Report from

CAMEO Workshop on End-to-End Modeling of Marine Ecosystems

held at

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Introduction

The Workshop addressed three themes chosen as important for the advancement of end-to-end food web models of marine ecosystems. These themes were:

(1) *Review extant end-to-end models and their underlying rationales*
(2) *Consider application to management and decision making*
(3) *Develop recommendations for skill assessment of end-to-end models*

The workshop consisted of plenary presentations (open to the whole WHOI community), focused workshop presentations, and working groups, that were designed to provide inputs for each theme. The opening keynote address, given by Dr. Steve Murawski, Director of Scientific Programs and Chief Scientific Advisor for NOAA Fisheries, was entitled:

> *Ecosystem-based research in the oceans: academic curiosity or operational technology?*

and set the background and context for the subsequent working groups and discussions. The papers presented at the workshop (see Appendix) gave a good representation of the U.S. component of what is a very international modeling activity. The one international contribution to the workshop (Heath, UK) was presented by teleconference because of the disruption in air travel caused by the Icelandic volcano. Plenary talks (Rose, Hofmann) reviewed the general field of food web modeling and the issues facing development of these models. . There were also two broad reviews of modeling at the global scale (Gregg, Murtugudde). The other papers can be considered in the context of the three themes.

The following sections provide summaries of discussions related to each of the three workshop themes. Conclusions from the workshop are given in the final section.

(1) End-to-end models

The main impression is of the very great variety in types of model. One general conclusion from the discussions stressed the need to use this variety to represent the broad range of questions we ask about ecosystems as well as the different systems themselves. The following categories are intended only to describe some topics that emerged in discussion.

I..*ECOPATH with ECOSIM* (EwE) (Gaichas and Townsend)

The EwE modeling framework, introduced by Christensen and Pauly in 1997, has been very widely used and has been the main tool to provide a top-down or fishery focus for the analysis of marine ecosystems, usually with a comprehensive set of fish species. The use of a linear steady state food web calculation (ECOPATH) to drive a spatially integrated dynamic simulation (ECOSIM) allows a variety of metrics to be calculated.

One strength of EwE is that the "common currency" of biomass and flow rates through food webs (regardless of units) facilitates a strong ability for interregional comparisons, and the development of "toolboxes" (standard techniques that could be applied across multiple systems with minimal modifications). Also, the scale of the models from a fisheries perspective (whole stock or ecosystem without spatial considerations) allows direct comparison of results with standard single-species stock assessment techniques and allows the models to be built with data already available from long-term stock assessment efforts. Finally, the relatively quick run-time of these models, allows complex analysis of outputs, including Monte Carlo methods and formal statistical fitting techniques. However, several other independent modeling approaches (e.g. size-spectrum models or inverse models) may provide substantial improvements over this approach, depending on the purpose of the modeling effort.

The main deficits in the EwE framework are the lack of structure for the microbial food web and of physical forcing of the ecosystem. But the EwE program has encouraged efforts to introduce these aspects.

II. P*rocess studies.* (Collie, Richardson, Brodeur, Ruzicka, Steele, Heath)

Insight into the complicated processes within food webs and their interaction with the physical and chemical environment can require a relatively simplified or integrated definition of components for both physical and ecological processes. One major trade-off involves the decision on whether to emphasize complex food web structure, as in ECOPATH or the detailed horizontal and vertical physical processes. In this context an important discussion that re-occurred throughout the workshop concerned the use of "guilds" rather than individual species, to represent the fish community. The lower trophic levels in food web models typically are represented by broad aggregate groupings such as micro/meso/macro zooplankton, or benthic in-and epi-fauna. For fish, should we use guilds such as planktivores, benthivores and piscivores? Is this just a convenience for relatively simple and rapid modeling and for comparisons between ecosystems? Or is it a

consequence of unpredictable longer-term variability in the species mix? Similarly, should there be a focus on physical processes such as vertical mixing that determine nutrient input, or do we need simulation of the details of horizontal advection? These questions provided a link to discussion of the other two categories.

These process models usually introduce some spatial structure for analysis of the microbial food webs but aggregate the system at higher trophic levels, so that the fish components have no spatial patterns. The alternative approaches retain spatial structure for the whole system. The trade-off is mainly in model complexity and run times.

III. *Spatial focused systems* (Fiechter, Rose, Chai, Costa)

Advances in coupled physical/biological models (in the GLOBEC program) have focused on representation of the planktonic realm and on one or two pelagic fish species, ignoring the shelf benthos. These models build on the ability to simulate physics at eddy resolving scales using circulation models, such as the Regional Ocean Modeling System (ROMS). The focus of the dynamics in these models is primarily planktonic, with extensions to planktivore species (forage fish) through approaches such as Individual-Based Modeling. Recent developments were represented in the workshop by models of sardine/anchovy dynamics in the California Current and off Peru, showing how these can be used for multi-decadal historical simulations, and potentially for management applications. A principal interest is in investigating the consequences of climatic change on patterns of lower-level production.

Part of the discussions highlighted the need for food web models to include a focus on the top trophic levels, particularly marine mammals and sea birds. These top predators can be regarded as indicators that integrate effects at lower trophic levels, as well as being very visible and iconic representatives of their ecosystems.

IV. *Spatial Fisheries Models* (Aydin, Kaplan)

The deficits in the EwE framework have been rectified by linking different models, such as a ROMS, with a nutrient-phytoplankton-zooplankton (NPZ) module, and with the upper trophic levels from ECOPATH. However the main new approach is a very comprehensive and detailed simulation, ATLANTIS, developed by Fulton in Australia and now being adapted for several US ecosystems, represented at the workshop here by an application to the California Current. Unlike previous approaches where the physical, NPZ and fish components are developed separately and then loosely coupled, ATLANTIS has complete integration of the circulation, derived from the ROMS, with a detailed comprehensive non-linear representation of the whole ecosystem including all significant fish species. A distinguishing aspect is that these models focus on details in the spatial patterns in fisheries and economics. The presentations and discussions indicated that the development time for these types of modeling system can involve a group effort over three years or more. There are several hundred parameters, generally

unconstrained by data. These parameters are used to "calibrate" the system to the available observations, principally the fish species. The output can represent the spatial distribution of individual fish species, their interaction with fishing fleets and their "response" to regulation. The general aim of these models in a fisheries management sense is to provide a platform on which realistic management strategies can be played out.

(2) Communicating with Users, Managers and Stakeholders (Toft, Ihde, Jin)

This theme, *application to decision makers,* aroused the most discussion at the workshop and broadened out to consider general categories of "stakeholders". There was discussion of the need to communicate with the general public – museums and aquaria were potential locales. It was accepted that most scientists do not communicate effectively and need either help from experts or training, particularly in dealing with the press on sensitive issues. At this general level there is awareness of the need to communicate effectively to a diverse range of stakeholders but no obvious simple solutions.

More specifically, discussions focused on the problems associated with communicating the output of models to "managers and decision makers", especially in representing the uncertainties inherent in the results. It is necessarily an interactive process requiring the construction of an agreed set of questions in a common language. The many issues and unknowns associated with this process are illustrated by the questions that arose from the discussions:

- Do decision makers want to be given uncertainties?
- How do particular models estimate acceptable levels of risk?
- Will it be useful for researcher and managersto examine jointly alternative model scenarios?
- What modeling capabilities and resources are needed to implement and evaluate alternative model scenarios at time scales appropriate for the decision makers?
- What approaches and safeguards (e.g. peer review) need to be in place to transition a research model to one that can be used for operational or regulatory applications?
- What resources are needed to develop experts who can act as a cultural facilitators between the modeling, regulatory and management communities?

There was a general sense that the output of single species models are not only mandated, but are accepted by many as "the truth". The concept of "ecosystem based management" is also accepted but more as a mantra rather than as a protocol. It may take a long time before E2E models are accepted as part of the discourse. The Integrated Ecosystem Assessments (IEA's) for Puget Sound and Chesapeake Bay were discussed as examples. One recommendation was to start a dialog with potential stakeholders to see what they want and what would be appropriate E2E models for IEA's.

There are also problems of communicating among scientific disciplines particularly oceanographic and socio-economic groups. One presentation at the workshop showed an

economic model that used an end-to-end ecosystem model to drive it, and representing a larger class of effort on economic modeling of fisheries. There was little subsequent discussion of this approach yet incorporation of the "human dimension" is considered a primary aim of the CAMEO program.

(3) Skill Assessment and Validation (Friedrichs)

One workshop presentation (Friedrichs) described specifically the process of skill assessment that was developed for a suite of 12 models used in ocean biogeochemistry (the JGOFS program). Methods developed to compare the skills of different models in terms of the number of state variables (4-12), their parameter requirements and their portability (application to other systems) were described. The usual procedures are to compare: (1) different models applied to the same system, (2) the same model in different systems, or as a compromise, (3) construct the model using part of a time series and test against other parts of the time series. The value of data assimilation procedures was stressed.

Relevance to E2E models was discussed sporadically throughout the meeting. It appears to be a problem to adapt these types of analysis to E2E models; in part for technical reasons (the large number of heterogeneous variables) but mainly because they may not fit with some of the aims of E2E practitioners. Some specific aspects relate to model categories

(a) Process models
It should be possible to apply some form of skill assessment for the process type models where the use of "guilds" is intended to facilitate comparisons across ecosystems. It was pointed out that, for quite a number of regions, there are multi-decadal time series from fish surveys as well as from fish catch data;
Could these be split and used to assess E2E models constructed using periods when data for other trophic levels are available? These procedures could investigate questions such as:

- Do we need a different model for each ecosystem?
- Is there an optimal level of complexity for "portability?
- What is gained and lost by aggregation into guilds?
- How much better does the model do than just measuring your observations?
- Do interactions between modeled components explain trends better than simple correlation models?
- Can these models complement stock assessments?
- What are the data limitations for process models?

(b) *Spatial focused models*
In retrospect, the pelagic models for anchovy/sardine that are an extension of the open ocean NPZD models, would appear to be a natural candidate for skill assessment given both the relative simple ecology (comparable to JGOFS) and the similar Eastern upwelling systems with extensive data.

(c) *Spatial fisheries models*
For ATLANTIS and other large complicated models, the management purpose is primarily defined as being an operating model (i.e. "basis of truth") for Management Strategy Evaluations (MSEs) using scenarios where different methods and levels of fishing in varying geographical regions within an ecosystem can be simulated. For these purposes, very detailed descriptions of individual fish populations are needed. To get these details, all available data for a given system are used for "calibration". It was recognized that calibration was different from skill assessment. Skill assessment (or validation) did not appear to be a requirement where the focus was on recreating a very detailed representation of a particular system. (There was consensus that "skill assessment" is a preferable term to "validation"). A primary issue with these models is run-time for repeated sensitivity testing; the increased development of high-performance computing (HPC) resources would facilitate these approaches.

(d) *Data requirements and management*
The general proposition that we are data limited underlies marine ecosystem research. Within this context there were specific points:

- The major inadequacies, determining overall uncertainties, are at intermediate trophic levels such as meiobenthos, gelatinous zooplankton ,and pre-recruit fish
- Rate processes such as growth and reproduction limit flux calculations
- Experimental data for functional responses, including diet variation over time, are needed at all trophic levels
- Information on relevant behavior (e.g. aggregation) for fish and other top trophic levels is lacking
- Historical data for fish populations derived from catch statistics is essential for skill assessment

We had a very informative presentation (Groman) on data acquisition and retrieval. In particular the NSF funded data center (BCO-DMO) is grappling with the problem of handling the potentially very large output from models. This could be comparable to or greater than traditional data handling. Is this necessary, or appropriate for programs such as CAMEO with diverse and sometimes confidential data sources?

Discussion: Virtual Worlds or Construction Kits

There was a certain aggregation of interest around two rather different approaches – different in model structure, application and skill assessment – that might be termed *Virtual Worlds* and *Construction Kits.*

Virtual Worlds. It is generally agreed that one important use of models is as intermediaries or decision support tools between the "researcher" and the "decision maker". For such models to play a full role, the questions that can be asked of them and their answers, or scenarios, should appear as realistic as possibleHowever, the large number of parameters, spatial detail, and extensive calibration associated with these models are likely to make them opaque to other practitioners. This may be a minor inadequacy compared with the value as a communication tool, similar to what has been done with climate models. The "skill" is in the ability to convey, realistically, possible consequences of management actions involving interventions in fishing practice, particularly, Marine Spatial Planning. We discussed ways to extend this communication (e.g. animated cartoons). From presentations and discussions at the workshop it was not clear whether, without testing for portability, these large models can be used to evaluate the consequences of changes *within* the ecosystem, such as those arising from climatic change. This unresolved aspect is a challenge for future work.

Construction Kits. The alternative approach covers the variety of possible food web models that can be assembled; and the consequences for input/output relations of changing internal processes such as variable nutrient recycling, seasonal and inter-annual patterns in upwelling, and the effects of increases in gelatinous zooplankton or rare species on the rest of the food web. For these purposes, and for portability, the physical processes determining nutrient input are caricatured to emphasize particular critical features, and the trophic components are kept at the functional or guild scale of aggregation. There was some discussion of concepts such as the "Minimum Realistic Model" and "Intermediate Optima" in skill assessment. These simplifications can aid comparison of ecosystems or skill assessment but, as was pointed out in several discussions, it is much more difficult to see how such models relate directly to management questions. This is a major challenge in the context of the workshop and of the CAMEO program.

To use another cliché, the elephants in the workshop were the highly developed single species stock assessment methods that are, and will remain, the mainstay of regulatory measures. It was pointed out frequently that for "managers" these methods are closest to "truth". Alternate E2E models must compete for that role. In an ecosystem context stock assessment models may be considered as an end point of the so-called "rhomboid" approach, (de Young et al., *Science*, 2005) that proposed focusing attention on one trophic level, using age structured populations and with much less detail above and below this level. The focused anchovy/sardine open ocean models discussed earlier are closest to this approach but we did not consider this aspect of their application.

Conclusions

There are certain general, and generally accepted, conclusions that emerged from the workshop. These are:

- There is a wide range of models that can fit under the E2E rubric. *Many "international" proponents were not represented. Nor were the more conceptual approaches to food web theory.*
- The diversity is valuable and should be encouraged. *There was consensus that no single package of models is preferable.*
- The diversity arises from the variety of possible applications or uses. *Simple categories such as "tactical" and "strategic" seemed inadequate*
- The applications can require long-term interaction with stakeholders. *These processes merit more study across research and user communities. It should not be assumed that the interactions will happen automatically after the modeling science is done.*
- In particular, specialist help or instruction may be necessary. *This is not cheap but is not usually budgeted.*
- Test of the models is a complex process and differs for different models. *.There needs to be more work on skill assessment and, particularly, on risk analysis – a topic we barely touched on.*

Discussion of these general conclusions often relates to the two categories of models – construction kits and virtual worlds. In the terms used in the opening plenary talk, these two main approaches might be labeled *academic* and *operational.* As discussed, there are significant questions relating to improvements in both approaches in terms of skill assessment and in the ability to communicate results. But the major unresolved issue from the workshop is whether these two approaches should continue on parallel tracks ("stovepipes" and "silos" were mentioned). Thus, a central issue for the CAMEO program is how to focus activities on integrating these two approaches (and their associated research communities) so that they became complementary rather than parallel, non-interacting activities. The workshop was a significant step in this direction.

Papers Presented at the Workshop

Kenneth Rose. *Can end-to-end models be assembled from existing models?*

Eileen Hofmann. *Physical-biological coupling in marine ecosystems and implications for food web models*

Michael Heath and John Steele. *Ecosystem limits to fisheries yields in the North Sea.*

Marjorie Friedrichs. *Using data assimilation techniques to assess the advantages and limitations of various marine ecosystem model structures and parameterizations*

Di Jin, Porter Hoagland and Eric Thunberg. *An integrated economic-ecological framework for ecosystem-based fisheries management in New England.*

Kerim Aydin. *End-to-end models as a tool for ecosystem assessments: incorporating time series data and uncertainties.*

Tammi Richardson. *Trophic web construction using inverse modeling approaches.*

Watson Gregg. *Modeling and data assimilation of global oceans using the NASA Ocean Biogeochemical Model.*

Howard Townsend, M. Sigrist, H. Ma and V. Christensen. *Modeling water quality to fisheries ecosystem in the Chesapeake Bay*.

Richard Brodeur, James Ruzicka and John Steele. *Alternate trophic pathways through gelatinous zooplankton and planktivorous fishes in an upwelling ecosystem.*

Daniel Costa, *The importance of top predators in marine ecosystems.*

Jeremy Collie, E. Bohaboy, K. Curti, and M.-J. Rochet. *Multi-species models of the Georges Bank fish community.*

James Ruzicka, J. Steele and R. Brodeur. *Interannual variability in the Northern California Current food web: trophic relations inferred from annual pelagic surveys and response to variable upwelling-driven productivity.*

Jerome Fiechter, K. Rose, E. Curchitser, K. Hedstrom, M. Bernal. S. Ito, S. Lluch-Cota, B. Megrey, C. Edwards, D. Checkley, A. MacCall, J. Koslow, S. McClatchie, K. Denman and F. Werner. *Development of an end-to-end ecosystem model: conceptual approach and application to population dynamics of anchovies and sardines in the California Current system.*

John Steele and James Ruzicka. *Using ECOPATH data to construct E2E models.*

Jodie Toft, A. Guerry, M. Ruckelshaus, A. Day, K. Arkema, J. Davies, G. Giuannel, C. Kim. M. Papelfus, Y. Qi, and H. Talis *MarineINVEST: a tool for assessing and valuing changes in coastal and marine ecosystem services under alternative functions.*

Raghu Murtugudde. *Regional earth prediction system for CAMEO.*

Fei Chai, Y. Xu, F. Chavez, Y. Vhao and K. Rose. *Using remote sensing and modeling in operational forecasting of fisheries.*

Sarah Gaichas and Kerim Aydin. *Fishing policy simulations in end-to-end models.*

Isaac Kaplan. *Can fisheries policy for the US west coast simultaneously sustain habitat, target species and ecosystem health?*

Thomas Ihde, T.J. Miller, M.J. Wilberg and D.H. Secor. *Project FishSmart: harnessing knowledge and insights of fishery shareholders through a model-informed decision making process.*

Bob Groman. *BCO-DMO: Managing modeling results.*

Poster Presentations

Tosca Ballerini, D. Ainley, K. Daly, E. Hofmann, M. Marrari, C. Ribic, W. Smith and J. Steele. *An analysis of consequences of modifications to a Southern Ocean food web*

Dian Gifford and Suzanne Strom. *The importance of parameterizing lower trophic levels in end-to-end models.*

Robert Groman. *BCO-DMO: Management of modeling results.*

Kelly Kearney, C. Stock, J. Sarmiento. *Analyzing links between changing biogeochemistry and ecosystem shifts using an end-to-end ecosystem model.*

David Mountain. *Georges Bank--A case study for development of an E2E model-based management tool: a data analyst's perspective.*

Sevrine Sailley, H. Ducklow, S. Doney and H. Moeller. *Modeling of the West Antarctic Peninsula.*