Report of the 5th National Ecosystem Modeling Workshop (NEMoW 5): Progress in Ecosystem Modeling For Living Marine Resource Management

Howard Townsend, Kerim Aydin, Stephanie Brodie, Geret DePiper, Yvonne deReynier, Chris Harvey, Alan Haynie, Elliott Hazen, Isaac Kaplan, Stephen Kasperski, Kelly Kearney, Scott Large, Sean Lucey, Michelle Masi, Ivonne Ortiz, Jonathan Reum, Christine Stawitz, Desiree Tommasi, Mariska Weijerman, Andy Whitehouse, Phoebe Woodworth-Jefcoats, Patrick Lynch, Kenric Osgood, and Jason Link (editors)

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U.S. Department of Commerce
Wilbur L. Ross, Jr., Secretary

National Oceanic and Atmospheric Administration
Neil Jacobs, Acting Under Secretary for Oceans and Atmosphere

National Marine Fisheries Service
Chris Oliver, Assistant Administrator for Fisheries

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Executive Summary

The NOAA - National Marine Fisheries Service (NMFS) held its 5th National Ecosystem Modeling Workshop (NEMoW 5) on December 9-11, 2019 at the University of South Florida - College of Marine Science in St. Petersburg, FL. In 2007, scientists and administrators at NMFS established the first NEMoW in response to needs for more formal review, evaluation, and projection of the ecosystem modeling efforts of NMFS. Since then, ecosystem modelers within NMFS have routinely met at NEMoWs to share methodologies and discuss recent advancements in the field to improve ecosystem modeling for living marine resource (LMR) management. The general objectives of NEMoWs are: 1) to address broad questions of national interest for applied LMR-oriented ecosystem modeling (EM), 2) to provide a forum for ecosystem modelers within NMFS to network and share information on ecosystem modeling advancements and best practices, and 3) to provide a vehicle to advance EM for LMR within NMFS as it meets its mandates and obligations.

As NMFS and its partners are progressing towards ecosystem-based fisheries management (EBFM) implementation, NEMoW 5 was timely, beneficial, and relevant. All attendees agreed that NEMoWs should continue to be convened. Most participants agreed that occasionally NEMoW should be focused on review of key topics with plans to develop manuscripts on those topics. In addition, smaller, inter-sessional NEMoW working groups should be developed to focus on specific issues common to many regions. NMFS is in a favorable position to apply ecosystem modeling to LMR management. Considerable advances in modeling for ecosystem-oriented management have been made, and, in large part, NMFS Fisheries Science Centers (FSCs) are moving towards operational application of ecosystem models (EMs) to address EBFM challenges.

NEMoW 5 was focused on the progress made in ecosystem modeling applications for LMR management and recommendations for future work to meet NOAA Fisheries' mission. Specifically, the ecosystem modeling community gathered to review progress in 5 topic areas: multimodel ensemble case studies; ocean model/fisheries model coupling; managers and Models: engaging managers in model use and development; ecosystem-level management strategy evaluations (MSEs); and coupled social-ecological models.

In previous NEMoWs, participants have focused on uncertainty and approaches to make EM available for living marine resource managers and stakeholders. We have previously outlined and begun to adopt best practices and approaches for developing and applying EM. For about 20 years ecosystem modelers have pursued activities that enable EMs to be used in a management context similar to the single-species stock and protected resource assessment models. This NEMoW focused on progress in applying EM efforts in the U.S. and making recommendations to ensure future successful application of EM for LMR management.

Prior to the workshop, topic teams had developed summaries and outlines to guide discussions on the topic areas listed in the objectives. During the workshop, participants presented on the topic areas, cross-fertilized among the topics, and further reviewed these topic areas.

In addition to the focused work on the review topics, each FSC reported out on ecosystem modeling efforts in their regions. This allowed participants to identify and share practices at FSCs that have improved utility of modeling for management. Additionally, modelers presented on tools they have developed to support modeling efforts. A hands-on, interactive session followed the tools demonstrations. This opportunity for cross-training on tools developed at other FSCs is a valuable part of the scientific exchange at NEMoWs.

Key conclusions on EM best practices were reviewed, reiterated, and are listed here:

1) The use of multiple models helps to address uncertainty and develop stakeholder buy-in. As much as is feasible, multiple models should be used.
2) Make sure that EMs have adequate process detail to ensure management utility but not so much detail that operational use is hindered.
3) Work with management bodies to refine and focus models to meet management needs. This requires time and effort to organize understanding of management challenges and objectives, to match extant operational models to those challenges, and develop or refine other models where needs are not fully met.
4) Use EMs for multiple points on the MSE loop to address uncertainty. Ensure that the points of uncertainty to be addressed are explicitly stated and clearly communicated and visualized.
5) Use coupled social-ecological models to more thoroughly understand human influences on ecosystems.
6) Use end-to-end models to structure data and information flow for end-to-end EBFM – i.e., from field operations planning to policy setting.

Six recommendations emerged from NEMoW 5:

1) Multiple models should be available for addressing regional ecosystem-oriented management issues.
2) End-to-end models should be available for regional ecosystems to help inform data and information needs in an EBFM program.
3) EMs should be presented and discussed regularly at regional management bodies to focus EBFM objectives and facilitate model refinement to address objectives.
4) EMs should be used regularly for MSEs.
5) Each region's ecosystem modeling tool set should include coupled ocean/fisheries models to address the influence of climate and environmental factors on regional ecosystems.
6) Coupled social-ecological models should be included in regional ecosystem modeling tool sets to a) aid with stakeholder engagement, b) improve understanding of the influence of human behavior on ecosystem structure, and c) provide a relatable common connection across ecosystem uses.

Acknowledgements

The NEMoW 5 Steering Committee, on behalf of all NEMoW 5 participants, would like to thank the local host of the workshop, University of South Florida - College of Marine Science – a Quantitative Ecology and Socioeconomics Training (QUEST) Program partner. We especially thank Dr. Cameron Ainsworth, Kelly Vasbinder, and Becky Scott for their tireless efforts in setting up local arrangements, handling workshop logistics, and enabling a productive meeting.

NEMoW 5 was convened in St. Petersburg to follow on from the Ecopath 35 International Conference. The theme of Ecopath 35 was “Making Ecosystem-Based Management Operational”. The Southeast Fisheries Science Center’s Trophic Ecology and Ecosystem Modeling Working Group Strategic Planning Meeting followed NEMoW in the same location. The NEMoW 5 steering committee appreciates the coordination with these other meetings. The timing and location of these conferences allowed for some interaction between NMFS scientists and national and international colleagues focused on a similar mission.

We thank the NMFS Office of the Assistant Administrator and the NMFS Office of Science and Technology for partial funding support to help defray the costs of this workshop.

Finally, we thank the NMFS Science Board for their continued, enthusiastic support.

Introduction

About 15 years ago, scientists and administrators at NMFS established the first National Ecosystem Modeling Workshop (NEMoW) in response to the need to create more formal review, evaluation, and projection of the ecosystem modeling (EM) efforts of NMFS. Since then, ecosystem modelers around NMFS have routinely met at NEMoWs to share methodologies and discuss recent advancements in the field in an effort to improve ecosystem modeling for living marine resource (LMR) management.

The general objectives of NEMoWs are: 1) to address broad questions of national interest for applied LMR-oriented EM, 2) to provide a forum for ecosystem modelers within NMFS to network and share information on ecosystem modeling advancements and best practices, and 3) to provide a vehicle to advance ecosystem modeling for LMR within NMFS. The specific objective for this 5th NEMoW (NEMoW 5) was to review progress in using EMs for ecosystem-based management of LMRs.

Ecosystem modeling is “a wide range of modeling and analysis tools that are used to support the implementation of ecosystem-based fisheries management (EBFM). These tools include conceptual models and related analytical approaches (Harvey et al. 2016) and a variety of biophysical, multispecies, food-web and end-to-end EMs (further described in Plaganyi 2008, Townsend et al. 2008). This range covers models and analyses that consider only a few external factors influencing a single fish stock to a more holistic set of factors (e.g., climate, currents, biogeochemistry, fisheries, human dimensions; Fulton et al. 2011, Rose et al. 2010) influencing multiple, interacting fish stocks”(Townsend et al 2019).

To advance ecosystem modeling science for LMR management, and with the stated objectives of evaluating progress in using EMs for management advice and making recommendations to ensure future progress in ecosystem-based management of LMRs, NMFS scientists conferred for three days at NEMoW 5. This technical memorandum captures the essential points that emerged from that workshop.

NEMoW 5 was important for continuing progress in integrating across NMFS mandates and advancing EBFM. Incorporating ecosystem considerations into fisheries management is underscored in the Magnuson-Stevens Fishery Conservation and Management Act. Similarly, incorporating ecosystem considerations is important for marine mammal and endangered species population assessment as required in the Marine Mammal Protection Act, the Endangered Species Act, and more broadly for cumulative effects analysis under the National Environmental Policy Act. In addition, ecosystem connections are core considerations in the habitat management science conducted by NMFS under multiple mandates. This progress review of EM for EBFM was centered on five topic areas - multimodel ensembles, ocean model/fisheries model coupling, engaging managers in model use and development, ecosystem-level management strategy evaluations (MSEs), and coupled social-ecological models. Many of these topics were cross-disciplinary, reflecting the multiple mandates and multiple management venues in which they need to be considered. By reviewing these topic areas and publishing the results of the reviews, participants hope to advance the field of ecosystem modeling and ensure that NMFS is prepared to meet its mandates as the future needs for operational EM increase. This report provides a brief summary of this effort. More details on some of the topic areas will be forthcoming in a special issue of *Frontiers in Marine Science*.

Background

The major legislative mandates for NMFS require a movement towards various levels of ecosystem-based management; NOAA's mission, vision, and policy statements continue to espouse an ecosystem approach. In addition, many of these mandates require the use of the best available science. Thus a need arises for ecosystem modeling to provide the best available science to inform NMFS in a variety of regulatory roles. The topic of "Progress in Ecosystem Modeling for Living Marine Resource Management" and the focal topic areas of review were chosen as a theme for NEMoW 5 for several reasons. NMFS EM applications for LMR management started about 20 years ago at two or three FSCs. Now every FSC has some ongoing ecosystem modeling development, with at least some initial applications for management. Some of the FSCs are generating operational products for management. That is, EM is moving away from being primarily a research and development venture and into application and operations. As the NMFS ecosystem modeling effort matures among the regions, more EMs are used operationally. NMFS scientists must continue to improve modeling tools and their use to provide the best available science across mandates and synthesize information from a range of scientific disciplines.

The format for NEMoW 5 was designed such that the first day and a half was primarily presentations on EBFM efforts at FSCs, recent tool developments, and overviews on topic areas by each of the topic teams. FSCs summarized their ongoing ecosystem modeling efforts generally and especially with respect to progress in the topic areas. These presentations 1) helped to provide topic groups some additional models and approaches that they might incorporate into their manuscripts and, at a broader level, 2) enabled idea-sharing among scientists from different regions. FSC presentations were followed by a plenary discussion on the common themes across regions and management contexts.

After the context-setting plenary discussion of regional progress, plenary presentations on the tools and the Fisheries Integrated Toolbox (FIT, https://noaa-fisheries-integrated-toolbox.github.io/) were held. These plenary presentations provided background information on the progress in tool development – models and other programs for generating and presenting ecosystem information. Brief, overview demonstrations of five different types of tools were given. The overview presentations were followed by hands-on sessions, where participants met in smaller groups with presenters to receive instruction on how to use the tools. Time was allotted such that participants could receive instruction on 2-3 different tools.

To better promote, review, and disseminate tools developed and used by NMFS scientists, the FIT has been established. Presentations on the FIT and the Ecosystem Modeling Tools in the FIT were given. Participants discussed the benefits and possible drawbacks of such a toolbox. Further discussion and ongoing development of the FIT is now being carried out in the monthly FIT Technical Team meetings, particularly as relates to EM tool development and how to add them to the FIT from various sources.

The last round of plenary presentations and discussions was on the progress review topic areas: multimodel ensembles, ocean model/fisheries model coupling, engaging managers in model use and development, ecosystem level MSEs, and coupled social-ecological models. Team leads for each topic group presented an outline of their reviews. Presenters received feedback from the other writing groups and discussed how their papers might be complementary.

For the remainder of the workshop, topic teams broke out into groups to incorporate feedback from the larger group and to further flesh out their reviews. The larger group reconvened periodically to discuss cross-cutting themes in their papers and to summarize the likely recommendations that would come from their reviews.

This workshop was planned with a format to maximize interaction and discussion and to allow revisiting topics from multiple perspectives, building upon the strength of having the NMFS ecosystem modeling community gathered from the different regions. The primary goal of this workshop was to address each of the Terms of Reference (TORs) listed below.

Terms of Reference (TORs)

Theme: Reviewing Progress in Ecosystem Modeling For Living Marine Resources

Objective: Review progress in EM development and application for living marine resource management and make recommendations for future work to meet the NOAA Fisheries mission. The review will cover 5 topic areas: multimodel ensembles; ocean model/fisheries model coupling; managers and models: engaging managers in model use and development; ecosystem level MSEs; and coupled social-ecological models.

Terms of Reference:

1) Update current EM efforts underway at FSCs. Identify FSC practices that have improved utility of modeling for management.

2) Outline and review tools being used at FSCs and cross-train on tools.

3) Review approaches for engaging managers in model use and development.

4) Review progress in model development and application with respect to:
    a) multimodel and ensemble modeling
    b) Ocean model/fisheries model coupling
    c) Ecosystem level MSEs
    d) Coupled social-ecological models, and
    e) End-to-end models for structuring EBFM.

5) Develop best practices and recommendations covering the reviewed topics.

Discussion Summary

More detailed summaries of presentations, tool demonstrations, and topic area reviews are given in the appendices. This section summarizes key discussion points under each term of reference.

ToR 1: Ecosystem modeling efforts underway at each FSC

Much of the discussion of FSC modeling efforts was centered on engaging managers in model development and use. This part of the discussion is included under the ToR 3 Discussion Summary. Other aspects of FSC modeling efforts that were discussed included: incorporating socioeconomic information into EMs, non-fisheries uses of models, connecting EM forecasts to tactical management, and the funding needed and challenges associated with moving towards operationalization. These discussion topics are summarized below.

Efforts to bring in socioeconomic information and couple this to ecosystem models

- Incorporating socioeconomic information requires considerable time and resources to obtain and analyze additional data; thus a clear policy need for doing so must be

identified. For example, Southwest Fisheries Science Center (SWFSC) models needed to engage with a salmon management and water policy process. Meeting these distinct objectives and working across disciplines and management arenas required a common language and approach to bridge them. Socioeconomic measures were needed.
- Participants emphasized the need for programs like the Integrated Ecosystem Assessment to incorporate the integration between biophysical and social sciences.
- Other participants noted that funding sources (grants) can and have encouraged social science collaborations.

Non-fishery uses: expanding to multi-sector EBM, from EBFM

- FSCs are expanding models to incorporate cultural and non-fishing value. SWFSC is beginning to handle this in terms of forage links to marine mammals, and then links from marine mammals to ecotourism or whale watching opportunities.
- SWFSC is also incorporating models that include ship strikes of whales as a major non-fishing effect of interest.
- Offshore energy is becoming an important focal point for FSC modeling efforts. AFSC discussed multi-agency planning of shipping lanes in Alaska, to minimize disturbance of marine mammal colonies. The main point is that multi-agency coordination is key, and negative impacts seem to be small compared to the gains.
- Northeast Fisheries Science Center (NEFSC) is working on ship strike and wind energy issues.

Forecasting and links to tactical management on 1-5 year time scales

- Participants stated that often we lack ocean forecasts on the time scales on which management acts, say, one to five years. However, the sablefish recruitment models at the NWFSC have used models with a timeframe of one to five years. These sablefish models worked well in the Pacific Fisheries Management Council (PFMC) process, partly because they could be slotted into risk tables that are standard management machinery of the fishery council. Despite the single sablefish example, the need for these forecasts at this time scale remains a major “sweet spot” for ecosystem modelers and stock assessors within NMFS.
- Other participants brought up the different needs to predict vs. to understand; often these are very different, and many statistical approaches like machine learning are fully sufficient for making good predictions, even if they do not aid understanding of process and mechanism. Generally when working with forecast models for management, the need to understand (and try to falsify) mechanisms in ecosystem models is emphasized, rather than simply relying on correlations. Often there may be challenges where we think we understand the mechanisms, and then these mechanisms break down due to unexpected ecological complexity. This remains a challenging area of active consideration.

Moving towards operationalization — funding sources and challenges

- A few participants pointed out that funding sources often emphasize innovation, and then we often must repurpose these innovations for operational use. Even within NOAA and NMFS, grants often fund innovative approaches, rather than operationalizing products for agency use.

- While many participants agreed with this concern, they also emphasized that operationalization does not always offer publication opportunities. Incentives for academic partners and contractors are often based on publication and novel research.
- Conversely, mission driven applications of EMs have other benefits, but they are often not discussed in a personnel/career development context.
- Similarly, continuity of personnel and institutional knowledge needed for operationalizing EMs can be a challenge with short term funding cycles.
- Participants identified a need for structuring FSC efforts to meet both research and development needs as well as needs for operationalizing models for management. Some suggested that we should be thinking of a research-to-operations continuum rather than a dichotomy.

ToR 2: Progress on tools developed at FSCs

Tool experts were asked to give a 10-15 minute presentation on their tool. After that, two rounds of 1-hour breakout sessions were held for the hands-on portion so participants had an opportunity to explore multiple tools. This provided an opportunity for the participants to spend time learning how to use the tools of interest to them. The leaders provided example data that participants used for exploring the tool. The leaders also worked with participants to load the participants' own data/model output into the tool to use for exploring the tool. .

The tool experts were asked to cover the following in their presentations:

- Background on why and how the tool was developed
- Specific examples of the types of trade-offs the tool can be used for
- Output and features of the tool – including types of input data the tool uses and outputs of the tool

The following tools were presented during this session:

- Atlantisom - Presenter: Christine Stawitz
- MSE capabilities in Rpath - Presenter: Sean Lucey
- Rshiny general (with Rpath specifics) - Presenter: Sean Lucey
- Fitting and sensitivity routines in Rpath - Presenter: Andy Whitehouse
- EcoCast & dashboard in development - Presenter: Stephanie Brodie
- WHAM - Presenter: Scott Large

Detailed descriptions of the tools presented during the workshop are given in Appendix A-3.

As tools are presented at NEMoWs, modelers across FSCs can learn new methods and apply them to issues in their regions. More rapid dissemination of tools and accessibility of tools for “off-the-shelf” use is necessary to enable modelers to spend more time applying tools to management issues. This is a vital step towards operationalizing EMs for EBFM. The Fisheries Ecosystem Tools within the Fisheries Integrated Toolbox (FIT) provide a repository for the products created at the FSCs to enable dissemination of tools across NMFS. Presentations on the FIT and ecosystem tools were given and the utility of the toolbox was discussed. Summaries of these presentations are given in Appendix A-4.

ToR 3: Engaging managers in model use and development

In the discussion, participants agreed that most FSCs have developed some level of sustained, robust ecosystem modeling effort. However, the FSCs have varying degrees of success in ecosystem modeling and other information being undertaken by Fisheries Management Councils (FMCs) and other management partners. Modelers in many FSCs have a general idea that their models (and other ecosystem products such as ecosystem status reports and Integrated Ecosystem Assessment analyses) are providing ecosystem context for management decisions (Figure 1). From FMC decision documents, it is challenging to understand where ecosystem information was used to make decisions. Identifying specifically how and why the FMC makes fishery decisions, other than from stock assessments, can be difficult. For example, Northwest FSC participants found it difficult to identify exactly how the PFMC used the Ecosystem Status Report (ESR) information on the warm blob (warm anomaly), when dealing with fishery decisions, but anecdotally their impression was that PFMC found this information to be useful.

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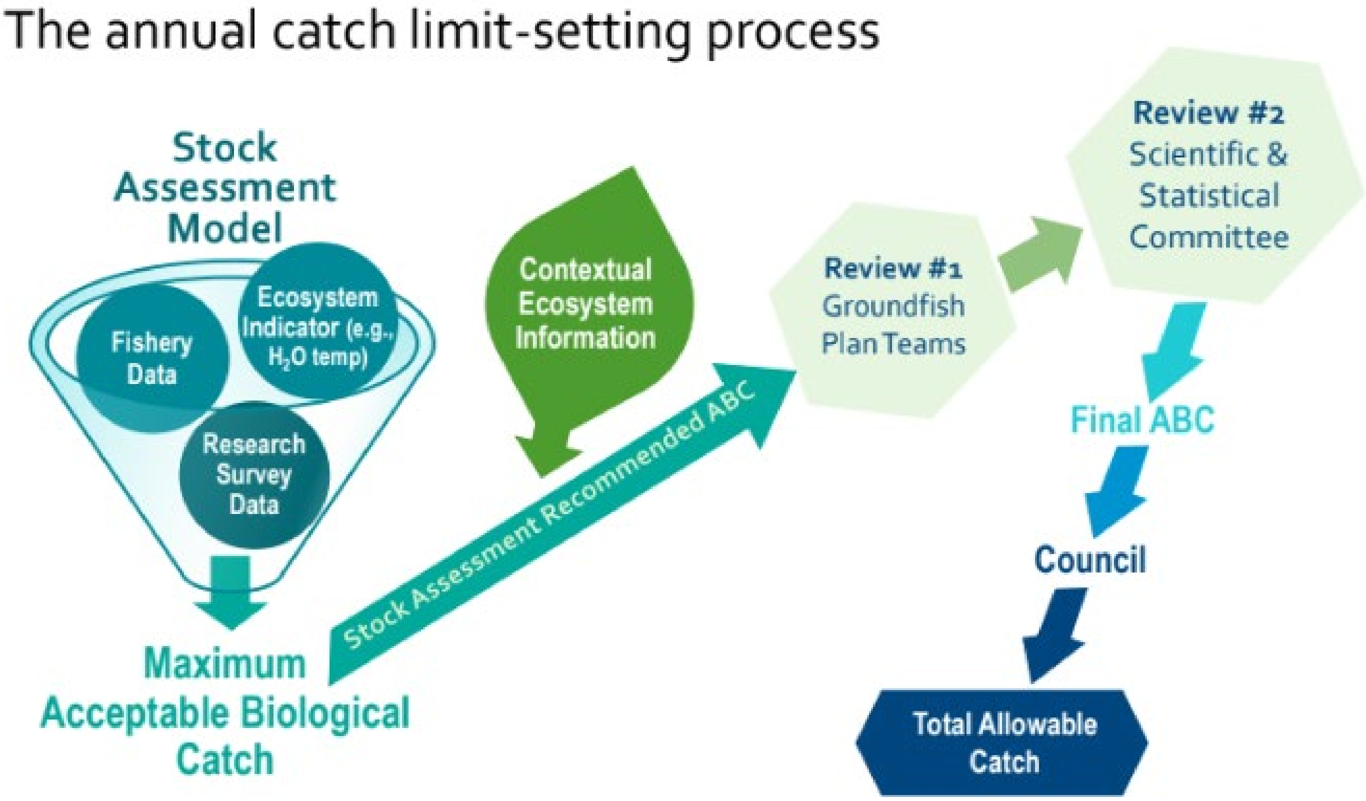

Figure 1. EMs and other ecosystem information products provide context for fisheries management decisions. Adapted from a presentation by Zador et al, AFSC.

Despite some challenges in the uptake of ecosystem information and EM outputs into management-decision making processes, several participants pointed out examples of successful uptake and specific applications of EMs and information. These examples include:

- AFSC has Risk Tables within each stock assessment, documenting the decision process, when they have considered ecosystem information, and when they have actually changed management decisions based on different sources of information. One interesting aspect of this is that the FMC has different levels of risk tolerance for different stocks. Table 1 illustrates risk levels applied for each stock based on issues associated with the assessment, a stock’s dynamics, ecosystem considerations, and fishery considerations.

Table 1. Structure of AFSC risk tables for fishery management. Adapted from a presentation by Zador et al, AFSC.

	Assessment-related considerations	**Population dynamics considerations**	**Environmental/ ecosystem considerations**	**Fishery performance considerations**
Level 1: Normal	Typical to moderately increased uncertainty/minor unresolved issues in assessment.	Stock trends are typical for the stock; recent recruitment is within normal range.	No apparent environmental/ ecosystem concerns.	No apparent fishery/resource-use performance and/or behavior concerns
Level 2: Substantially increased concerns	Substantially increased assessment uncertainty/ unresolved issues.	Stock trends are unusual; abundance increasing or decreasing faster than has been seen recently, or recruitment pattern is atypical.	Some indicators showing an adverse signals but the pattern is not consistent across all indicators.	Some indicators showing adverse signals but the pattern is not consistent across all indicators.
Level 3: Major Concern	Major problems with the stock assessment, very poor fits to data, high level of uncertainty, strong retrospective bias.	Stock trends are highly unusual; very rapid changes in stock abundance, or highly atypical recruitment patterns.	Multiple indicators showing consistent adverse signals a) across the same trophic level, and/or b) up or down trophic levels (i.e., predators and prey of stock)	Multiple indicators showing consistent adverse signals a) across different sectors and/or b) different gear types.

Level 4: Extreme concern	Severe problems with the stock assessment, severe retrospective bias. Assessment considered unreliable.	Stock trends are unprecedented. More rapid changes in stock abundance than have ever been seen previously, or a very long stretch of poor recruitment compared to previous patterns.	Extreme anomalies in multiple ecosystem indicators that are highly likely to impact the stock. Potential for cascading effects on other ecosystem components	Extreme anomalies in multiple performance indicators that are highly likely to impact the stock.

- The Atlantic States Marine Fisheries Commission (ASMFC) has spent several years in a major effort to refine EMs to answer managers' questions about the influence of Atlantic menhaden management on key predators (e.g., striped bass, bluefish, and weakfish). This effort resulted in a multi-model approach – a lead model with supporting models – for setting ecological reference points for the menhaden management. This result highlights the need for engagement with managers, and refining models to address the questions of those managers.

- NEFSC participants discussed that the Mid-Atlantic State of the Ecosystem report documents some of the inclusion of ecosystem information into the management system. Total commercial fishery landings were scaled to ecosystem productivity. Primary production required to support Mid-Atlantic commercial landings has been declining since 2000. Fish condition, "fatness", is an important driver of population productivity. Condition is affected by changing habitat (e.g., temperature) and ecosystem productivity, and in turn can affect market prices. Despite mostly meeting fishery management objectives at the single species level, long term declines in total seafood production and commercial revenue remain apparent.

The discussion of management challenges and successes led participants to a few main conclusions. FSCs need to have models "on the shelf" in the toolbox to rapidly deal with new management questions as they arise. FSCs also need to be prepared to work iteratively with management bodies. In addition, FSCs need to recognize that the FMC process is a multi-stakeholder process, so there may be multiple points of entry for incorporating ecosystem advice into management processes. Participants identified a general need to better document the decisions that management bodies make regarding whether to change management, and how far to change, and why (what justification) a change was made when incorporating ecosystem advice.

A final point was raised on the need to operationalize ecosystem modeling at the FSCs. During the workshop, participants looked back over the 20+ years that NMFS scientists have been developing EMs for LMR applications. Participants observed that incorporation of ecosystem modeling into management decision-making has followed a path similar to the Gartner Hype Cycle (Figure 2). This cycle is used in business fields to understand how applications of a new technology will evolve over time. At this stage of the NMFS Ecosystem Modeling enterprise, most ecosystem modeling efforts at the FSCs are beginning to meet some realistic expectations of management bodies – i.e., on the “Slope of Enlightenment”. As FSCs find and develop entry points for ecosystem modeling and other ecosystem info into operational management decision-making, the need for operationalizing FSC modeling efforts becomes apparent to ensure that the high levels of productivity needed by managers are met.

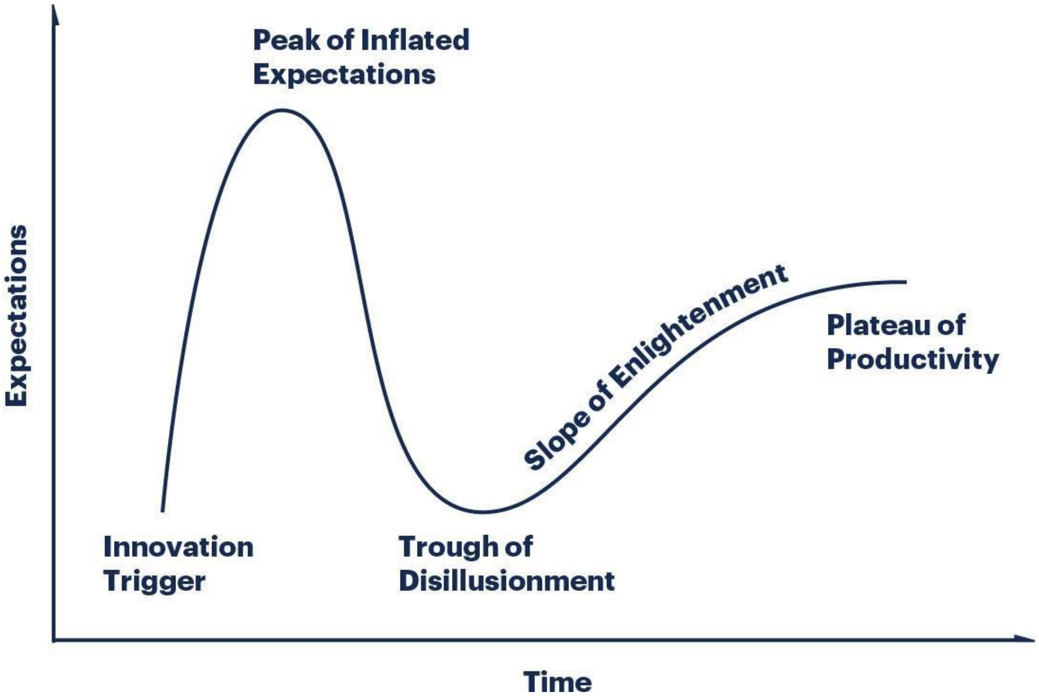

Figure 2. Gartner Hype Cycle. Adapted from: https://www.gartner.com/en/research/methodologies/gartner-hype-cycle

ToR 4: Review progress in model development and application in each topic area

Summaries of the topic reviews are presented in Appendix A-5. Some of the topic teams are planning to submit papers that more thoroughly review the progress made in the topic areas. These papers are planned for submission to a *Frontiers in Marine Science* Research Topic titled: "Using Ecological Models to Support and Shape Environmental Policy Decisions". This section covers the discussion of the key points in the topic areas and some cross-linkage between the topic areas.

Participants noted a few examples of multimodel approaches being used for MSEs (specifically with highly migratory species in the Pacific). This combination allows the exploration of multiple axes of uncertainty (e.g., model structure uncertainty as well as parameter uncertainty and natural variability). Participants suggested that some of the discussion sections should cover the barriers to uptake of ensembles by management.

In the discussion on the ocean model/fisheries model coupling, the presenter noted that NMFS modelers should pay careful attention to the point of connection between ocean and fisheries models, primarily the biogeochemical models that link the two. Participants emphasized that these efforts should specifically consider how focus should be spent on lower and higher trophic level processes – i.e., the level of detail needed for the processes may be driven by the management objective of a coupled model.

The ecosystem-level MSE review aims to identify recent examples where management strategy evaluation has included ecosystem aspects and ecosystem modeling. In particular, the paper identifies the extent to which EMs can be used as 'raw material' within the MSE loop, meaning that these models can slot into the simulation testing of management strategies. For instance, EMs can serve as operating models ('virtual worlds'), they can inform harvest rules or performance metrics, or statistical EMs can estimate ecological interactions. The efficacy of added consideration of ecosystem elements can be tested within MSE. Work from NEMoW 2 and a resulting manuscript focused on uncertainty (Link et al. 2010, Link et al. 2012), which can be addressed in part by explicit representation within the MSE loop.

The coupled social/economic and ecological models review suggests that a range of approaches including conceptual modeling efforts as well as coupling of more quantitative models should be considered. In addition, participants discussed the fairly common use of extant 1-way coupled models (e.g., bioeconomic models) and the potential need to expand the use of 2-way coupled models. Participants noted some potential parallel structure and perhaps overlap between this review and the review on connecting fisheries policy challenges and models.

The aim of the end-to-end modeling review is to illustrate and improve two-way information flow from field to policy. Mapping the information flow from field operations and research to management is helpful for identifying where the choke points are along the process. Knowing these choke points is important for getting the managers the information that they need in a timely manner. Participants noted that this information flow will also be useful for modelers when they consider how to refine their models.

In the review on connecting fisheries policy challenges with models and analysis, the presenter observed that EBFM uptake and implementation have been slow. To improve ecosystem understanding, NOAA has prioritized ESRs. ESRs provide many indicators, but interpretation and contextualizing those indicators in order to address management needs is dependent on understanding the system. The review will use the California Current as a case study for demonstrating how management challenges can be linked to existing models to expedite the use of ecosystem information in management processes. A major step in this effort involves workshops with managers to learn more about models and review management needs and objectives. This step enables scientists to gain familiarity with policy needs and managers to get a better sense of capabilities and limitations of models.

ToR 5: Develop best practices and recommendations covering the reviewed topics

Participants discussed the take-away points and best practices for each of the NEMoW 5 topic areas. These points serve as a basis for the overall best practices and recommendations listed in the Conclusions section.

Multimodel Ensembles

- As noted in NEMoW 2 & 3 (Link et al. 2010, Townsend et al. 2014), the process of using multiple models and ensemble modeling can improve credibility and aid in uptake and use of EMs by managers. When feasible, multiple models should be used for addressing EBFM issues.
- A good practice is for NMFS scientists to have a suite of models on the shelf (hence the development of the FIT).
- Models within the ensemble should be compared, even qualitatively, to help inform management decisions.

Ocean Model/Fisheries Model Coupling

- NMFS projects on coupling oceanographic and fisheries models may benefit from further consideration of Coupled Model Intercomparison Project Phase 6 (CMIP6). CMIP6 is focused on reviewing multiple models to 1) assess possible mechanisms for poorly understood feedbacks between poorly understood models, 2) examining coupled model predictability and the ability of models to predict on different scales, and 3) examine why similarly forced models produce a range of responses. Applicable model comparison approaches from CMIP6 should be adopted for ocean-fisheries model coupling.
- Because model development is frequently funded with targeted, short-term funding, it is important to fully document the model development and validation processes. Decision criteria for model parameters and parameter tuning should be well documented.
- Biogeochemistry is an evolving discipline, and some of its aspects cannot be easily operationalized yet. The modeling of biogeochemical processes is currently more reliant on empirical relationships (as opposed to well-quantified mechanisms or first principles) than its physical model counterparts. These empirical relationships are often poorly constrained beyond a narrow range of historical observations. Accounting for and fully acknowledging the larger uncertainty levels associated with these processes when using these models in an operational context is a best practice.
- It is wise to link to NOAA's Unified Modeling Committee and how they are bringing online some of these models, especially the transition of ROMS to MOM6.

Engaging Managers in Model Use and Development

- Many existing EMs in the West Coast case study are either already operational or are nearing operational status and can be connected to each of the five management challenge themes. Other regions are making similar progress. Distilling regional management concerns down into challenges and linking those challenges to extant operational models is a good practice for manager engagement.
- Several models can be linked to multiple themes, and different themes may relate back to different ecosystem management objectives, legislative or executive mandates, and policy levers. (For example, some mandates, policies, and levers may reside within an FMC under Magnuson-Stevens, while others may be transboundary and bring other mandates, agencies, and levers into play.) This points to the utility of the models. It also demonstrates the need for modelers to understand distinct management needs and contexts, and for managers to understand model capabilities and limitations. Linking models to management objectives and mandates is a good approach to demonstrate the utility of models.
- Better understanding of the exact needs of managers and advisory groups is necessary. We will need to engage policy makers directly to ensure we are addressing Step 2 of Figure 3 (below) for implementation (scientists understand policy; managers understand capabilities/limits of models). For example, is an annual average of the last year the desired temporal resolution? It is possible for modelers to transform data to appropriate scale but they should communicate with managers on what scale is desired.

- Many questions from managers and stakeholders imply the need for a model without specifically calling for one to help interpret and integrate ecosystem indicators. This may require some focus on communication with managers and stakeholders under Step 1 of Figure 3, because in those cases we would be using models to provide context or to identify emerging ecosystem issues. That communication may lead to mutual development of ecosystem objectives and better understanding of one another's perspectives.
- This process can also be used to identify gaps in modeling capability (when no EM matches up to an identified need), and we can also give the managers an idea of how long it might take to develop a model for the need and its likely capabilities; this could be a good way to identify priorities for new EM development, particularly of MICE models.
- Indicators and information/data integrated into ESR often come from a diversity of EMs, such as multi-species, single species, and environmental models. Having a suite of models available can help build consensus. Flexibility in the format and content of ESR is needed to allow modification in response to managers/advisory group feedback. Operational EMs are particularly important for ongoing ESR.
- We can improve communication between ESR writers and modelers who have operational outputs. Some operational models may require revision of outputs to support integration into ESR.
- We need multiple iterations of modeler-manager communication.

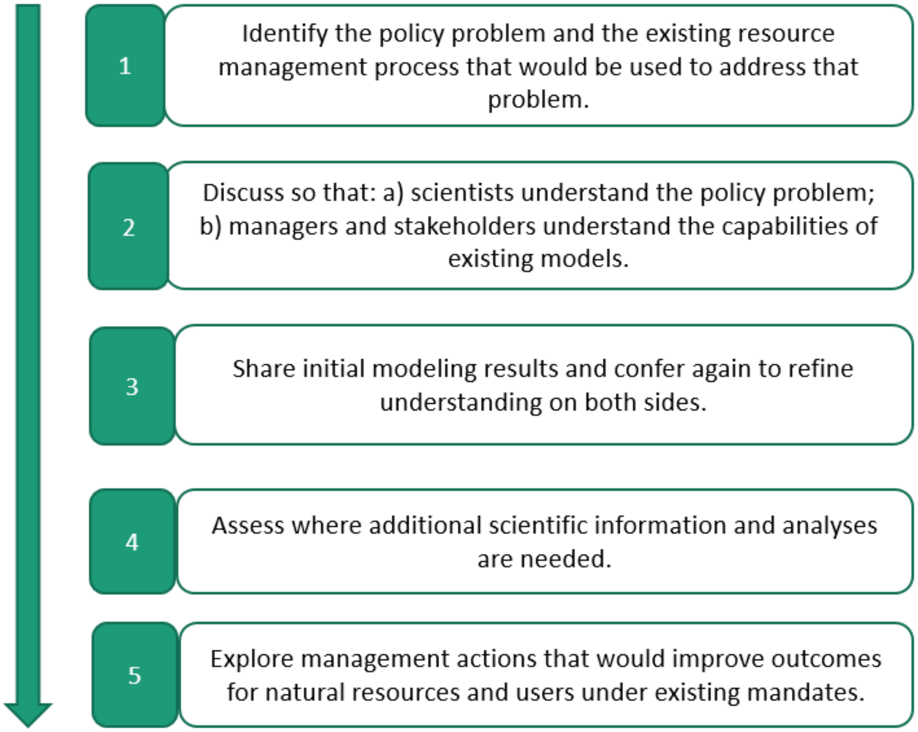

Figure 3. Outline of the steps for incorporating information for EMs into management. Adapted from Townsend et al. 2019

Ecosystem-level MSEs

- When using EMs as operating models, a best practice is to use operating models with structures that do not perfectly match the estimation models' structure; however, a cost (in terms of time to fit estimation models) is associated with this practice.
- When using EMs for MSEs, there are multiple points in the MSE loop where the models can be used to address uncertainty. To avoid confusion, modelers should explicitly state and clearly visualize how the model was used to handle uncertainty.
- Overall, MSE is appropriate for simulation testing a wide range of policies for living marine resources, beyond just fisheries harvest. Modelers should be prepared to interact in these other management venues.

Coupled social-ecological models

- A range of approaches is available for connecting social/economic aspects of ecosystems with ecological aspects. These broad categories include qualitative models, one-way coupled models, and two-way coupled models. Modelers should find opportunities to demonstrate the utility of this range of approaches to ensure managers understand how and when the approaches can be used as well as the value of doing so.
- One-way coupled models (e.g., outputs form ecological models used as inputs to economic models) are fairly commonly used. Qualitative models have become more commonly used in management applications. Further use of two-way models (where social and economic behaviors are influenced by environmental/ecological properties as

well as influence ecological systems) is needed to provide managers and stakeholders with an understanding of complex interactions within the social-ecological system.

End-to-End Modeling for Structuring Ecosystem Based Fisheries Management Programs

- End-to-end ecosystem modeling allows a field-to-policy approach that enables the evaluation of gaps and information flow, all the way from collecting data/observations to the design or evaluation of policies and strategies to address specific management questions.
- Additionally, using end-to-end models as a tool to isolate specific data needs and detailed policy questions/scenarios helps focus and prioritize programmatic or institutional resources, to both advance and strengthen EBFM.
- Operational end-to-end models should be available in all regions and used to help structure EBFM implementation.

Conclusions

A major conclusion from the participants of NEMoW 5 was that NMFS and its partners have made considerable advances in applying ecosystem modeling for LMR management. This workshop provided an opportunity to review those advancements and consider what lies ahead to ensure NMFS has the capability to meet future needs as the nation advances towards implementing EBFM. A number of FSCs have had some success working with FMCs and other management and planning bodies in using EMs, analysis, and other information for supporting decision-making. Workshop participants took this opportunity to learn lessons and on-the-ground approaches for providing model-based advice to managers. The proceedings of NEMoW 5 in this Technical Memorandum represent the tip of the iceberg of knowledge exchanged. As a part of the topic reviews, some participants fleshed out outlines for manuscripts to more thoroughly review the progress in ecosystem modeling for LMR. These participants have continued developing manuscripts which will provide further detail and outline lessons learned and future directions to ensure that future EBFM needs are met.

Evaluation of the topic area best practices led to a few key best practices and recommendations that are more broadly applicable. These best practices and recommendations are listed below. As we move forward with ecosystem-oriented management of LMRs (including EAFM, EBFM, and EBM), modelers are advised to follow these best practices. In addition, the recommendations listed below will facilitate the improvement in scientific advice for LMR management.

Best Practices

1) The use of multiple models helps to address uncertainty and to develop stakeholder buy-in. As much as is feasible, multiple models should be used.
2) Make sure that EMs have adequate process detail to ensure management utility but not so much detail that operational use is hindered.

3) Work with management bodies to refine and focus models to meet management needs. This requires time and effort to organize understanding of management challenges and objectives, to match extant operational models to those challenges, and to develop or refine other models where needs are not fully met.
4) Use EMs for multiple points on the MSE loop to address uncertainty. Ensure that the points of uncertainty to be addressed are explicitly stated and clearly communicated and visualized.
5) Use coupled social-ecological models to more thoroughly understand human influences on ecosystems.
6) Use end-to-end models to structure data and information flow for end-to-end EBFM – i.e., from field operations planning to policy setting.

Recommendations

In developing the list of best practices for applying EMs for LMR management, participants identified steps that could be taken with NMFS and the FSCs. The major recommendations are outlined below.

1) Multiple models should be available for addressing regional ecosystem-oriented management issues.
2) End-to-end models should be available for regional ecosystems to help inform data and information needs in an EBFM program.
3) EMs should be presented and discussed regularly at regional management bodies to focus EBFM management objectives and facilitate model refinement to address objectives.
4) EMs should be used regularly for MSEs.
5) Each region's ecosystem modeling tool set should include coupled ocean/fisheries models to address the influence of climate and environmental factors on regional ecosystems.
6) Coupled social-ecological models should be included in regional ecosystem modeling tool sets to a) aid with stakeholder engagement, b) improve understanding of the influence of human behavior on ecosystem structure, and c) provide a relatable common connection across ecosystem uses.

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Appendix A -Abstracts and Summaries of Plenary Presentations

A-1: Summary of Introduction and Opening Remarks

Dr. Jason Link, NMFS Senior Scientist for Ecosystem-based Management and Peg Brady, NMFS Office of Science and Technology, Marine Ecosystems Acting Division Chief kicked off the meeting with some opening remarks. They reviewed the progress and capacity building that has occurred for NMFS ecosystem modeling efforts over the past 20+ years. They set the stage for why ecosystem modeling is important in NMFS, and where future ecosystem modeling efforts will be headed and how those efforts tie into other EBFM work in the agency.

Jason Link began by welcoming all participants from NMFS FSCs, ROs, and other NOAA line offices, as well as invited guest observers and speakers.

Link highlighted that this workshop (and the NEMoW series) is a key part of the ongoing NMFS EBFM efforts. Link reviewed the general objectives of the NEMoWs and provided some historical background on the origin of NEMoWs, why NEMoWs are still needed, and what we aimed to achieve at NEMoW 5.

He outlined some of the key accomplishments for supporting NMFS EBFM efforts that sprang from NEMoWs and related efforts. These outcomes include:

- Went from 1 out of 7, to now all FSCs having formal ecosystem modeling groups or capacity
- Now at least some form of End-to-End model, Model of Intermediate Complexity, food web model, aggregate production/biomass model, and climate-linked model in almost all regions
- Increasing demand, interest, and need for MSEs; but also increasing confusion as to what they provide and entail
- More LMR assessments quantitatively including ecosystem linkages based on EM work (increased from about 4% to 8%)
- Ecosystem Status reporting routinely using EM outputs
- Enough development to have best practices for 4 specific and 3 classes of models
- Enough development to begin standardization of tools

He urged modelers to move towards operationalization of models, pointing out the following:

- A need to spend less time on development and more on increasing operationalization of models
- NMFS has more FMC and related management partners routinely asking for this type of information
- A continued need for clearer and routine EM review venues and protocols exists
- Ongoing & expanding need for operational application of EMs with Protected Resources and Stock Assessment colleagues
- Increasing need for operational application of system-level outputs

In the context of EBM of marine resources, operationalization means: 1) models are routinely and regularly provided (i.e., not research), 2) models are using already vetted and verified methods, approaches (i.e., not research), 3) models incorporating the latest data updates (which along with synthesis outputs are reviewed), and 4) using models to inform, support, or assist decisions (i.e., applied, not theoretical). Operational is typically tactical (focused on the short term or on specific actions) and focused on actionable choices, outcomes, and impacts; but it can also be strategic, heuristic, or contextual, specifically to bound tradeoff solution space. Some of these ideas were summed up in a quote by Rick Methot: "Holistic models do not need to be operational and tactical in order to be a full partner in development of advice. Holistic models will be better, in a MSE kind of way, at designing harvest policies; then leave the implementation to the tactical models. Weather is to climate as fish assessment is to EBFM."

This presentation was wrapped up with some points about the future direction of Ecosystem Modeling. Future growth and application areas for EM that he pointed out include application for MSEs, producing ecosystem-level reference points, coupling social science and ecological models, and linking with climate models. These future growth areas match up well with the Topic areas of the workshop. Finally, he noted the importance of EM for forecasting.

Peg Brady followed Link's remarks. She noted that EM is an integral part of the agency's drive towards implementing EBFM. In addition, Brady discussed the NMFS EBFM Policy and the EBFM Road Map as well as connections between the agency's habitat and climate efforts.

A-2: Extended Abstracts on Ecosystem Modeling efforts at NMFS FSCs

Alaska Fisheries Science Center Ecosystem Modeling Efforts

The Alaska Fisheries Science Center ecosystem modeling efforts are organized by ecosystem, covering the four large marine ecosystems in Alaska: the eastern Bering Sea, Gulf of Alaska, Aleutian Islands, and the high Arctic (Chukchi and Beaufort Seas). Modelling efforts are generally focused on the federally-managed groundfish stocks in the region.

Ecopath/Ecosim models have been built for each region (four models in total), and have recently been part of a cross-comparative study of ecosystem structure (Whitehouse and Aydin 2020). This includes the development of new sensitivity analysis tools for Ecosim models, released as part of Rpath, an R implementation of Ecopath/Ecosim recently completed as part of a collaboration between NEFSC and AFSC (Lucey et al. 2020).

For the eastern Bering Sea, a suite of modeling tools has been created or improved for use in a multimodel management strategy evaluation (the ACLIM project; Hollowed et al. 2020) to test fishery management strategies in anticipation of future climate change. For these purposes, a Bering Sea 10-km ROMS/NPZ has gone through iterative improvements (Kearney et al. 2020) to establish capabilities both for long-term oceanographic projections driven by IPCC scenarios of climate change (Hermann et al. 2019), and for short-term (1-9 month) forecasts driven by seasonal atmospheric models. These projections, in particular for temperature and plankton production, drive several developed multispecies and EMs, including Ecosim, the multispecies statistical catch-at-age model CEATTLE (Holsman et al. 2016), a multispecies size-structured model (Reum et al. 2020) and the spatially-explicit foraging model FEAST (Ortiz et al. 2016). A similar modeling effort is underway in the Gulf of Alaska to develop a similarly-broad suite of models that further includes a spatially-explicit MICE model (Thorson et al. 2019) and the future development of an ATLANTIS model for the Gulf of Alaska. CEATTLE is also used for tactical management as an alternate model in the annual Bering Sea walleye pollock assessment (e.g. Holsman et al. 2019).

Further, several local-scale modeling efforts have focused on community engagement through collaborative building of Qualitative Network Models, including a model focused on the communities of the Pribilof Islands (Reum et al. 2019) and Sitka Sound (Rosellon-Druker et al. 2019).

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Northeast Fisheries Science Center Ecosystem Modeling Efforts

The Northeast Fisheries Science Center (NEFSC) is making progress in efforts to support ecosystem modeling for living marine resource management. During NEMoW 5, the NEFSC highlighted progress towards operationalizing EMs and establishing better practices for improving model utility for management.

Herring MSE

In 2016, a stakeholder-driven management strategy evaluation (MSE) that incorporated a broad range of objectives for Atlantic herring was completed (Deroba et al. 2019, Feeney et al. 2019). Herring were linked to three sensitive predator types with adequate data to justify modeling; no existing model addressed all objectives. Three control rule types -- constant catch, conditional constant catch, and 15% restriction on change -- were rejected at the second stakeholder meeting for poor fishery and predator performance. Predators were not sensitive to the range of habitat control rules because they were evaluated within F_{MSY} for herring. Multispecies models of intermediate complexity were informative for managers and provide a foundation for future improvements.

MAFMC EAFM Risk Assessment

Since the previous NEMoW meeting, there has been considerable progress towards a MSE for the Mid-Atlantic Fishery Management Council (MAFMC). The MAFMC has approved an EAFM Guidance Document that aims to incorporate ecosystem science into species-specific management science. The Council established a structured framework to account for and incorporate ecosystem consideration (Gaichas et al. 2016) and implemented the initial risk assessment based on ecosystem indicator reporting (Gaichas et al. 2018). In 2019 a working group of habitat, biology, stock assessment, management, economic, and social scientists developed: 1) draft conceptual models of high risk elements and linkages, 2) dataset identification and gap analysis for each element and link, and 3) draft questions that the Council could pursue with additional work.

The final conceptual model and supporting information (DePiper et al. 2019) was presented at the December 2019 Council meeting. The Council approved the model and agreed to use MSE to evaluate management strategies to realize biological and economic benefits of minimizing discards and converting discards into landings in the recreational summer flounder fishery.

Performance of a state-space multispecies model

An age-structured multispecies operating model was developed that simulated data with errors in observations, recruitment, and fish abundance (Trijoulet et al 2019). Four estimation models were developed to account for combinations of predation and process error. Ignoring trophic interactions introduces biased assessment outputs and results in poor predictive capability and potentially biased reference points.

Condition factor modeling

Climate change can affect the health of fish populations in many ways including increasing the energetic requirements to search for prey and to find suitable thermal habitat. Managed populations may experience declines in condition as habitats become less favorable, but before they alter their distribution. In this study, 27 years of relative condition factors (Kn) were analyzed for 40 finfish stocks commonly caught on the Northeast Fisheries Science Center's autumn bottom trawl survey. A generalized additive model was used to test if indices of bottom temperature, stomach fullness, local population density, copepod size structure, or bottom trawling fishing effort contributed to the prediction of relative condition of individual fish. Sexes were analyzed separately for species that showed sexually dimorphic growth rates. Declines in condition occurred around the year 2000 across many fish species on the Northeast US Continental shelf, with some species recovering around 2010. Temperature predicted relative condition for some stocks, indicating that these stocks may be particularly sensitive to thermal changes, whereas density dependence, food availability, and other factors are likely the primary drivers for other stocks. These changes in condition have direct implications for stock assessments, catch quotas and management and may indirectly impact fish recruitment and mortality.

CIE model review

An Ecosystem Based Fishery Management Strategy Review Panel was convened on April 30 – May 3, 2018 in Woods Hole, MA. The review was conducted by a team of experts under the auspices of the Center for Independent Experts. The goal of the review was to evaluate a proposed strategy for implementing Ecosystem Based Fishery Management (EBFM) on Georges Bank for the New England Fishery Management Council (NEFMC). The work reviewed by the Panel was conducted by Northeast Fisheries Science Center (NEFSC) scientists in collaboration with the NEFMC Ecosystem Plan Develop Team and with input from the NEFMC. The panel consisted of Dr. Lisa Kerr (Chair, Gulf of Maine Research Institute), and Council of Independent Expert reviewers: Dr. Keith Brander (Technical University of Denmark), Dr. Villy Christensen (University of British Columbia), and Dr. Daniel Howell (Institute of Marine Research, Norway). The Panel reviewed the written materials and presentations on the proposed EBFM procedure and addressed nine terms of reference. The Panel reviewed the general EBFM approach proposed for implementation by the NEFMC and a simulation tested example of EBFM implementation on Georges Bank.

NEFSC scientists have been engaged in the development of an example Fishery Ecosystem Plan for Georges Bank for the New England Fishery Management Council. Three NEFSC staff members have been involved in the development of the plan since 2015. In September 2019, the PDT delivered a draft plan to the NEFMC which was accepted for further development. A series of stakeholder workshops will be held to chart the development of a Management Strategy Evaluation to test core elements of the proposed approach.

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Southwest Fisheries Science Center Ecosystem Modeling Efforts

The SWFSC carries mandates for a number of species and guilds including coastal pelagics, highly migratory species, demersal species, anadromous species, invertebrates, marine mammals, and marine turtles. This requires a diversity of modelling approaches from statistical to mechanistic to mass-balance based approaches. SWFSC has no formal modeling division, although significant effort occurs within the Environmental Research and Fisheries Ecology Division, often tied in as part of Integrated Ecosystem Assessment efforts. Following from the ecosystem review, the SWFSC is making multiple strides towards improving modeling at the center with the creation of a Management Strategy Evaluation position to focus on Albacore Tuna, swordfish, and sardines. Below are examples of modeling efforts completed or underway.

The Environmental Research Division, Fisheries Resource Division, Fisheries Ecology Division, and the Marine Mammal and Turtle Division are using statistical habitat models to look at species distribution relative to anthropogenic threats and human activities (Abrahms et al. 2019, Becker et al. 2019, Brodie et al. 2018, Brodie et al. 2019, Carroll et al. 2019, Muhling et al. 2019, Santora et al. 2019, Welch et al. 2019). These efforts include a range of fish, sharks, mammal, and turtle species using generalized additive mixed models, boosted regression tree models, and Bayesian approaches to understanding species-habitat relationships, and using these relationships to predict habitat in space and time. These tools assume maintenance of the relationships to allow persistence through time and require ongoing validation when operationalized. Further, ongoing efforts are assessing the dynamics of fishing fleets, and the socioeconomic assessment of the impacts of changing albacore distributions.

Dynamic energy budgets and stochastic dynamic approaches can be used to model physiological response to changing environmental conditions, such as for salmon adjusting to water temperature and stream flows (Pike et al. 2013, Lindley 2015), and for ecosystem responses under climate change. These models can focus on first-principles to provide a mechanistic approach to habitat and survival. They also can be generalized as physical-biological models that couple physics to lower trophic levels to understand how environmental conditions translate to ecosystem productivity. Conceptual models have been used to understand complex processes such as salmon ocean survival to understand how oceanic processes translate to growth and survival (Wells et al. 2016). Mass-balance models were originally developed for the California Current by John Field (Field et al. 2006), and have been expanded by academic researchers to look at finer resolutions and different environmental forcings (Koehn et al. 2016). Mass-balance approaches for the California Current are presently largely outside the SWFSC.

Finally, the outlier, but also a promising approach, is to use non-frequentist approaches including Bayesian population models and empirical dynamic programming where data sets are lacking or to understand population fluctuations as a function of their previous state in addition to extrinsic forcing (Deyle et al. 2013, Moore and Barlow 2013, Munch et al. 2016).

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Pacific Islands Fisheries Science Center Ecosystem Modeling Efforts

The Pacific Islands Fisheries Science Center (PIFSC) is focusing on ecosystem modeling efforts that will be of interest to and use by regional managers. These efforts include but are not limited to expanding the use of ecosystem modeling platforms, research towards better incorporating human wellbeing into EMs, and several projects with the goal of broadening the scope of existing stock assessment models. Across these endeavors, PIFSC continues to support and encourage cross-program and cross-division approaches. These and other modeling efforts are summarized below.

Expanding the capabilities of ecosystem modeling platforms

PIFSC has focused much of its ecosystem modeling efforts on expanding the capabilities of ecosystem modeling platforms. Work has largely focused on two projects: constructing an Atlantis model of the main Hawaiian Islands and developing an integrated size- and species-based food web model. The Atlantis model domain, species of interest, objectives, and key indicators were identified through the course of several workshops. Work is currently underway to research species' responses to aspects of climate change such as ocean warming and ocean acidification. Staff are also working to operationalize a social-economic-ecological-system model that includes the Atlantis model output as a component.

The therMizer food web model (Woodworth-Jefcoats et al. 2019) was used to project the effects of climate change on Hawaii's longline bigeye tuna fishery under a suite of possible future fishing scenarios. This model incorporates a dynamic background resource and the effects of temperature on both metabolism and aerobic scope. Results showed that climate change is likely to reduce fishery yield under all future fishing scenarios (both increasing and decreasing fishing mortality). However, reduced fishing mortality may allow some capacity for ecosystem resilience in the face of climate change, with resilience being represented through increasing fish biomass and body size.

Better incorporating social and economic systems into ecosystem modeling

A comprehensive effort was undertaken to better capture human wellbeing in the West Hawaii Integrated Ecosystem Assessment (Leong et al. 2019). This involved working with subject matter experts, community leaders, and resource managers to better understand relationships between West Hawaii's marine ecosystems and human wellbeing. The results highlighted a need to represent two-way reciprocal relationships between people and the ecosystems with which they interact, broaden the scope of disciplines included in ecosystem modeling efforts to include a diversity of social sciences, and realize the often fractal-like nature of coastal communities. This work is being incorporated in the social-economic-ecological-system Atlantis model discussed above, and can inform ecosystem modeling more broadly.

Broadening the scope of stock assessment models

Several projects are working to broaden the scope of stock assessment models. These include developing a Metapopulation Assessment System (MAS) and addressing non-stationary stock dynamics. MAS is an object-oriented, spatially explicit model that uses structural uncertainty to construct an ensemble model. This approach allows users to assess various model choices to aid in management strategy evaluation. A similar approach could be used to incorporate uncertainty into ecosystem modeling.

Work is also underway to identify fish species that exhibit non-stationary dynamics. Identifying these stocks is crucial to prioritizing research and assessment efforts. Early results show that both Western and Central North Pacific swordfish and striped marlin stocks may have environmentally driven non-stationarity. The latter is of particular concern as it is both overfished and experiencing overfishing. Beyond informing stock assessments, understanding environmental effects on stock dynamics can also inform ecosystem modeling efforts.

Research to support ecosystem modeling

Over the past several years, PIFSC has expanded the degree to which projects, including ecosystem modeling, work across programs and divisions. For example, a collaboration to understand how oceanographic transport of toxoplasmosis oocysts affects monk seals' risk of infection may also prove useful in understanding residence time and bleaching risk for coral reefs as well as larval fish transport. An effort to merge fishery catch data with environmental data in order to understand drivers of protected species interactions is also shedding light onto drivers of catch magnitude, composition, and value. Fishery data are also being examined in relation to satellite remotely sensed data to understand how mesoscale features affect community composition. Archived telemetry data is being aggregated and paired with climate model output to project the effects of climate change on tunas, billfish, and sharks. Cooperative fishing gear and drop cameras that are being used in a fishery-independent bottomfish survey are being equipped with environmental sensors in order to gain insight into characteristics of bottomfish habitat. Cross-program and cross-division collaborations such as these serve to broaden both the information used to inform ecosystem models as well as the management questions to which ecosystem models are applied.

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Southeast Fisheries Science Center Ecosystem Modeling Efforts

The NMFS Southeast Fisheries Science Center (SEFSC) has personnel based at separate laboratories, spread out across the region (Beaufort, NC; Miami, FL; Panama City, FL; Stennis & Pascagoula, MS; Lafayette, LA; and Galveston, TX). The SEFSC is responsible for three marine ecosystems – the U.S. Gulf of Mexico (GoM), the Southeastern U.S. Atlantic (hereafter South Atlantic) and the U.S. Caribbean. Thus SEFSC reports to three Fishery Management Councils (Gulf, South Atlantic, and Caribbean) and two Marine Fisheries Commissions (Atlantic States and Gulf States). In addition, SEFSC has staff dedicated to highly migratory species and international management entities. The SEFSC pursues major programs in the areas of stock assessment, fishery independent and dependent surveys, socioeconomics/human dimensions, protected species research and monitoring, and applied fisheries and habitat research. The SEFSC has staff assigned to support each of these operational tasks. At this time, the SEFSC does not have a coordinated organizational structure for ecosystem modeling and instead uses a “matrix” approach that pulls talent as-needed to complete specific projects. Due to the large number of operational tasks, ecosystem modeling projects at the SEFSC are often pushed out to our affiliated research partners through research grants (e.g. RESTORE).

Major SEFSC ecosystem science activities

Ecosystem Status Reports (ESR) (http://www.aoml.noaa.gov/ocd/ocdweb/ESR_GOMIEA/) and an Integrated Ecosystem Assessment group that is focused on the GoM (https://www.integratedecosystemassessment.noaa.gov/regions/gulf-of-mexico/index.html). The GoM ESR was completed in 2013 and updated in 2017. A draft ESR for the South Atlantic was recently completed, with a final report expected in FY20. There are 2 recent examples of how staff at the SEFSC are incorporating ecosystem considerations into single species assessments: the 2019 red grouper (for the GoM) and the menhaden assessment (for the South Atlantic). The 2019 red grouper assessment incorporated the predicted intensity of red tide (from a 2018 ecological survey) as "extra" episodic natural mortality, then let the model estimate the removals it expects based on the data in the model (SEDAR61). The second application uses a multi-model ensemble approach, where Amy Schueller’s Beaufort Assessment Model (BAM) combined with predictions from Dave Chagaris’s EwE-MICE model were selected at a recent Atlantic States Marine Fisheries Council (ASMFC) workshop for providing total allowable catch advice (TAC).

Below are highlights of the SEFSC’s recent or ongoing ecosystem modeling efforts that SEFSC personnel are project leads or participants on:

- Ainsworth et al.’s GoM Atlantis Model is an “end-to-end” (i.e. bacteria to apex predators) Atlantis model that includes age structure, larval transport, space limitation, habitat, nutrient and waste cycling, and detailed fisheries accounting. Recently the model has been applied to evaluate the role of diet uncertainty in predicting oil spill impacts, to consider the impacts of the IXTOC and Deepwater Horizon oil spills, and to test harvest control rules in the GoM using the internal MSE routine.

- Sagarese et al.’s northern GoM Ecopath model (“nGoM Ecopath”) was recently rebalanced to 1980 conditions. Skyler Sagarese’s postdoc (Igal Berenshtein) is currently tuning the nGoM model to historic time series data in Ecosim using a hindcast analysis. The hindcast approach fits the Ecosim model to the full time series, then truncates the last 5 years of the data set, reruns the model, and assesses the predictive capability of the model to forecast those truncated 5 years. Preliminary results from this analysis suggest that EwE has a significant predictive capacity when accurate forcing and a bias correction algorithm are used.

- De Mutsert et al.’s wGOM (LA shelf) EwE and Sable et al.’s CASM models have both been used to represent the mid-Barataria Bay marine ecosystem. By comparing model outputs we have increased confidence (and thus acceptance) in model predictions.

Northwest Fisheries Science Center Ecosystem Modeling Efforts

Ecosystem modeling efforts at the Northwest Fisheries Science Center (NWFSC) are making substantial inroads in themes of NEMoW 5: coupling ocean and fisheries models, ecosystem level MSEs, multimodel ensembles, and coupling social-ecological models to biophysical variables.

Coupled social-ecological models

Recent multi-disciplinary work by NWFSC scientists and collaborators (Moore et al. 2019) has applied the framework of Breslow et al. (2016) to operationalize the concept of human wellbeing, so that wellbeing can be coupled to ecological models, economic metrics, and the physical sciences. Breslow et al. define wellbeing in terms of connections, capabilities, conditions, and cross-cutting domains. Moore and colleagues have applied these concepts to analyze impacts of delays and closures to the Dungeness crab (*Metacarcinus magister*) fishery on the U.S. West Coast due to harmful algal blooms. Methods used include surveys of fishermen, economic data collection, and application of community social vulnerability indices (by authors including K. Norman and A. Varney, NWFSC), similar to the community social vulnerability indices developed in other regions by NOAA and collaborators (Jacob et al. 2013; Colburn et al. 2016).

Ocean model/fisheries model coupling

NWFSC has made substantial advances in species distribution modeling and the related influence of ocean conditions, and in understanding and forecasting fish recruitment. Malick et al. (in review) have identified relationships between temperature (hindcast from ROMS) and the spatial distribution of Pacific hake (*Merluccius productus*), an abundant stock that moves northward during the summer, extending into Canada by varying extents each year. Building on this work, Malick et al. (2020) find substantial forecast skill of hake presence/absence based on temperature at depth from the J-SCOPE seasonal ocean forecasts (Siedlecki et al. 2016). Haltuch et al. (2019) and Tolimieri et al. (2018) provide insights into how future ocean conditions may affect sablefish (*Anoplopoma fimbria*) fisheries. Tolimieri et al. (2018) have worked with the Pacific Fishery Management Council to re-evaluate ecosystem drivers of sablefish recruitment, improving the skill of previous statistical predictors of recruitment (Schirripa and Colbert 2006). Ongoing work includes using global climate models to predict future ocean conditions and subsequent changes in recruitment and the effectiveness of management strategies. Nowcasts of recruitment in absence of survey data, and short-term forecast of recruitment ~ 1 year ahead (if oceanographic covariates can be forecasted) may be useful for tactical management.

Ecosystem-level MSEs

In a recent NEFSC publication (Gaichas et al. 2017) and at NEMoW 4, Sarah Gaichas illustrated that ecosystem-based management procedures can be tested in a multispecies modeling framework, and can be evaluated in terms of ecosystem-based performance metrics. NWFSC, IFREMER (France), and IMR (Norway) have now developed machinery to achieve similar goals using the Atlantis EM. Kaplan and coauthors have tested threshold harvest control rules for California Current hake and Nordic/Barents Sea (Norway) mackerel. Additionally, they investigated threshold harvest control rules that either increase or decrease fishing mortality rates when productivity (i.e. the zooplankton prey base) varies. This testing of harvest control rules is not full management strategy evaluation but is a stepping stone toward ecosystem-level MSEs using the Atlantis platform.

Multimodel ensemble case studies

Previous modeling efforts by NWFSC and collaborators included development of a suite of models focused on the food web role of sardine and anchovy in the California Current (Kaplan et al. 2019, Francis et al. 2018). We are collaborating on the development of a similar ensemble of ecosystem and multispecies models for the Salish Sea and Puget Sound (in Washington State and British Columbia). NWFSC's efforts focus on the development of an Atlantis model (Fulton 2011, Audzijonyte et al. 2019) for Puget Sound. CSIRO collaborators are building a comparable Atlantis model with a larger geographic domain but coarser spatial and taxonomic resolution. Fisheries and Oceans Canada is building an OSMOSE model (Fu et al. 2019) for the Strait of Georgia, and the effort will also include a MICE model that represents salmon and predators such as pinnipeds. An Ecopath (Christensen and Walters 2004) model is being developed by Western Washington University, and Ecospace is being developed by University of British Columbia. The model ensemble builds on tools developed as part of the Salish Sea Marine Survival Project, tackling questions related to survival of juvenile salmon (*Oncorhynchus spp.*), effects of contaminants such as PCBs and oil, and the impacts of recent Washington State policies and proposals aimed at recovering endangered southern resident killer whales (*Orcinus orca*).

Additional modeling efforts at NWFSC may not fit cleanly within the core themes of NEMoW 5, but nonetheless these efforts advance ecosystem science and ecosystem-based management. These include application of qualitative modeling approaches to understand early marine survival of Puget Sound salmon (Sobocinski et al. 2018), and risk assessment for California state fisheries (Samhouri et al. 2019), consistent with support for these modeling approaches at previous NEMoWs. In collaboration with academic partners, SWFSC, and AFSC, NWFSC scientists have contributed to distribution modeling of whales and groundfish (Selden et al. 2019, Brodie et al. 2019, Abrahms et al. 2019), including presenting species shifts as part of the 2019 Ecosystem Status Report to the Pacific Fishery Management Council. Species distribution shifts have been identified as a national priority (Karp et al. 2019) and NWFSC scientists are also part of the NOAA DisMAP (distribution mapping) working group. Particularly relevant to climate change research under the National Climate Science Strategy, NWFSC recently published a climate vulnerability assessment for salmon populations (Crozier et al. 2019), building on previous methodology from the Northeast Fisheries Science Center (Hare et al. 2016). This salmon assessment and the parallel effort for non-salmonids help to identify species and regions of focus for future modeling efforts.

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A-3: Summary of Tools Session Presentations

Atlantisom – Presenter: Christine Stawitz

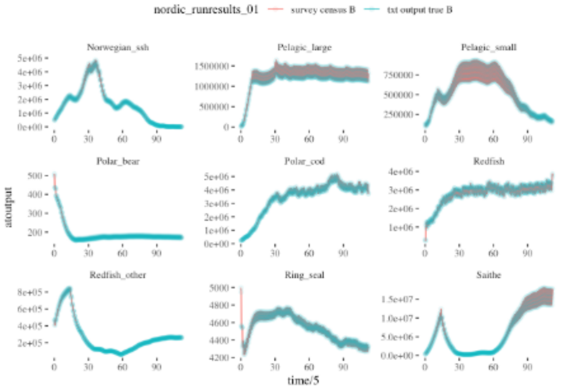
Atlantisom – Atlantis Operating Model – is an R package that uses an Atlantis model to generate data sets from various scenarios run in Atlantis. It uses Atlantis model output to generate time series and composition data for given species in an Atlantis model. This creates the “true” ecosystem. The package also allows users to derive “data” from Atlantis by simulating survey sampling. Survey specifications can come from other information such as the overlap of actual survey stations with Atlantis polygons, experiments evaluating survey selectivity and efficiency, actual sample-based survey coefficient of variation, etc. Atlantis generates age structured biomass and abundance outputs for given species. Atlantisom allows the modification of species composition outputs to align with assessment models’ compositional data needs (survey and fishery catch at age, survey and fishery lengths, survey and fishery weight at age). More information on Atlantisom is at: https://github.com/r4atlantis/atlantisom

Example Atlantisom workflows:

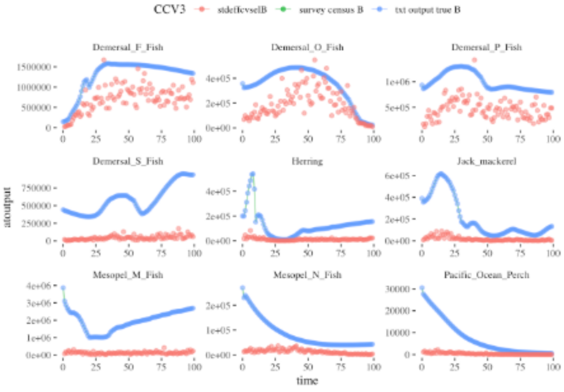
1. Get true biomass, abundance, age composition, length composition, weight at age, fishery catch, fishery catch at age, fishery length composition, and fishery weight age for a "sardine-like species": https://sgaichas.github.io/poseidon-dev/FullSardineTruthEx.html
2. Format these outputs and get other life history parameters for input into a stock assessment model (Stock Synthesis, using r4ss): https://sgaichas.github.io/poseidon-dev/CreateStockSynthesis.html
3. Get true and observed input data, format inputs, and run the assessment model: https://sgaichas.github.io/poseidon-dev/SardinesHakeatlantisom2SStest.html
4. In progress: compare assessment results with truth: https://sgaichas.github.io/poseidon-dev/SkillAssessInit.html

Example Atlantisom output:

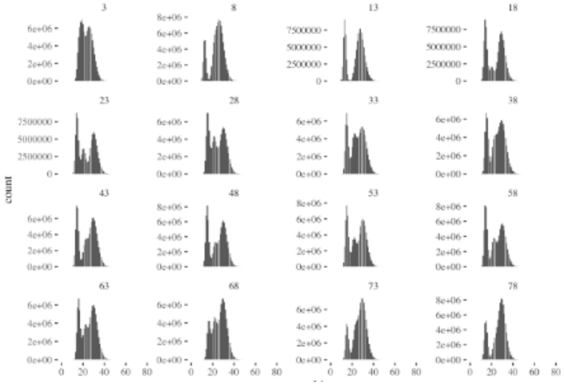
Survey census test NOBA



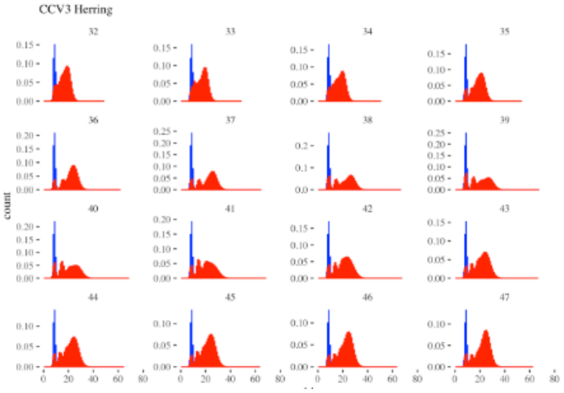
Standard survey test CCA



True length composition NOBA



Survey length composition CCA



Rpath – Sean Lucey

Rpath demo

A common way of analyzing the flow of energy through an ecosystem is to utilize a mass balance model. As the name implies, mass balance ensures that energy inputs and energy outputs are balanced. This approach has been used since at least the early 1940s but was popularized by the Ecopath algorithm designed by Polovina (1984). Since then, Ecopath was extended to incorporate temporal dynamics through the Ecosim module (Walters et al. 1997). The underlying code for Ecopath with Ecosim is open source, meaning that is freely available and that the code can be redistributed or recreated by any interested users (Steenbeck et al. 2015). The code has been ported to several different programming environments including Fortran and Matlab (Akoglu et al. 2015, Kearney nd). Recently, members of the Northeast Fisheries Science Center and the Alaska Fisheries Science Center re-coded the algorithms in C++ and then R (Lucey et al. 2020). Rpath, the R implementation, is coded in a language that is familiar to many marine ecologists. Common practices in R should aid in the reproducibility of conducting analysis using a mass balance model as all of the code is contained within a single script file. Rpath also takes advantage of the built-in statistical and graphical functions of R. This offers great flexibility for practitioners to tailor the model to their needs. The code is available on GitHub at https://github.com/NOAA-EDAB/Rpath. The open source nature of the code and software development platform should aid in continuous community development of this tool.

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Fitting and sensitivity routines in Rpath – Andy Whitehouse

Ecosense - Andy Whitehouse and Kerim Aydin

Ecosense is a tool for generating ensembles of Ecosim models that have been built with the Rpath package (Lucey et al. 2020). Ecosense (Whitehouse and Aydin, 2020) generates multiple versions of the same Rpath model by drawing random sets of model parameters from the described range of uncertainty around parameter estimates. The generated parameter sets are then subjected to a burn-in simulation (user defined, but usually 50 years). Generated ecosystems that “crash” during this burn-in period are discarded and those that survive are retained for further analyses. Ecosystems crash during burn-in primarily because of thermodynamically inconsistent parameter draws. This generally happens when a generated ecosystem has a parameter set that pairs small biomass pools of unproductive prey with large pools of productive predators that have high consumption rates. Such ecosystems tend to crash within the first few years.

Experiments can be conducted with food web models that would be impractical to implement in the real world, such as exploring policy options, future climate scenarios, or other anticipated stressors. Ecosense provides a simulation framework to conduct such experiments with Rpath models while accounting for uncertainty in model parameters, and uncertainty in model results. Including uncertainty in model results helps to communicate the strength of results to stakeholders and decision makers, and helps to avoid a false sense of certainty in model outcomes.

Rpath can be downloaded from the NOAA toolbox at https://github.com/NOAA-EDAB/Rpath. (Ecosense has not been formally incorporated into Rpath yet. We are working through a number of minor refinements that are necessary to formally include Ecosense within the Rpath package.) Ecosense is available from the author: andy.whitehouse@noaa.gov

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WHAM!- Scott Large

The Woods Hole Assessment Model (WHAM)
Brian Stock and Tim Miller
Northeast Fisheries Science Center (NEFSC)
https://github.com/timjmiller/wham

WHAM is a single-species, state-space, age-structured stock assessment model designed to include environmental effects on population processes. The primary factors motivating WHAM development are the state-space formulation and incorporation of environmental covariates on time-varying population processes. Several recent applications to Northwest Atlantic stocks have shown that these models can outperform traditional SCAA models in terms of reduced bias, retrospective pattern, AIC, and uncertainty in reference points (Miller et al. 2016, Miller et al. 2018, Miller and Hyun 2018). In addition, large changes in oceanographic conditions are occurring on the Northeast U.S. shelf, and WHAM has been designed to evaluate how these changes may affect productivity of the commercially important stocks in the region (Hare et al. 2016).

WHAM builds off ASAP (Age-Structured Assessment Program, Legault and Restrepo 1998), the statistical catch-at-age (SCAA) model commonly used at the NEFSC, to facilitate easy 1) replication of ASAP models, and 2) testing of alternative stock-environment models. As such, WHAM has many similarities to ASAP, including the input data file structure, reliance on empirical weight-at-age data (i.e. growth parameters are not estimated), and many of the plotting functions for input data, results, and diagnostics. WHAM is written in R and TMB (Kristensen et al. 2016) and can be configured to estimate a range of assessment models:

- traditional SCAA model, e.g. ASAP, with recruitments as (possibly penalized) fixed effects
- SCAA with recruitment or mortality as random effects or linked to an environmental covariate
- full state-space model with abundance at all ages treated as random effects, e.g. SAM (Nielsen and Berg 2014)

WHAM is an R package on GitHub and will be linked to the NOAA Fisheries Toolbox. R functions allow users to load input data files, specify model options, fit the model in TMB, conduct retrospective and one-step-ahead residual analysis, check convergence, plot diagnostics and results, and compare alternative models. Three vignettes are currently available, describing:

1. Basic use, age-composition model options, SCAA vs. state-space
2. Options for recruitment, environmental covariate process, and how to link recruitment to the environmental covariate
3. Options for fishing mortality/catch and the environmental covariate in projections/forecasts

Installation with vignettes:

```
devtools::install_github("timjmiller/wham", dependencies=TRUE, build_vignettes = TRUE,
build_opts = c("--no-resave-data", "--no-manual"))
```

Installation without vignettes:

```
devtools::install_github("timjmiller/wham", dependencies=TRUE)
```

To view vignettes:

```
library(wham)
browseVignettes("wham")
```

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EcoCast & Dashboard – Stephanie Brodie

Spatial management is a useful strategy to regulate human activities and provide protection for vulnerable species and habitats. Dynamic management – a subset of spatial management in which boundaries are flexible in space and/or time – is gaining traction as one solution for managing features with variable distributions, for example highly migratory species. This tool demonstration introduces three applied dynamic management tools the SWFSC has co-developed: 1) a thermal indicator designed to mitigate loggerhead turtle bycatch (Welch et al. 2019), 2) the fisheries sustainability tool – EcoCast (Hazen et al. 2018), and 3) WhaleWatch, designed to reduce ship strike risk to blue whales (Hazen et al. 2017; Abrahms et al. 2019). These tools allow scales of management to align with scales of environmental variability, animal movement, and human activities. The demonstration explored the process of building, operationalizing, and disseminating the three tools. The three tools are now online, with the loggerhead tool found here https://coastwatch.pfeg.noaa.gov/loggerheads/. The EcoCast nearreal time output can be found here https://coastwatch.pfeg.noaa.gov/ecocast/, and the historical explorer app here http://oceanview.pfeg.noaa.gov/ecocast/explorer.html. The whalewatch tool can be found here https://www.westcoast.fisheries.noaa.gov/whalewatch/, and the recent dynamic blue whale distribution predictions found here https://heatherwelch.shinyapps.io/benioff_app/. Finally, a general approach to operationalizing near real time tools has been developed, with EcoCast presented as an example tool (Welch et al. 2018).

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A-4: Summary of Toolbox Presentations

Fisheries Integrated Toolbox

Fisheries Ecosystem Tools is the ecosystem “drawer” of the FIT. The Fisheries Integrated Toolbox (FIT) was establish as a coordinated, interdisciplinary process to operationalize innovative research and development from NOAA Fisheries scientists and make that work available to a diverse user base via a centralized toolbox. This toolbox uses current staff and ongoing efforts to achieve the objectives described here to create a prioritized suite of operational tools capable of addressing NOAA Fisheries’ diverse mandates and drivers. FIT is an interdisciplinary, web-based repository of operational tools that can be used for a variety of applications, can facilitate ensemble modeling, model coupling, and management strategy evaluation via standardized templates and libraries that are built using modern capabilities and the latest advancements in software programming, statistics, and scientific hypotheses.

The NOAA FIT hosts a variety of operational tools developed by NOAA scientists and programmers, as well as those developed in collaboration with, and exclusively by, external developers. The NOAA FIT is maintained by the National Modeling Team in NOAA Fisheries Office of Science and Technology. The National Modeling Team supports scientists, developers, and users to facilitate accessibility and efficient usage of software and tools. The NOAA FIT also provides resources for developers and users of the tools to ensure best practices and ease of use.

NOAA Fisheries Toolbox (NFT) is becoming a centralized repository of modern, interdisciplinary, integrated tools. By taking an interdisciplinary approach, this national fisheries integrated toolbox not only addresses priority agency actions, but also seeks to improve collaboration across disciplines and regions to provide efficient advancement of the science enterprise.

The FIT is managed by a steering committee that includes representatives across disciplines, science centers, and headquarters programs with a mix of scientific programmers and subject matter experts. To produce a modern, national toolbox, the steering committee works through existing working groups (e.g. Assessment Methods Working Group, NOAA Fisheries Economics Program, Ecosystem Modeling Steering Committee) to facilitate interactions with tool developers in the science centers via the FIT Technical Team. The existing working groups will provide discipline-specific subject matter expertise and suggestions for the interdisciplinary Toolbox Steering Committee to evaluate, prioritize and build into a work plan. The objective of the FIT steering committee will be to establish a process for tool development, hosting, and prioritization of tasks to facilitate research-to-operational tool development at the enterprise level. FIT tool development will primarily rely on NOAA’s Virtual Lab (VLAB) and GitHub functionality to facilitate community development, testing, review and documentation. This approach will provide verified and validated tools that start at a research level (developed within a small group) and move to an operational level where multiple analysts can access and use the tools for a variety of purposes, as well as foster ongoing development through the contribution of new modules.

The national protocol will follow accepted approaches to validation, verification, and documentation of tools. This professional approach will facilitate trust that the tools perform as they are intended. Additionally, a well-designed and understood process will enhance developmental collaboration, thereby capitalizing on the diverse expertise within the NOAA Fisheries science enterprise. A key objective of this project is to enhance innovation by regional scientists. This project emphasizes a national team of developers that will be available to help regional scientists follow a professional and efficient approach to operationalizing their innovative ideas and making them available to other FSCs and to users around the world. Thus, tool development will be prioritized to provide the maximum benefits to the most possible FSCs and will seek to balance tool advancement with the need to deliver a high quantity of operational tools being used in current applications.

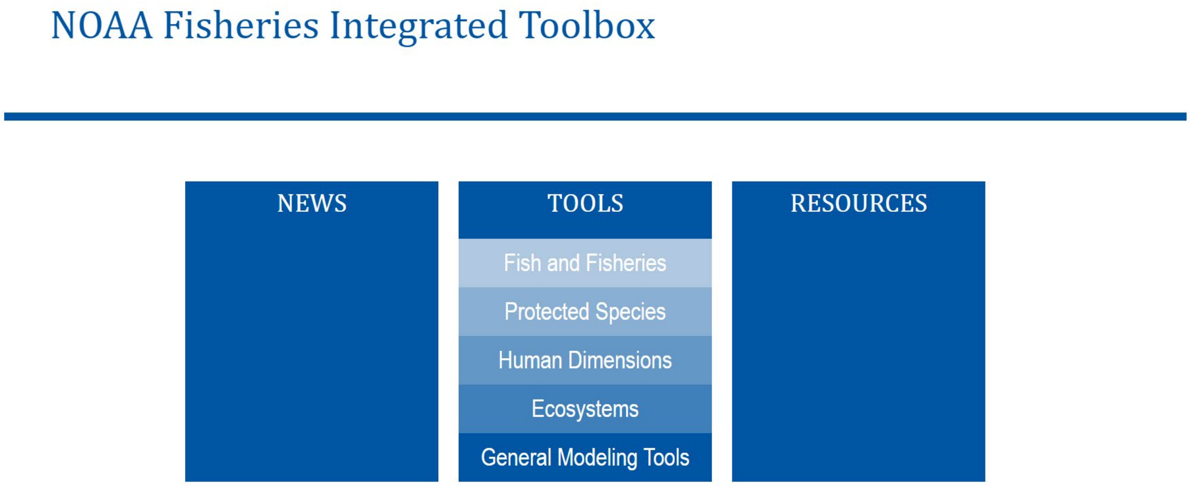

Figure A-4-1. FIT landing page – https://noaa-fisheries-integrated-toolbox.github.io/

Fisheries Ecosystem Tools

NOAA Fisheries is using sophisticated ecosystem modeling tools, coupled with input from stakeholders, to explore the tradeoffs inherent in natural resource management decisions. The models incorporate classic population biology and a range of climate, environmental, ecological, and human impacts to the ocean. These models, which are relied on by our scientists and managers, provide essential data for making well-informed decisions.

NMFS has primarily worked to improve the development and applications of ecosystem models and coordinate efforts among FSCs via NEMoWs. The next steps in improving NMFS ecosystem modeling efforts is outlined in the NMFS EBFM Road Map. A major step outlined in the Road Map is the "Development of an EBFM analytical toolbox that includes ecosystem modeling tools and best practices; data-poor qualitative and semi-quantitative tools; and related decision support tools." The objective of the Toolbox is to support national-scale technical activities important to maintaining & improving the EBFM analytical enterprise through development, maintenance, availability, standardization, testing, and user support for EBFM analytical tools. In short, the Toolbox should enable modelers to spend more time operating and applying models by reducing time spent on development and maintenance.

Implementation of the Toolbox has begun (website: https://nmfs-ecosystem-tools.github.io/, repository: https://github.com/NMFS-ecosystem-tools). Initially this was done by updating older tools and creating graphical user interfaces (GUIs) for existing tools – Multispecies Surplus Production Modes (MSSPM – originally developed as Kraken by Robert Gamble, NEFSC), Multispecies Virtual Population Analysis (MSVPA – originally developed by Lance Garrison and Jason Link, SEFSC and NEFSC), and Multispecies Statistical Catch-At-Age Model (MSCAA – originally developed by Kiersten Curti, NEFSC).

This presentation was part demo and part discussion. Ron Klasky (S&T) demonstrated the GUI for MSSPM. The software provides a flexible framework to allow users to build, fit, and evaluate multi-species surplus production models. Users can build models selecting from a variety of population growth forms, species interactions/functional response curves, and harvesting strategies. These models can then be fit to data by optimizing from a range of objective functions and optimization algorithms. Diagnostic tools are then available to evaluate the model fit and model robustness.

Discussion focused on the onboarding process for bringing new tools into the toolbox. Participants discussed the badging system (for indicating levels of operational readiness), coding best practices, and reviewing standards. This discussion is now ongoing in the FIT Technical Team meeting and plans for onboarding new tools are being discussed.

A-5: Summaries of Topic Reviews

Multimodel Ensembles

Over the last 20 years (e.g. since The Ecosystem Principles Advisory Panel Report) a range of multispecies and EMs focused on EBFM (and in particular, on interacting fish/fisheries) have been developed and increased in technical sophistication. A number of reviews of the relative strengths and weaknesses of each type of model have been published describing use-cases for each type of model (e.g. Plaganyi 2008). In addition to peer-review, many of these individual models have been reviewed for various uses in fisheries management settings (e.g. CIE reviews – list examples by region, such as CEATTLE and Ecosim for Alaska). They have also been incorporated into management documents (e.g. in Alaska, Bering Pollock Assessment and ESR). However, there has been limited experience in using these models in combination on a single issue, as an "ensemble". Ensembles can be formal (averaging/combining quantities quantitatively) or qualitative (using insights from each model in a combined synthesis). (Note: ensembles are multiple models covering the "same" species groups, not hierarchical linked models such as NPZ -> fish).

There are recent applications of model ensembles in the U.S. that are noteworthy but have not directly influenced management, even if they have been presented in the management context. One example is the Ocean Modeling Forum California Current sardine case study (Kaplan et al. 2019; Francis et al. 2018). This effort applied an ensemble of trophic modeling approaches (Atlantis, Ecopath, MICE), and statistical relationships (PREP relationship of Pikitch et al. 2012) to understand the food web effects of concurrent declines in sardine and anchovy, and to test an existing harvest control rule. The case study benefited from Ecopath and Atlantis models 'on the shelf' that could be refined and applied, and also included creation of a new MICE model (Punt et al. 2016). The ensemble results were presented to subgroups within the Pacific Fishery Management Council, but as the fishery is closed due to low stock abundance, the suite of models has not directly influenced policy.

However, the Atlantic States Marine Fisheries Commission Ecological Reference Point Workgroup has recently applied multiple models for ecological management objectives of the Atlantic Menhaden fishery. Ultimately a single model was used as the lead model for key runs. The ensemble was used to demonstrate that the lead model was adequately dealing with uncertainty.

While the use of multiple models for EBFM is considered a best practice, they are not commonly used. Further exploration to understand the challenges to using ensembles for EBFM is needed.

Future areas to explore for EM ensembles include:

- Discussions of quantitative averaging of fisheries-relevant reference points as well as qualitative examination of multiple hypotheses using.
- Regional case studies to answer questions such as:

- What is gained by using an ensemble of models within a management context?
- Is the benefit adequate considering the additional work needed to produce an ensemble?
- For a given region, are there ways to reduce the cost of building ensembles? What models are low hanging fruits/simple to parameterize and construct that could be promulgated to other regions?
    - e.g. various MICE models - MIZER, QNMs, FCMs, BBNs, CEATTLE, ….
    - The Fisheries Ecosystem Tools section of the Fisheries Integrated Toolbox can help lower the build time of models and reduce costs associated with ensembles.

Ocean Model/Fisheries Model Coupling

Over the last decade or so, the use of IPCC-class climate models in the context of fisheries science has greatly increased. During the CMIP5 project, a number of papers (e.g. Stock et al. 2011) suggested guidelines for making use of these (and similar global-scale models) for living marine resource studies. In the intervening years, many FSCs have begun using global-scale climate models in a fisheries management support context. In this paper, we will review a variety of climate-to-fish coupling projects across FSCs, and highlight best practices, lessons learned, and unanticipated challenges (and potential solutions) encountered across all of these studies. The U.S.-centric case studies allow us to limit the scope of this paper while still incorporating a wide variety of ecosystem types, spanning open ocean to coastal, subtropical to subarctic, etc.; we believe the overall conclusions can be applicable globally.

One of the first common themes that arose from our brainstorming is that it is a challenge for scientists outside of the major climate model labs to access and understand the choice of models available from each major modeling experiment (e.g. CMIP5, CMIP6, MARine Ecosystem Model IntercomparisonProject(MAREMIP), North American Multimodel Ensemble (NMME)) and where they are documented in the primary literature. This is particularly true of the biogeochemical models attached to each earth system model (ESM), which vary from very simple carbon closures to Nutrients-Phytoplankon-Zooplanktion-Detritus (NPZD) to full plankton functional type models. This section will address issues of figuring out which models exist, what they do differently, and how one can and/or should choose between them. An initial listing of these models is given in the table below.

Table A-5-1. List of models.

Center	Coupled Model		Dataset	Ecosystem/Biogeochemical Model	
	Abbreviation	**Full**		**Abbreviation**	**Full**
Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia	ACCESS-ESM1-5	Australian Community Climate and Earth System Simulator	CMIP6	WOMBAT	Whole Ocean Model with Biogeochemistry and Trophic-dynamics
Canadian Centre for Climate Modelling and Analysis (CCCMA)	CanESM2	Canadian Earth system model	CMIP5	CMOC	Canadian Model of Ocean Carbon
Canadian Centre for Climate Modelling and Analysis (CCCMA)	CanESM5	Canadian Earth system model	CMIP6	CMOC	Canadian Model of Ocean Carbon
Canadian Centre for Climate Modelling and Analysis (CCCMA)	CanESM5-CanOE	Canadian Earth system model with CanOE	CMIP6	CanOE	Canadian Ocean Ecosystem
Centro Euro-Mediterraneo sui Cambiamenti Climatic (CMCC), Italy	CMCC-CESM	Centro Euro-Mediterraneo sui Cambiamenti Climatici Carbon Earth System Model	CMIP5	PELAGOS	PELAgic biogeochemistry for Global Ocean Simulations)
National Meteorological Research Centre (CNRM), France	CNRM-CM5	National Meteorological Research Centre earth system model	CMIP5	PISCES	Pelagic Interactions Scheme for Carbon and Ecosystem Studies
National Meteorological Research Centre (CNRM), France	CNRM-CM5-2		CMIP5	PISCES? (Assuming based on CNRM-CM5)	Pelagic Interactions Scheme for Carbon and Ecosystem Studies
National Meteorological Research Centre (CNRM), France	CNRM-ESM2-1	National Meteorological Research Centre earth system model	CMIP6	PISCES 2.s	Pelagic Interactions Scheme for Carbon and Ecosystem Studies volume 2
NOAA Geophysical Fluid Dynamics Laboratory (GFDL), USA	GFDL-ESM2G	NOAA Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized ocean layer dynamics	CMIP5	TOPAZ	Tracers of Ocean Phytoplankton with Allometric Zooplankton

NOAA Geophysical Fluid Dynamics Laboratory (GFDL), USA	GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory Earth System Model with Modular Ocean Model	CMIP5	TOPAZ	Tracers of Ocean Phytoplankton with Allometric Zooplankton
NOAA Geophysical Fluid Dynamics Laboratory (GFDL), USA	GFDL-CM4	NOAA Geophysical Fluid Dynamics Laboratory Coupled Physical Model	CMIP6	GFDL-BLINGv2	Biogeochemistry-with-Light-Iron-Nutrients-Gas
NOAA Geophysical Fluid Dynamics Laboratory (GFDL), USA	GFDL-ESM4	NOAA Geophysical Fluid Dynamics Laboratory Earth System Model	CMIP6	GFDL-COBALTv2	Carbon, Ocean Biogeochemistry and Lower Trophics
NOAA Geophysical Fluid Dynamics Laboratory (GFDL), USA	GFDL-OM4p5B	NOAA Geophysical Fluid Dynamics Laboratory ocean-only with flux-anomaly-forcing	CMIP6	GFDL-BLINGv2	Biogeochemistry-with-Light-Iron-Nutrients-Gas
NASA Goddard Institute for Space Studies (GISS), USA	GISS-E2-H-CC	NASA Goddard Institute for Space Studies ModelE2 Earth System Model with carbon cycle coupled to the HYCOM ocean model	CMIP5	NOBM? (Assume based on GISS-E2-1-G-CC)	NASA Ocean Biogeochemistry Model
NASA Goddard Institute for Space Studies (GISS), USA	GISS-E2-R-CC	NASA Goddard Institute for Space Studies ModelE2 Earth System Model with carbon cycle coupled to the Russell ocean model	CMIP5	NOBM	NASA Ocean Biogeochemistry Model
NASA Goddard Institute for Space Studies (GISS), USA	GISS-E2-1-G-CC	NASA Goddard Institute for Space Studies ModelE2.1 Earth System Model with carbon cycle coupled to the Russell ocean model	CMIP6	NOBM	NASA Ocean Biogeochemistry Model
Met Office, UK	HadGEM2-CC	Hadley Global Environment Model 2 - Carbon Cycle	CMIP5	diat-HadOCC	diat?-Hadley Centre Ocean Carbon Cycle
Met Office, UK	HadGEM2-ES	Hadley Global Environment Model 2 - Earth System	CMIP5	diat-HadOCC	diat?-Hadley Centre Ocean Carbon Cycle

Met Office and National Environment Research Council (NERC), UK	UKESM1-0-LL	UK Earth System Model	CMIP6	MEDUSA2	Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification, ver. 2
Institute of Numerical Mathematics, Russian Academy of Sciences	INM-CM4	Institute of Numerical Mathematics Climate Model	CMIP5		
Institut Pierre-Simon Laplace (IPSL), France	IPSL-CM5A-LR	Institut Pierre-Simon Laplace Low Resolution CM5A	CMIP5	PISCES	Pelagic Interactions Scheme for Carbon and Ecosystem Studies
Institut Pierre-Simon Laplace (IPSL), France	IPSL-CM5A-MR	Institut Pierre-Simon Laplace Medium resolution CM5A	CMIP5	PISCES	Pelagic Interactions Scheme for Carbon and Ecosystem Studies
Institut Pierre-Simon Laplace (IPSL), France	IPSL-CM5B-LR	Institut Pierre-Simon Laplace Low resolution CM5B	CMIP5	PISCES	Pelagic Interactions Scheme for Carbon and Ecosystem Studies
Institut Pierre-Simon Laplace (IPSL), France	IPSL-CM6A-LR	Institut Pierre-Simon Laplace Low resolution CM6A	CMIP6	PISCES	Pelagic Interactions Scheme for Carbon and Ecosystem Studies
Institut Pierre-Simon Laplace (IPSL), France	IPSL-CM5A-LR	Institut Pierre-Simon Laplace Low Resolution CM5A	MAREMIP	PlankTOM5.3	
University of Tokyo, National Institute of Environmental Studies (NIES), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	MIROC-ESM	Model for Interdisciplinary Research on Climate	CMIP5	NPZD	Oschlies et al, 2001 NPZD model
University of Tokyo, National Institute of Environmental Studies (NIES), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	MIROC-ESM-CHEM	Model for Interdisciplinary Research on Climate	CMIP5	NPZD	Oschlies et al, 2001 NPZD model

University of Tokyo, National Institute of Environmental Studies (NIES), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	MIROC-ES2L	Model for Interdisciplinary Research on Climate, Earth System version 2	CMIP6	OECO ver.2.0	Ocean Ecosystem Component
University of Tokyo, National Institute of Environmental Studies (NIES), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	MIROC5	Model for Interdisciplinary Research on Climate	MAREMIP	NSI-MEM	Nitrogen Silica Iron Marine Ecosystem Model
University of Tokyo, National Institute of Environmental Studies (NIES), and Japan Agency for Marine-Earth Science and Technology (JAMSTEC)	MIROC5	Model for Interdisciplinary Research on Climate	MAREMIP	REcoM2	Regulated Ecosystem Model, version 2
Max-Planck-Institute fur Meteorologie (MPI), Germany	MPI-ESM-LR	Max-Planck-Institute fur Meteorologie Earth System Model low resolution	CMIP5	HAMMOC5.2	Hamburg ocean carbon cycle model, v5.2
Max-Planck-Institute fur Meteorologie (MPI), Germany	MPI-ESM-MR	Max-Planck-Institute fur Meteorologie Earth System Model medium resolution	CMIP5	HAMMOC5.2	Hamburg ocean carbon cycle model, v5.2
Max-Planck-Institute fur Meteorologie (MPI), Germany	MPI-ESM-1-2-HAM		CMIP6	HAMOCC6	Hamburg ocean carbon cycle model, v6
Max-Planck-Institute fur Meteorologie (MPI), Germany	MPI-ESM1-2-HR	Max-Planck-Institute fur Meteorologie Earth System Model high resolution, version 1.2	CMIP6	HAMOCC6	Hamburg ocean carbon cycle model, v6

Max-Planck-Institute fur Meteorologie (MPI), Germany	MPI-ESM1-2-LR	Max-Planck-Institute fur Meteorologie Earth System Model low resolution, version 1.2	CMIP6	HAMOCC6	Hamburg ocean carbon cycle model, v6
Max-Planck-Institute fur Meteorologie (MPI), Germany	MRI-ESM1	Meteorological Research Institute Earth System Model Version 1	CMIP5	NPZD	Oschlies et al, 2001 NPZD model
Meteorological Research Institute (MRI), Japan	MRI-ESM2-0	The Meteorological Research Institute Earth System Model Version 2.0	CMIP6	MRI.COM4.4	Meteorological Research Institute Community Ocean Model
NOAA National Center for Atmospheric Research (NCAR), USA	CESM1-1-CAM5-CMIP5	Community Earth Systems Model, version 1.1	CMIP5?	BEC	Biogeochemical Elemental Cycling Model
NOAA National Center for Atmospheric Research (NCAR), USA	CESM2	Community Earth Systems Model, version 2	CMIP6	MARBL	Marine Biogeochemistry Library
NOAA National Center for Atmospheric Research (NCAR), USA	CESM2-FV2		CMIP6	MARBL	Marine Biogeochemistry Library
NOAA National Center for Atmospheric Research (NCAR), USA	CESM2-WACCM	Community Earth Systems Model, version 2 with high-top atmosphere	CMIP6	MARBL	Marine Biogeochemistry Library
NOAA National Center for Atmospheric Research (NCAR), USA	CESM2-WACCM-FV2		CMIP6	MARBL	Marine Biogeochemistry Library
NOAA National Center for Atmospheric Research (NCAR), USA	CESM1-BGC	Community Earth Systems Model	MAREMIP	BEC	Biogeochemical Elemental Cycling Model
Norwegian Climate Center (NCC)	NorESM1-ME	Norwegian Earth System Model	CMIP5	HAMOCC5.1	Hamburg ocean carbon cycle model, v5.1

Norwegian Climate Center (NCC)	NorCPM1	The Norwegian Climate Prediction Model (with data assimilation)	CMIP6	HAMOCC5.1	Hamburg ocean carbon cycle model, v5.1
Norwegian Climate Center (NCC)	NorESM1-F	Norwegian Earth System Model, fast version	CMIP6	HAMOCC5.1	Hamburg ocean carbon cycle model, v5.1
Norwegian Climate Center (NCC)	NorESM2-LM	Norwegian Earth System Model, version 2, low resolution atmos land	CMIP6	HAMOCC	Hamburg ocean carbon cycle model
Norwegian Climate Center (NCC)	NorESM2-MM	Norwegian Earth System Model, version 2, medium resolution atmos land	CMIP6	HAMOCC	Hamburg ocean carbon cycle model

Future work on this topic should include:

a. Expanding the table of models to include: number of functional groups (especially P and Z), nutrients tracked, resolution, and extant applications for LMR management.
b. Delineating criteria for choosing model. How have models been chosen in the past? Balance of “best practices” with “practical practices”.
    i. Example: selecting all models that include zooplankton, but removing models with unrealistic output (e.g. negative biomass densities)
    ii. Example: selecting only models that include sea ice
    iii. Example: Select models to capture the range of potential futures (i.e. spanning the CMIP5 ensemble spread)
    iv. Selecting models that include biogeochemical variables of interest
c. Describing Challenges in access
    i. The potential role of tools like pangeo; Google’s new tools, etc.
    ii. Challenges in storing the data and sharing the data (connected to the one above)

Other future work will cover additional information on biogeochemical (BGC) models. For some LMR applications, climate models can be used directly, and/or statistical downscaling is used. However, in many cases, dynamical downscaling is favored. When this option is used, one typically “overwrites” the biogeochemistry of the parent climate model with a single BGC model in the regional model. The uncertainty associated with this model choice is rarely quantified. In the absence of a detailed uncertainty analysis, we would at least like to be transparent about why a particular model was chosen and how well it performs in the region of interest. In regions where dynamical downscaling is used, what model is used and why (both scientific and practical considerations)? What level of validation was used? Are there specific validation criteria for LMR purposes, or more generic validation?

In addition, future work will cover common issues/challenges encountered in model coupling, such issues include geographic boundaries; nearshore processes (i.e. rivers and estuaries); sediment and bottom processes; and mesozooplankton and higher trophic levels. Other practical challenges will be considered as well. A summary list of some of these challenges and approaches for dealing with them is given below.

Geographic boundaries: Management polygons are often used in analyzing output, but exact boundaries of these polygons may be determined by features that are not perfectly matched up in the models. For example, bathymetric smoothing may move the shelf break a bit. Features like currents and gyre boundaries may be present but offset from their real locations in the model. Be aware of where these mismatches occur prior to conducting any analysis of model output. When possible, match across features (e.g. current, gyre boundaries) rather than geographic boundaries.

Nearshore processes: Gridded river datasets are rare; those that exist typically target global scale applications. Lots of variation in how rivers are modeled exists. This can be important to resolve for biology for many reasons (source of hydrodynamics, nutrients/low O_2, high alkalinity, etc.).

Sediment/bottom processes: Sediments and benthos play a role in controlling pelagic nutrient concentrations, which has implications for primary and secondary production. A strong effect on nutrient cycling may occur in shallow regions. Often the role of benthic organisms (plant and animal) is poorly constrained.

Mesozooplankton and higher trophic levels: how do underlying processes translate to certainty in higher trophics? Structural mismatch may be an issue for LMR applications often interested in higher resolution (small vs. large, copepod vs. euphausiid, individual species) that BGC models cannot skillfully distinguish between.

Resolving these challenges has important implications for understanding climate impacts on LMRs as well as short-term forecasts.

Engaging Managers in Model Use and Development

Scientists in the United States have been exploring and coordinating the use of EMs to address ocean ecosystem science and management questions for over a decade (Townsend et al. 2008, 2010, Townsend et al 2014). The National Oceanic and Atmospheric Administration (NOAA), the U.S. federal agency responsible for marine ecosystem science and ecosystem-based fisheries management, has prioritized ecosystem modeling as necessary to better assess the trade-offs we make to maintain resilient and productive ecosystems, and to respond to climate, habitat, and ecological change (NMFS 2016a, NMFS 2016b).

One of the significant challenges to using information and ideas generated through ecosystem modeling can be a lack of connection between modeling and management priorities (Link et al. 2012). Ecosystem modelers are not necessarily asking the same questions of their models as the ecosystem questions asked by legal mandates or by managers implementing those mandates. This disconnect between scientific interest and management needs may contribute to the perceived slow pace in the uptake and implementation of ecosystem-based management (Marshall et al. 2018, Cowan et al. 2012, Hilborn 2011). Townsend et al. (2019) suggest that scientists can better understand and tune models to analyze management priorities by working more closely with managers, within existing processes to implement legal mandates.

U.S. marine fisheries are managed under the Magnuson-Stevens Fishery Conservation and Management Act (MSA) [16 U.S.C. §1801, *et seq.*] first adopted in 1976 (Pub. L. 94-265). The MSA established eight Regional Fishery Management Councils, each of which is responsible for advising the federal government on managing fisheries within the U.S. exclusive economic zone (EEZ) of one or more large marine ecosystems. Councils support the federal government by developing fishery management plans (FMPs) and by developing fishery regulations to implement the FMPs. Councils coordinate fishery management ideas and planning for major marine regions across a range of federal, state, and tribal jurisdictions [16 U.S.C. §1852(a)]. The MSA sets broad U.S. fisheries management priorities, which are interpreted and refined by the councils to develop regional management goals and fisheries regulations. Council meetings are also required to be open to the public, which encourages stakeholder input on Council deliberations and decisions [16 U.S.C. §1852(h)]. In addition to providing science support for the councils, NOAA implements and enforces the fisheries regulations developed by the councils.

Fisheries in the EEZ off the U.S. West Coast are managed under the advice of the Pacific Fishery Management Council (PFMC). The PFMC has long depended on ecosystem information and model results to inform management measures and harvest policies, while primarily constraining short term tactical management (such as the setting of harvest limits) to single species stock assessment results. In 2013, the PFMC formally assessed and acknowledged its ecosystem-based management (EBM) principles with the adoption of its Fishery Ecosystem Plan (FEP, PFMC 2013). The Pacific Coast FEP established a regular process through which the PFMC takes up new ecosystem initiatives to address ideas and issues that affect multiple species and fisheries (PFMC 2013). In doing so, it provided an avenue for managers, stakeholders, and scientists to work together to find solutions to policy issues, the type of forum identified as necessary by Townsend et al. (2019). The PFMC's first ecosystem initiative reviewed and restricted the fishing gears allowed for use off the U.S. West Coast (50 CFR §600.725,) and placed a precautionary ban on the development of new fisheries for a suite of previously unexploited lower trophic level (forage) species (50 CFR §660.6). Gear restrictions give the PFMC more control over any new gear or fishery introductions to West Coast waters, with particular restrictions for the small mesh net gears that are used to target forage species elsewhere in the world. Limiting the future development of fisheries for currently unfished lower trophic level species helps to preserve the forage base within the West Coast EEZ, based on comparable logic used in previous management actions to limit the development of new fisheries for krill (family Euphausiidae) and shortbelly rockfish (*Sebastes jordani*), as well as the earliest effort from the northern anchovy (*Engraulis mordax*) management plan that "benefit to the nation occurs by leaving fish in the ocean (PFMC 1983)."

For its second ecosystem initiative, the PFMC coordinated a stakeholder review of NOAA's annual ecosystem status report (ESR) for the California Current Ecosystem (CCE). NOAA has been producing a variety of reports on the states of different marine ecosystems for decades (e.g. CalCOFI, NPFMC Ecosystem Considerations). However, those efforts have only become more nationally organized in recent years (NOAA 2016b, Slater et al. 2017). ESRs provide managers and stakeholders with a big picture ecosystem overview outside of focal resource stocks and populations, helping the PFMC consider how outside factors influence focal resources and what the linkages between different ecosystem components, including managed species, are. NOAA's EBFM Roadmap recognizes ESRs as a required element of EBFM, necessary to building more broad public understanding of our marine ecosystems' health, status, and functions (NOAA 2016b).

The NOAA California Current Integrated Ecosystem Assessment (CCIEA) team produced the first ESR for the PFMC in 2012, and has provided ESRs annually since 2014. The annual reporting process was outlined in the FEP (PFMC 2013): the PFMC requested a report in March of each year, roughly 20 pages in length and "tailored to providing information on indicators directly relevant to Council decision-making." The suite of indicators included in these reports have been almost entirely empirically derived (e.g. Harvey et al. 2020), partly reflecting the wealth of annual survey data on physical and ecological dynamics and human activities in the CCE. The emphasis on empirically derived time series also reflects the CCIEA team's underlying indicator selection framework, in which nearly half of the criteria are related to empirical data collection and analysis (Kershner et al. 2011). Few of the indicators or analyses included in California Current ESRs have been derived from models of ecosystem dynamics, despite the great potential for models to synthesize and integrate information across ecosystem components, to provide insight about ecosystem components and processes that are difficult to measure directly, and to provide forecasts and projections across a range of spatiotemporal scales, all of which can serve PFMC needs identified in the FEP (PFMC 2013) and elsewhere.

In this paper, we discuss using the PFMC's second ecosystem initiative process to review and revise indicators of ecosystem status for the CCE. We first demonstrate how this structured approach enabled identification of policy issues that require ecosystem information. We then connect the management questions to existing models or assess the need to develop models that could answer some of the concerns raised by stakeholders and decision-makers about future trade-offs expected for living marine resource management in the CCE.

Ecosystem level MSEs

Management strategy evaluation (MSE) is a simulation approach that serves as a "light on the hill" (Smith 1994) to test options for marine management and assessment against simulated ecosystem and fishery dynamics, including uncertainty in both processes and observations. MSE has become a key way to evaluate trade-offs between management objectives, and to communicate with decision makers. Here we describe how and why MSE is continuing to grow from a single species approach to one relevant to multi-species and ecosystem-based management. In particular, different ecosystem modeling approaches can fit within the MSE process to meet particular natural resource management needs. We present five case studies that illustrate how MSE is being increasingly expanded to include ecosystem considerations and EMs, as 'operating models' (i.e. virtual test worlds), and to simulate monitoring, assessment, harvest control rules, and performance metrics. We highlight five US case studies related to fisheries regulations and climate, which support NOAA's policy goals related to the Ecosystem Based Fishery Roadmap, but vary in the complexity of population, ecosystem, and assessment representation. We emphasize methods, tool development, and lessons learned that are relevant beyond the US, and the benefits relative to single-species MSE approaches.

Coupled social-ecological models

NOAA's EBFM roadmap, published in 2016, states "NOAA Fisheries needs to bolster its ecosystem modeling capacity and harmonizes its ecosystem modeling efforts with its fish assessment and protected species modeling efforts." The roadmap makes clear that modeling efforts should be coupled social-ecological endeavors to allow for effective trade-off analysis, and that they should run the gamut from qualitative conceptual models through end-to-end quantitative system models. Three years later, where does NOAA stand on social-ecological modeling capacity? This manuscript assesses the state of the science within NOAA Fisheries, as situated in the broader international context. Specifically, where does NOAA lead the international community in the advancement and operationalization of these models, and where is additional work needed to achieve parity? Of particular interest is the use of these coupled models in support of management decision-making.

Future work will discuss not only approaches employed, but reasons why certain approaches have lost momentum (e.g. fuzzy cognitive mapping, Bayesian Belief Network models, etc.). This might be most easily done in a table identifying the approach, examples of the approach's implementation, and limitations, caveats, and drawbacks encountered or identified.

End-to-end Modeling for Structuring Ecosystem Based Fisheries Management Programs

End-to-end modeling of Large Marine Ecosystems allows a field-to-policy approach that enables the evaluation of gaps and information flow, all the way from collecting data/observations to the design or evaluation of policies and strategies to address specific management questions. Applying ecosystem thinking to field operations and survey design as well as policy is an important part of EBFM. This end-to-end application of ecosystem thinking for EBFM often requires establishing a network of contributors, from database managers and field researchers who design and conduct surveys and provide the data and advice to build the models, to fisheries managers, policymakers, and other stakeholders who provide scenarios or issues of concern. Using end-to-end models as a tool to isolate specific data needs and detailed policy questions/scenarios helps focus and prioritize programmatic or institutional resources, to both advance and strengthen ecosystem-based fisheries management. In this paper we provide examples of building and applying end-to-end models that have shaped data collection and research, and informed management strategy evaluations, long-term and tactical management, Ecosystem Status Reports, and Fisheries Ecosystem Plans. While end-to-end models are particularly useful to identify data gaps, they are also a test of the internal and cross-institutional communication network. The process of translating data and management questions into mechanistic processes often exposes communication bottlenecks due to slow response times, lack or unawareness of appropriate channels, as well as lack of clarity on what is needed or what the ultimate objectives are. Future work will include some recommendations on how to approach these communication bottlenecks to further strengthen ecosystem-based fisheries management from program to institutional level.

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Appendix B – Agenda

Day 1- December 9, 2019

8:30-9 - Welcome, Introduction, Layout plans and logistics for NEMoW 5. Overview and Welcome (**Jason Link, Peg Brady, Howard Townsend**)

9-10:30 - Center presentations (ToR 1) - (**Moderator: Howard Townsend, A/V guru: Ronald Klasky**)

- PIFSC - Presenter: **Phoebe Woodworth-Jefcoats**
- SWFSC - Presenter: **Stephanie Brodie**
- NWFSC - Presenter: **Isaac Kaplan**
- AFSC - Presenter: **Kerim Aydin**
- SEFSC - Presenter: **Michelle Masi**
- NEFSC - Presenter: **Scott Large**

10:30-11:00 - Break

11:00-12:00 - Plenary discussion on Center programs and modeling efforts (**Moderator: Mariska Weijerman, Rapporteur: Isaac Kaplan**)

12:00-1:00 - Lunch

1:00-3:00 - Center tools demonstrations (**Moderator: Patrick Lynch, A/V guru: Matthew Campbell**)

- Atlantisom - demo - Presenter: **Christine Stawitz**
- MSE capabilities in Rpath - Presenter: **Sean Lucey**
- Rshiny general (with Rpath specifics?) - Presenter: **Sean Lucey**
- Fitting and sensitivity routines in Rpath - Presenter: **Andy Whitehouse**
- EcoCast & dashboard in development - Presenter: **Stephanie Brodie**
- WHAM! - Presenter: **Scott Large**

3:00-3:30 - Break

3:30-5:30 - Center tools training sessions (2-rounds, 1-hr each)

5:30 - Adjourn for the day

6:30ish - Bonus Round: For those interested, we will explore options for replicating/expanding on paper by Fulton et al Ecosystems say good management pays off

Day 2- December 10, 2019

8:30-9 - Recap Day 1,
Layout plans for Day 2

9-10:30 - Fisheries Integrated Toolbox (FIT)

- Presentation on FIT – Christine Stawitz
- Presentation on Ecosystem Modeling Tools in the FIT – Ronald Klasky
- Discussion on linking regional tool development into the FIT

10:30-11:00 - Break

11:00-12:30 - Presentations on Progress Topic areas (**Moderator: Phoebe Woodworth-Jefcoats, Rapporteur: Stephen Kasperski, A/V guru: Ian Zink**)

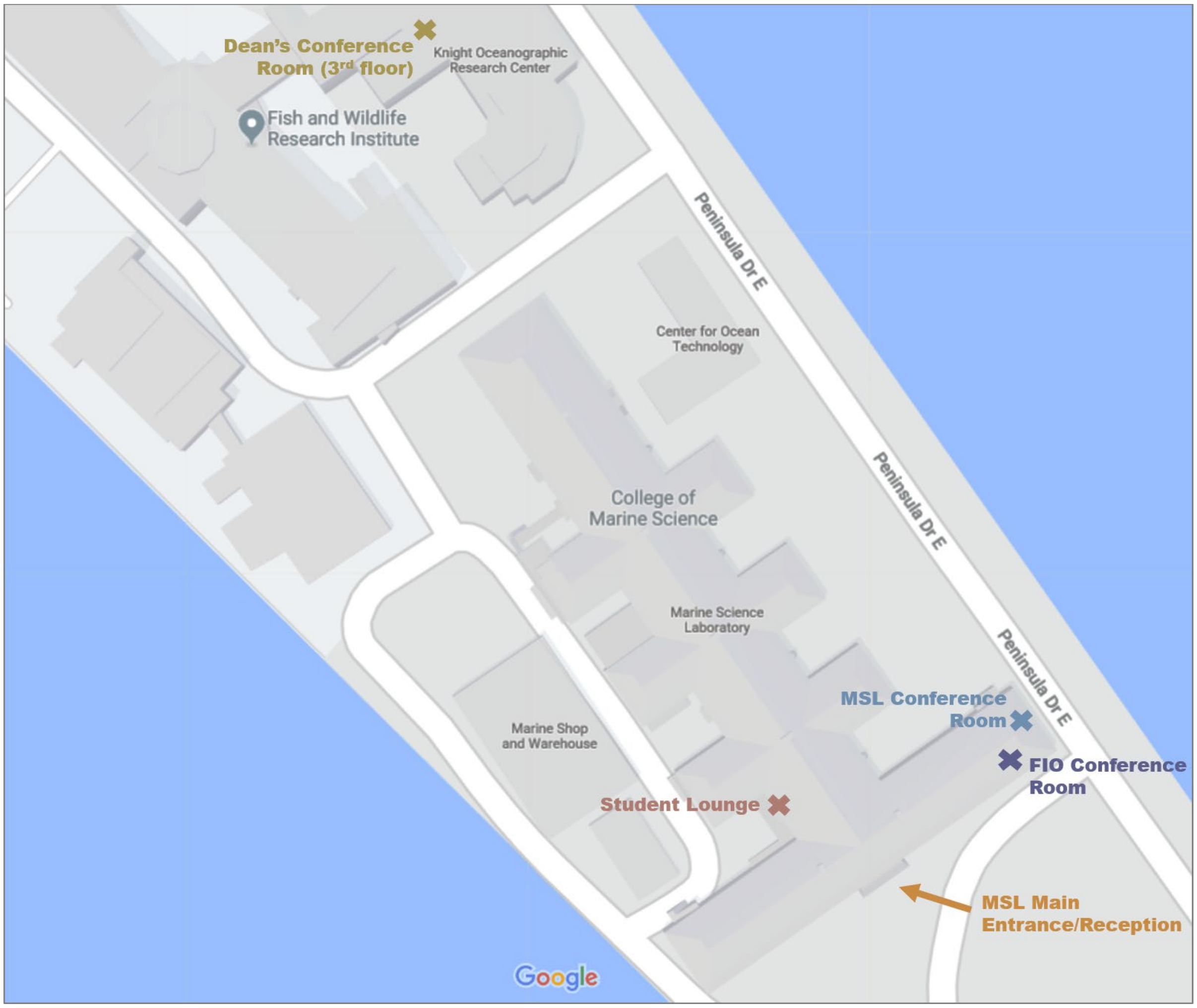
- Multimodel ensemble case studies - Presenter: **Jonathan Reum**
- Ocean model/fisheries model coupling - Presenter: **Kelly Kearney**

- Ecosystem level MSEs - Presenter: **Isaac Kaplan**
- Coupled social-ecological models - Presenter: **Mike Jepson**
- End-to-end modeling for structuring EBFM - Presenter: **Ivonne Ortiz**
- Connecting Fisheries Policy Challenges with Models and Analysis: - Presenter: **Chris Harvey**

12:30-1:30 - Lunch
1:30-2:30 - Plenary feedback and discussion on Progress Topic areas (cross-cutting recommendations and best practices) (**Moderator: Mariska Weijerman, Rapporteur: Isaac Kaplan**)
2:30-3:00 - Writing Team
Breakout - writing teams incorporate feedback and discussion
3:00-3:30 - Break
3:30-5:30 - Writing Team
Breakout - drafting manuscripts
5:30 - Adjourn for the day
6:30ish - Social - Dinner or beverages somewhere fun

<u>Day 3- December 11, 2019</u>
8:30-9 - Recap Day 2, Lay out plans for Day 3
9-10:00 - Plenary Discussion on Topic areas - writing teams discuss how they have incorporated feedback (**Moderator: Peg Brady, Rapporteur: Joan Browder**)
10:00-12:00 - Writing Teams finalize manuscripts
12:00-1:00 - Lunch
1:00-2:00 - Writing Teams present on Topic-specific best practices and recommendations (**Moderator: Howard Townsend, Rapporteur: Isaac Kaplan**)
2:00-3:00 - Final discussion
3:00 - Adjourn

Plenary session will be in the MSL Conference Room. Writing Team breakouts will be in the MSL conference room, FIO room, grad student lounge, and maybe the Dean's conference room. See map below for locations.


Dean's Conference Room (3rd floor)
Knight Oceanographic Research Center
Fish and Wildlife Research Institute
Peninsula Dr E
Center for Ocean Technology
Peninsula Dr E
College of Marine Science
Marine Science Laboratory
Peninsula Dr E
MSL Conference Room
FIO Conference Room
Marine Shop and Warehouse
Student Lounge
MSL Main Entrance/Reception
Google

Appendix C – Participants List

Participant Name		Program Office	Email
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Michael	Drexler	University of South Florida	
Rebecca	Scott	University of South Florida	

Appendix D – Topic Team Leads and Steering Committee

Topic Team Leads

Subject	**Leads/POCs**
Multimodel ensemble case studies	Jon Reum (jonathan.reum@noaa.gov), Kerim Aydin (Kerim.Aydin@noaa.gov)
Ocean model/fisheries model coupling, especially for climate issues	Kelly Kearney (Kelly.Kearney@noaa.gov)
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