi-species stock assessment; SS: single-species stock assessment.

Task 1 was accomplished through 16 oral presentations during the first day. The first four speakers discussed existing work on global climate models and earth system models. The spatial distribution of global climate models and earth system models varies. Charles Stock reviewed the types of models currently developed or under development at the Geophysical Fluid Dynamics Laboratory in the U.S. Enrique Curchitser discussed ongoing collaborations between Rutgers University and the National Center for Atmospheric Research (NCAR) and presented several examples where models developed by the climate modeling community have been used to project changes in habitat quality and quantity (*e.g*., polar bear habitat in the Arctic and spatial extent of future coral reef bleaching). Scientists at Rutgers and NCAR are partnering to develop high resolution coupled models (the Community Earth System Model, CESM) of the California Current ecosystem. Icarus Allen described the United Kingdom Earth System Modeling Project (UKESM). Members of this project are developing suites of models at different spatial and temporal resolutions that will contribute to the sixth Climate Model Intercomparison Project 6 (CMIP6) effort. Scientists are exploring outcomes from nutrient, phytoplankton and zooplankton models with different levels of complexity. The inter-comparison will attempt to have common computing platforms, common physics, common forcing, and common initial conditions. New models with 1/10 degree spatial resolution of the physical models are being tested in the UK. Michio Kawamiya discussed the status and future of Japanese climate models. Japanese scientists are testing new models in preparation for CMIP6 that will include improved spatial resolution (vertical and horizontal) and enhanced complexity of the nutrient, phytoplankton and zooplankton components of the models. Nesting models at different spatial scales provide improved ability to resolve fine-scale physical features in waters off the coast of Japan.

The next suite of modelers presented results of efforts to force regional marine ecosystem models with boundary conditions from climate models. Beth Fulton described the on-going research in Australia to project the implications of decadal variability and climate change on marine ecosystems. Australian modelers are also striving to improve the biological realism and spatial resolution of models. She introduced an existing effort to develop a Fish Model Intercomparison (FISH-MIP) and an Intersectoral Impact Model Intercomparison (ISI-MIP). Workshop participants recognized that the goals of FISH-MIP and ISI-MIP are similar to S-CCME and therefore, participants will pursue possible future collaborations with these groups. Michael Foreman provided an overview of the current status and future plans for ocean ecosystem modeling in Canada. He noted that efforts are underway to improve the spatial resolution and biological realism of the ocean models. Recent retrospective comparisons showed that current regional circulation models were not reproducing offshore upwelling and downwelling winds and seasonal transitions correctly so additional work is needed. In addition, Canadian scientists are developing a high-resolution regional model for the high Arctic. Al Hermann discussed a regional ocean model for the southeastern Bering Sea that was first developed as part of the GLOBEC program and has been improved as part of the BEST-BSIERP Bering Sea Project. This model reproduces known physical features with reasonable accuracy and preliminary projections through 2040 are now available for use in fisheries models.

Afternoon presenters continued to discuss the status of regional ocean model experiments. Shin-ichi Ito noted that several models have been developed to project climate impacts on Japanese fish distribution and abundance. The complexity of the nutrient-phytoplankton-zooplankton components of these models differed substantially.

Projections through 2100 are available for some species (*e.g.*, Pacific saury and sardine). William Cheung presented a global assessment of the catch potential of fisheries in the future based on available climate model outputs. Kirstin Holsman gave a talk on behalf of Kerim Aydin who was unable to attend the meeting. Aydin's model extends the coupled bio-physical model described by Hermann to include fish and fishers. The model tracks local environmental conditions, and fish movement emerges as a property of energetic demands, prey availability and predation. Retrospective runs of the model are able to reproduce the general spatial pattern of key ecosystem components. Projections should be available within the next 6 months. Melissa Haltuch and Kirstin Holsman provided an overview of available methods for projecting future abundance of key species using climate-enhanced single species or multispecies models. Using approaches similar to Cheung's dynamic bioclimatic window approach, Elliott Hazen estimated the impact of future climate change on the availability of suitable habitat for several top predators. Pheobe Woodworth-Jencoats compared projections based on an ecosystem model (Ecopath with Ecosim) and a size spectrum modeling approach. She found similarities in model outputs at lower trophic levels but important differences between the two modeling approaches for larger predators. This finding provided insight into the range of possible projected future outcomes. The last speaker of the day was Nicholas Bond who discussed a relatively new effort to develop short-term now-casts of climate. These now-casts can be utilized to estimate uncertainty in short-term model projections.

Discussion

In most regions increases in computing power and storage have facilitated refinements in the spatial and temporal scale of climate models[6], and ESMs have been developed that incorporate terrestrial and oceanic biosphere processes. Conceivably, ESM outputs could be used to project climate change impacts on the distribution and abundance of phytoplankton and zooplankton in marine systems[7], eliminating the need for dynamic downscaling of global climate projections to regional circulation models. However, because ESMs do not yet appropriately capture important small-scale oceanographic features (*e.g.*, regional upwelling zones, coastal eddies, or benthic processes), in the near-term the use of ESMs in a unified, global approach should (minimally) be coupled with regionally-tailored marine ecosystem modeling frameworks.

Definitions

The workshop participants held a lengthy discussion regarding terminology for this experiment. Our experiment differs substantially from the Coupled Model Inter-comparison Phase 5 used to support the most recent Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5. In our experiment, estimates of higher tropic level responses to climate will be derived from different scenarios regarding regional ocean conditions. To the extent practicable, investigators will strive to utilize a common suite of representative concentration pathways (RCPs) and a common suite of GCMs (Global Climate Models) or ESMs. However, the methods used to downscale these global boundary conditions to derive regional ocean conditions will differ between modeling approaches. Thus, disparate projected impacts of climate change on higher trophic levels will partially reflect different mechanisms incorporated into the models utilized by the modeling teams. We anticipate that the models will span a wide range of mechanistic complexity ranging from minimally realistic approaches to fully coupled end-to-end ecosystem models (Fig. 1). Thus, our proposed experiment will not represent a true model inter-comparison, wherein the conditions are held constant to the extent practicable and the structural aspects of the model are evaluated. The comparison will be an evaluation of the projected higher trophic level responses to regional ecosystems change caused by a common suite of climate forcing scenarios.

The participants discussed a variety of issues related to evaluating model performance. They considered the approach often used in the stock assessment community, where analysts develop a simulated system with known properties and then evaluate their model's ability to correctly identify the properties of the system. In the context of the proposed experiment, analysts would have to develop a simulated ocean and lower trophic level system with known properties as a test-bed for evaluating model performance. While this is a useful idea, the feasibility of analysts developing a simulated ocean was deemed too difficult at this time. The group recommended that the modeling framework should include retrospective runs and short-term predictions as potential diagnostics on model performance and agreed that the goal of this experiment was not to judge the models but to compare the projected scenarios of higher trophic level response across a range of models.

The group recognized that defining the framework to conduct this experiment is a very high priority as it sets the stage for each of the modeling teams. Workshop participants will work off-line to develop this framework. Details of the modeling framework can be discussed during the S-CCME meetings at ICES' Annual Science Conference and at PICES-2014. The group will propose a workshop to be held in 2015 to re-convene the group to finalize the framework.

Results of a subsequent workshop (see the workshop on "*Climate change and ecosystem-based management of living marine resources*") provided substantial evidence that assumptions regarding the response of fishers to changes in the distribution and abundance of target species are important and must be incorporated into the framework of the experiment. Participants in that workshop recommended that a range of possible fisher responses should be considered and thus, the framework for the proposed upper trophic level projection experiment should also describe how to treat this issue.

Discussion questions

1. Are ESMs ready to be implemented for use in forcing regional ecosystem models?

The group agreed that the current practice of using ocean and atmospheric conditions derived from GCMs can be extended to utilize outputs from ESMs. Between now and 2021, the spatial resolution of global climate models (GCMs) and ESMs are likely to be reduced to 0.25–0.1 degree. Initial runs of ESMs at 0.1 degree resolution reveal the models are capable of resolving finer-scale ocean current features, including eddies and upwelling. Atmospheric and physical features derived from these models can continue to be used as boundary conditions for regional ocean circulation models. There is wide diversity of opinion whether, or how, nutrient, phytoplankton and zooplankton outputs from ESMs should be used as boundary conditions for regional models. There are presently no biological feedbacks between the regional models and ESMs.

Some outputs from climate models are available to the scientific community. However, the temporal resolution of the output from some models is coarse and information from vertical layers is not always available. The regional modeling community should develop a request of key outputs with consistent spatial and temporal resolutions needed from global models to adequately force regional models.

The group noted that several organizations around the globe have initiated model inter-comparison projects including:

a) The Coupled Model Intercomparison Project Phase 5 that formed the basis for the most recent IPCC report;
b) The Arctic Model Intercomparison Project;
c) The Geoengineering Model Intercomparison Project;
d) The Atmospheric Model Intercomparison Project;
e) The Carbon–Land model Intercomparison Project;
f) The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP) which has a sub-component dealing with marine ecosystems and fisheries (FISH-MIP);
g) In 2009, PICES initiated a Marine Ecosystem Model Intercomparison Project (MEMIP) to examine regional zooplankton productivity. Extensions of this effort could contribute to the proposed project focused on fish and fisheries;
h) The international MARine Ecosystem Model Inter-comparison Project (MAREMIP), which is an ecosystem model inter-comparison focusing on hindcasting phyto-plankton concentrations as measured by ocean color;
i) At the same time as these formal inter-comparison projects, biological ensemble modeling has been conducted using projections from multiple GCMs on a single model[8] and one GCM using multiple biological models[9], showing the potential benefits of critically examining the outputs of biological models with structural differences.

The group recommended that the proposed PICES and ICES initiative to compare projections of future fish and fisheries using different models could contribute to the FISH-MIP effort.

2. Do existing higher trophic level models use a common set of the most recent IPCC projections?

Yes and No. While regional teams are using forcing from models that have implemented the IPCC emissions scenarios, they do not all use the same specific (or ensemble) GCM or ESM for downscaling RCMs. Regional ocean circulation modelers often work with modeling teams in closest proximity to their laboratories. There are several advantages to this including ease of access to experts for discussions and a general sense of comfort that the ESM modeling teams are familiar with the local physical and environmental features of the region. In a few cases, regional modeling teams have evaluated GCM or ESM modeling performance relative to reproducing important features of a regional ocean. Model selection is based on performance. For example the Bering Sea modeling team used the MIROC, CGCM3 and the ECHOG models. Likewise, the Japanese regional modeling teams plan to work with modeling teams from the Geophysical Fluid Dynamics Laboratory and the Hadley Center as well as their local modeling nodes.

The regional modeling teams had a mixed track record with respect to access and utilization of the most current version of GCM and ESM models. In several regions the regional ocean circulation models were being forced with models developed for AR4 rather than the more recent CMIP5 models. This time-lag needs to be addressed to ensure that regional ocean model projections are based on the best available science.

3. How should IPCC scenarios be selected (e.g., a specific emission scenario, multiple, etc.)?

Multiple model scenarios are needed to reflect the full range of possible future conditions. As noted above, a framework for implementing multi-model higher trophic level projections will be needed. Time did not permit a full discussion of this framework.

4. Is (or will) the quality and spatial resolution of phytoplankton and zooplankton output from ESMs be of sufficient quality to use as boundary conditions for regional models or as indices for stock projection models?

Unclear. The methodology for coupling biological responses derived from ESMs and regional models has not been fully developed. A few starting steps have been taken, and these make clear that dealing with differences in scale and the resolution of processes in the different models raises scientific issues that need careful handling to avoid the introduction of artifacts when shifting from one scale to another.

5. What is the state of coupled RCMs/NPZ models?

See Workshop 4 presentations. Multiple regions have begun or are already using coupled RCMs/NPZ models.

6. How sensitive are NPZ models to structural assumptions (i.e., boxes)? Should we try to standardize this across regions?

Models are sensitive to their formulations, but it would not be advisable to insist upon a common modeling platform to be used universally, as system-specific idiosyncrasies are required for making robust projections of the dynamics of different ecosystems. Trying to develop and implement a universal model would likely require resources and data sets in excess of what is currently available.

7. What are the most confident outputs from NPZ and ecosystem models (e.g., biomass, abundance, shifts in distribution, upper trophic consumers or lower trophic level biota [e.g., phyto- or zooplankton])?

While there is agreement that the general patterns produced by NPZ models are capturing system dynamics, the absolute values remain uncertain. Zooplankton dynamics are perhaps the weakest terms at present, with phytoplankton much more reliable. This is, in part, because of how the zooplankton are currently represented, and also because there are significant gaps in available data, which become increasingly spatially and seasonally heterogeneous with higher trophic levels, particularly in key processes such as the partitioning of mortality across different sources of natural mortality. This is important because zooplankton are a key trophic link between the plankton communities and fish communities (*via* larval, juvenile fish age classes and planktivorous species). Many subtle features of ecosystem evolution are currently missed and a review of what works where and why would be a valuable exercise, though it may be contingent on the original motivation for the development of the initial models.

8. What are the strengths and weakness of simplifying assumptions for higher trophic level projection?

While individual modeling teams have a strong appreciation of the shortcomings of their own model representations, they are not well known outside these expert user groups. This is, in part, because it would be a significant undertaking to document these features. The proposed intermodel comparison, suitably documented, would be a useful step forward in disseminating this information in a tangible and tractable way.

General timelines

- *April 2014:* Workshop 1 at the FUTURE Open Science Meeting, Hawaii;
- *May–December 2014:* Design a framework for comparing within region multi-model projections;
- *March 2015:* Workshop 2 to be held in 2015 (Proposals to be submitted to ICES, PICES and NOAA);
- *2015–2016:* Complete Phase 1 comparison of multi-model projections for selected regions;
- *Summer 2016:* Submit (Phase 1) results to target journal;
- *March 2016:* Workshop 3 – review frameworks for comparing between region multi-model projections for selected species groups;
- *2016–2017:* Complete Phase 2 comparison of region multi-model projections for selected species;
- *2019:* submit Phase 2 results to target journal;
- *December 2020:* Published results for use in next IPCC assessment.



See Dr. Anne Hollowed's bio in the previous article.

Dr. Kirstin Holsman (kirstin.holsman@noaa.gov) is a research scientist with the University of Washington Joint Institute for the Study of the Atmosphere and Ocean. In collaboration with colleagues at the Alaska Fisheries Science Center (NOAA Fisheries), her current work is focused on developing quantitative methods for ecosystem-based approaches to management and methods to assess and manage for climate-change impacts on fish and fisheries. In particular, her research includes climate specific multi-species stock-assessment models for the Bering Sea (AK, USA), Integrated Ecosystem Assessments, bioenergetics and food-web models, and field studies of multi-trophic effects of fishery and aquaculture interactions with marine and estuarine ecosystems.

Dr. Kerim Aydin (Kerim.Aydin@noaa.gov) is the program leader of the Resource Ecology and Ecosystem Modeling Program at the Alaska Fisheries Science Center. His current research is focused on modeling predator/prey interactions, both from an individual behavioral standpoint and from a population (food web model).

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