

PARADIGM: The Partnership for Advancing Interdisciplinary Global Modeling – Year 4 Annual Report

Lewis M. Rothstein
Graduate School of Oceanography
University of Rhode Island
Narragansett Bay Campus, Narragansett, RI 02882
phone: (401) 874-6517 fax: (401) 874-6728
email: lrothstein@gso.uri.edu

Mark R. Abbott
College of Oceanic and Atmospheric Sciences
Oregon State University
Corvallis, Oregon, 97331-5503
phone: (541) 737-4045 fax: (541) 737-2067
email: mark@oce.orst.edu

Eric P. Chassignet
University of Miami
4600 Rickenbacker Causeway,
Miami, Fl 33149-1098
phone: (305) 361-4041 fax: (305) 361-4696
email: echassignet@rsmas.miami.edu

John J. Cullen
Department of Oceanography
Dalhousie University
Halifax, Nova Scotia B3H 4J1, Canada
phone: (902) 494-6667 fax: (902) 494-2039
email: John.Cullen@Dal.CA

Kenneth L. Denman
Canadian Centre for Climate Modelling and Analysis
University of Victoria
P.O. Box 1700, STN CSC
Victoria, BC, Canada, V8W 2Y2
phone: (250) 363-8230 fax: (250) 363-8247
email: ken.denman@ec.gc.ca

Scott C. Doney
Department of Marine Chemistry and Geochemistry
WHOI, MS 25
Woods Hole, MA 02543
Phone: (508) 289-3776
Fax: (508) 457-2193
email: sdoney@whoi.edu

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 2005		2. REPORT TYPE		3. DATES COVERED 00-00-2005 to 00-00-2005	
4. TITLE AND SUBTITLE PARADIGM: The Partnership for Advancing Interdisciplinary Global Modeling - Year 4 Annual Report				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Rhode Island, Graduate School of Oceanography, Narragansett Bay Campus, Narragansett, RI, 02882				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 15	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Hugh W. Ducklow
Virginia Institute of Marine Sciences
Box 1346
Gloucester Point, VA 23062
phone: (804) 684-7180 fax: (804) 684-7293
email: duck@vims.edu

Michael Follows
Dept. of Earth, Atmosphere and Planetary Science
Massachusetts Institute of Technology
Cambridge, MA 02139
phone: (617) 253-5939 fax: (617) 253-4464
email: mick@plume.mit.edu

Dale B. Haidvogel
Institute of Marine and Coastal Sciences
Rutgers, The State University of New Jersey
71 Dudley Road
New Brunswick, NJ 08901-8521
phone: (732) 932-6555 x256 fax: (732) 932-8578
email: dale@imcs.rutgers.edu

Eileen E. Hofmann
Center for Coastal Physical Oceanography
Crittenton Hall
Old Dominion University
Norfolk, VA 23529
phone: (757) 683-5334 fax: (757) 683-5550
email: hofmann@ccpo.odu.edu

David M. Karl
University of Hawaii, Oceanography
1000 Pope Road
Honolulu, HI 96822
phone: (808) 956-8964 fax: (808) 956-5059
email: dkarl@soest.hawaii.edu

John C. Kindle
Naval Research Laboratory
Code 7331
Stennis Space Center, MS 39529
phone: (228) 688-4118 fax: (228) 688-5997
email: kindle@nrlssc.navy.mil

Charles R. McClain
 NASA Goddard Space Flight Center
 Code 970.2
 Greenbelt, MD 20771
 phone: (301) 286-5377 fax: (301) 286-0268
 email: mcclain@calval.gsfc.nasa.gov

Dennis J. McGillicuddy, Jr.
 Department of Applied Ocean Physics and Engineering
 Woods Hole Oceanographic Institution
 Woods Hole, Massachusetts 02543
 phone: (508) 289-2683 fax: (508) 547-2194
 email: dmcgillicuddy@whoi.edu

Richard D. Smith
 Theoretical Division,
 Group T-3, MS B216,
 Los Alamos National Laboratory,
 Los Alamos, NM 87544
 phone: (505) 667-7744 fax: (505) 665-5926
 email: rdsmith@lanl.gov

James A. Yoder
 Graduate School of Oceanography
 University of Rhode Island
 Narragansett Bay Campus, Narragansett, RI 02882
 phone: (401) 874-6864 fax: (401) 874-6728
 email: jyoder@gso.uri.edu

Award Number: N000140210370
<http://www.gso.uri.edu/paradigm/>

LONG-TERM GOALS

To develop an efficient, community-based coupled biogeochemical-physical modeling framework that will enable the addition of new oceanographic processes in a straightforward and transparent manner, allowing new model structures to be developed and explored as our understanding of ocean ecology and biogeochemistry improves. To develop such a modeling framework within the context of our initial, specific overarching scientific focus: an inter-comparison study between the subtropical-subpolar gyre systems of the North Pacific and North Atlantic basins, including an explicit coastal component, with particular emphasis on understanding:

- new paradigms for physical and chemical control of plankton community structure and function,
- the consequences for biogeochemical cycling,
- the effects of sub-mesoscale and mesoscale forcing, and
- the dynamics of long-term, climate driven ecosystem regime shifts.

In support of these, we have programs to meet the challenge of merging observations and models through:

- advanced data assimilation techniques,
- the development of interdisciplinary data products for incorporation into models, and
- the application of new statistical and complex dynamical systems analysis techniques.

The merging of observations and models supports a rigorous model validation program that is central to PARADIGM.

OBJECTIVES

To improve our understanding of the mean state, seasonal cycle, and natural interannual to decadal variability of global and basin-scale biogeographical patterns. Why do different ecosystems reside where they do? What combination of forcing and biological responses drives the observed long-term variability and apparent ecosystem regime shifts? The intrinsic scales of ocean ecology are set by the growth and removal of phytoplankton, with time-constants of one to a few days. Our project scope, therefore, encompasses the range of coupled dynamics of ocean ecology, biogeochemistry, and physics on scales from sub-diurnal to multi-decadal and submesoscale to global.

The project is divided into four major scientific themes, with associated fundamental questions:

- 1) Biogeochemical cycles.** *What factors govern phytoplankton biomass, productivity and export, the net remineralization of organic matter below the euphotic zone, and the spatial (e.g., biogeographical regimes) and temporal (e.g., climate regime shifts) variations in these global processes?*
- 2) Community structure.** *What processes govern plankton community structure and function and how do physical-chemical-biological interactions influence biogeochemical processes in the ocean system?*
- 3) Scales of physical forcing.** *How do mesoscale and sub-mesoscale physical variability impact ecosystem fluxes and community structure?*
- 4) Advanced interdisciplinary models.** *How do we best merge observations and models?*

APPROACH AND WORK PLAN

PARADIGM is a group of 16 scientists committed to building and deploying new, advanced models of ecology and biogeochemistry for understanding and predicting the future states of the ocean. The group combines expertise of observers and modelers, ecologists and physicists, biogeochemists and numerical specialists. Our overall scientific goal is a rigorous, model- and observation-based intercomparison of ecosystem/biogeochemical dynamics of the North Pacific and Atlantic subtropical - subpolar gyres. Our central objective is creation of new global ocean biogeochemistry community models, comprising complex ecosystem dynamics based on functional groups (e.g., *Archaea*, diatoms, copepods, gelatinous predators), individual keystone species (e.g., *Trichodesmium*, *Euphausia superba*) and multielement limitation and cycling (e.g., C, N, P, Si, Fe). The physical model platform is composed of a hierarchy of mature, general circulation models each the focus of extensive community model development programs. PARADIGM models will be capable of emergent behavior testing the hypothesis that fundamental regime shifts occur in response to climate change. Community models will be developed by interdisciplinary teams devoted to five program elements: (1) data fusion, synthesis and validation; (2) ecosystem model development; (3) high-resolution basin scale and regional process studies; (4) focus sites (i.e., regional test-beds) and (5) numerical method development (including data assimilation).

WORK COMPLETED

There has been excellent scientific progress in the fourth year of the program. Because of the space limitations imposed upon this report, we are here only able to present a select few of our efforts. Last year we highlighted our *community global modeling* effort. In this report we present progress towards *modeling fundamental ecosystem behavior*. The following summaries are excerpted from an invited article for Oceanography Magazine entitled "Modeling Ocean Ecosystems: The PARADIGM Program" that will appear in March 2006. More complete individual program reports from all PARADIGM sub-programs are available upon request.

RESULTS - Contemporary Approaches to Modeling Marine Ecosystems

Computer Generated Functional Groups of Phytoplankton and Natural Selection

New observational approaches, including molecular and genetic probes, show great levels of diversity in the marine ecosystem, with several functional types within species populating distinct physical domains (Ferris and Palenik, 1998; Johnson et al., 2005). We therefore seek to adopt modeling strategies that can interface with, and help interpret the new, genomic view of ocean ecology. In one PARADIGM study, we are exploring an approach to marine ecosystem modeling which explicitly brings to bear natural selection (Follows, Grant, Dutkiewicz and Chisolm, in prep). Instead of imposing the community structure, we construct a model with

many tens or hundreds of functional groups of phytoplankton, each of which has characteristics determined in part by chance, from within plausible bounds. Embedded initially in a one-dimensional, oceanic physical framework, plausible and robust community structures emerge in ensemble integrations of this model (Figure 1, Follows et al., in prep) molded by the physical environment and nutrient availability (Tilman, 1977; Tozzi et al., 2004; Johnson et al., 2005). We are also exploring this strategy for modeling the ecosystem in more complex physical and biogeochemical environments.

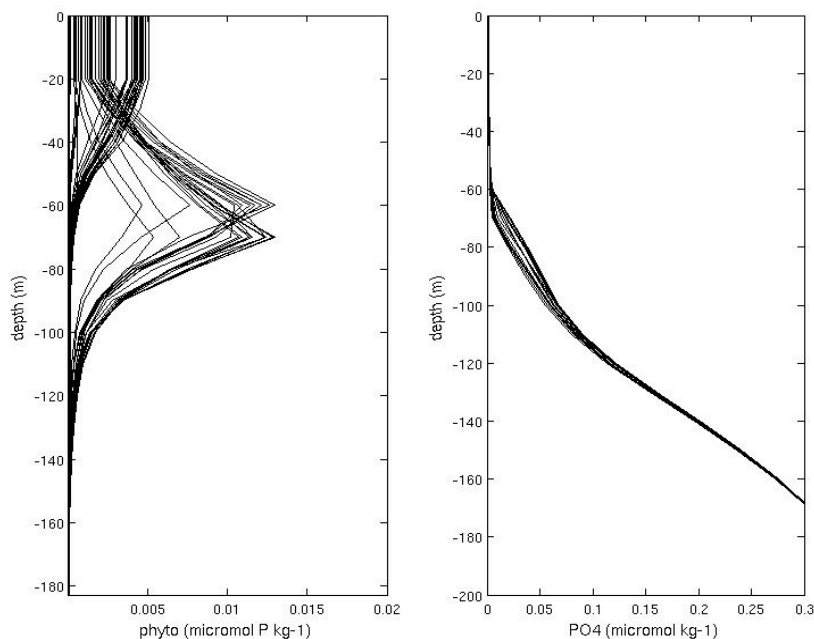


Figure 1. (a) Modeled annual mean phytoplankton phosphorus concentration ($\mu\text{mol P kg}^{-1}$) and (b) annual mean phosphate concentration ($\mu\text{mol kg}^{-1}$) as a function of depth from an ensemble of twenty integrations with a one-dimensional ecosystem model (Follows et al., in prep). The idealized model represents the annual cycle by imposing sinusoidal cycles of sea-surface temperature, which drives wintertime convection, and insulation. Winter mixed layers reach 120m depths, shoaling to 25m in the summer. Thirty-six functional groups of phytoplankton are initialized in each integration, differing in light sensitivity and phosphate half saturation coefficient assigned randomly within plausible ranges. The figure shows the annual mean phytoplankton and phosphate profiles from the tenth year of integration of each of the twenty ensemble members. The simple environment with only two resources, light and phosphate, supports limited diversity and selecting for a surface-oriented, “high-light, low-nutrient” functional group and a “low-light, high-nutrient” functional group forming a deep chlorophyll maximum in each integration. Of a possible 720 functional groups (the total from all ensemble members) only about 40 are viable (left panel) after a decade of competition. The nature of the viable functional groups is qualitatively consistent and robust between ensemble members, a consequence of the control of the resource environment (Tilman, 1977). The annual mean phosphate profiles of the ensemble members are dependent on ecosystem structure but closely consistent (right panel).

The Microbial Foodweb - Microzooplankton and Bacteria

Defining and/or generating functional groups of phytoplankton and biogeochemical functions and their environmental sensitivities is only one step in the process of modeling marine ecosystems. Ecological processes must be described by modeling the fate of materials produced by each functional group. There are two basic pathways of material flow from the phytoplankton in a functional or biogeochemical view of the marine ecosystem. The first is the export pathway by which biogenic particles and semi-labile dissolved organic matter are exported from the surface ocean to the ocean interior below. The second, and usually the larger, is the recycling pathway within the upper ocean that remineralizes organic matter into inorganic nutrients and carbon dioxide. Unicellular heterotrophic microbes, protozoans and microzooplankton dominate nutrient recycling. As

a consequence of dominance of primary production (see above) and recycling by microbes, the ocean ecosystem has in essence a background recycling web of microbes and an episodic export foodweb of larger organisms (diatoms and copepods); Figure 2. As modelers our challenge is to represent the functions of export and recycling and their control and variability in space and time without expanding model complexity beyond tractable limits.

The challenge is compounded by the realization that a wide range of physiological and trophic capabilities exists besides the traditional autotroph and heterotroph modes – mixotrophy and photoheterotrophy – to name just two. Our job as modelers now lags considerably behind new observations as far as incorporating recent genomic and ecological discoveries of the diverse and complicated foodwebs in the open sea. Despite the exploding genomic information on microbial organisms, our understanding of their role in regulating elemental cycles is still insufficient for much more than a crude ‘black box approach’ to incorporating microbial processes in models. One approach is to apply the ‘background’ state hypothesis whereby the microbial foodweb is a relatively stable presence in surface waters, through which nutrients escape to fuel larger cells, higher trophic levels and vertical flux only when physical and biogeochemical perturbations supply nutrients to the surface layer in excess of the microbes’ ability to absorb them (reviewed by Cullen et al. 2002). This hypothesis is being tested by analysis of field data, along with complementary modeling of food web responses to varying nutrient supply, including purposeful fertilization with iron (Denman et al., in press). Conventional models underestimate the magnitude of recycling in ocean systems. Few models can address variations of nutrient stoichiometric ratios and formation and cycling of DOM, and a greater level of model sophistication is needed to include diverse functional groups and trophic modes.

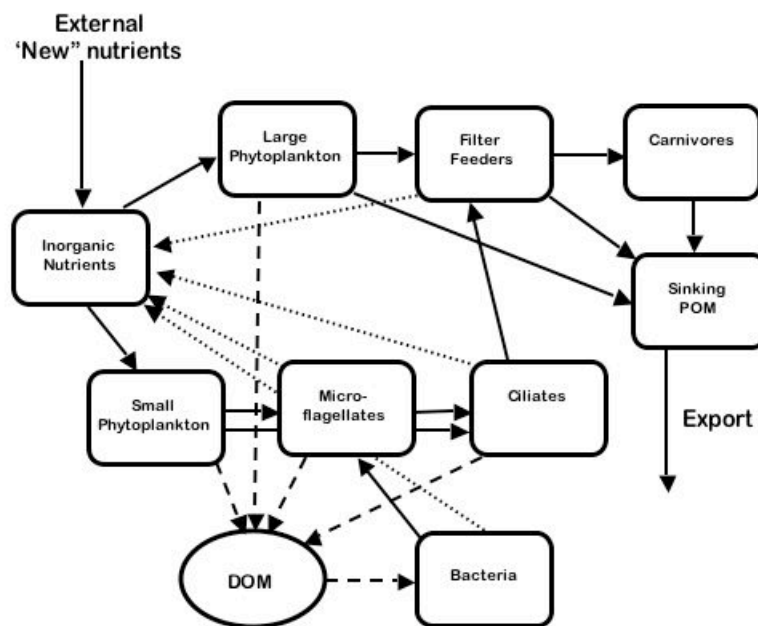


Figure 2. Oceanic plankton foodweb, after Laws et al. (2000). The upper pathway initiated by large phytoplankton contributes primarily to export from the upper ocean. The lower pathway starting with small phytoplankton is mainly a nutrient recycling pathway. Solid arrows: flows of organisms and particulate matter (detritus and fecal pellets). Dashed arrows: flows of dissolved organic matter (DOM). Dotted arrows: flows of regenerated inorganic nutrients. Note that all organisms leak DOM but not all flows are depicted for clarity. All consumers release inorganic nutrients but not all arrows are shown.

Model Closure and Mesozooplankton – Emergent Behavior

With the recent emphasis in ‘biogeochemical’ ecosystem models on phytoplankton and recycling via the microbial foodweb, early lessons on the sensitivity of marine ecosystem models to the formulation of the loss terms associated with mesozooplankton grazing have been deemphasized (Fasham et al., 1990; Steele and Henderson, 1992; Frost and Franzen, 1992; Edwards and Yool, 2000). Regional and global physical-biological models typically utilize a classical predator-prey representation within a continuum-based ecosystem framework that includes, at most, a limited number of pre-determined functional groups of phytoplankton and simplistic grazer representations. Thus descriptions of the latter in biogeochemical models are generally rudimentary and, perhaps more crucially, the continuum approach is inappropriate due to the life cycles and foraging behavior of meta- and mesozooplankton. Indeed, their treatment may be more aptly considered a convenient means of mathematical closure that can be a hindrance to achieving realistic simulations of the pelagic environment. Critical questions that PARADIGM scientists are investigating include: Can we continue to develop models with little or no validation of predicted zooplankton dynamics or parameterizations? Can we represent mesozooplankton meaningfully without any life history development? If not, can we represent the essence of life history development in a compact form? Such an alternative approach is now being attempted with behaviorally explicit numerical models that can explore how zooplankton feeding strategies and morphological differences contribute to efficiency of consumption and recycling of particulate organic material.

As a first step toward incorporating emergent behavior into large-scale models’ grazing formulations, a stochastic Lagrangian model has been developed that explicitly simulates the distinct feeding methods of three prominent tropical copepod species: *Clausocalanus furcatus*; *Paracalanus aculeatus*; and *Oithona plumifera*. The three components to copepod foraging are sampling ambit, area(s) of perception (sensory regions) and prey perception (size preference). The first two components utilize characteristics ascertained through careful behavioral studies (see Figure 3 caption) while prey size preference consists of increasingly reduced uptake efficiency as prey diameter ranges below 15 microns. The final aspect of the model needed to accurately simulate copepod foraging was a realistic prey field that was based on observed size spectra (Paffenhöfer et al., 2003). With these components in place, size-partitioned grazing rates from the individual based model compared very well with the observational data (see Figure 4 in Wiggert et al., 2005).

The simulation results indicate that adult copepod populations in an oligotrophic environment are limited by prey concentration and/or predation but not by resource competition, though this question must remain open until the full range of copepodite stages is included (Wiggert et al., 2005). Additionally, the simulations demonstrate that their various foraging behaviors allows each species to access distinct sub-domains of the prey spectrum; yet all three have the same prey concentration threshold above which their metabolic needs can be attained. This implies that behaviorally induced prey size preferences contribute to the coexistence of these copepod species in the dilute prey environment that they inhabit.

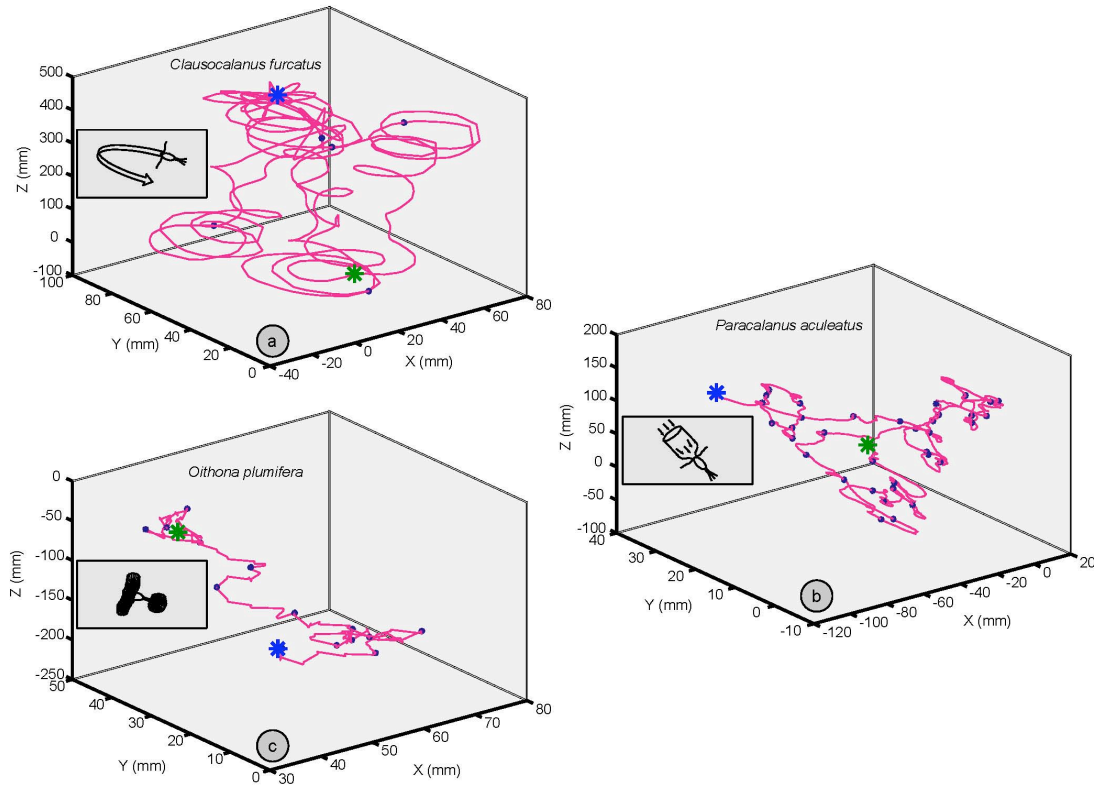


Figure 3: *Clausocalanus furcatus* (a) is a fast continuous swimmer (Mazzocchi and Paffenhöfer, 1999). *Paracalanus aculeatus* (b) is a slow continuous swimmer that employs chemoreception and generates a feeding current (Paffenhöfer, 1984; Paffenhöfer, 1988). *Oithona plumifera* (c) is an ambush predator that uses long feathered setae to sense for hydrodynamic signals emitted by its prey (Paffenhöfer and Mazzocchi, 2002; Svensen and Kiørboe, 2000). Representative simulated sampling ambits are shown for each copepod species, with the corresponding sampling method illustrated in the inset diagram. The start (large green star) and end (large blue star) points of each ambit are shown, along with intermediate steps (small black stars) at 50 second intervals. The individual trajectories represent 5, 30 and 12 minutes respectively, with corresponding travel distances of 4.2, 1.3 and 0.6 meters.

How Much Complexity is Enough?

Experience suggests that the answer to this question depends essentially on the specific context. PARADIGM scientists are trying to model both the behavior of living organisms *and* the processes that trigger changes in that behavior. A better question to ask is whether there are alternative approaches to compartment modeling that might better capture changes both in ecosystem structure and in the behavior of individuals or groups of organisms, in response to changes in the ocean environment.

So how can we proceed? Borrowing from the ‘scientific method’ for laboratory science we may develop the model step by step, varying one parameter or process at a time while keeping all others constant and examining the consequences on the overall system behavior and for the skill of the model in reproducing pertinent observations. We should aim to add complexity only where there are appropriate observations by which it can be constrained or evaluated (see Figure 4).

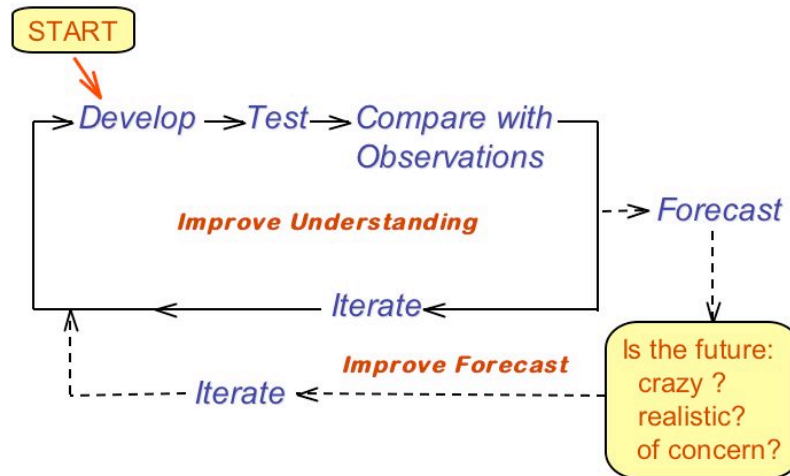


Figure 4: Top down approach to developing coupled ocean biogeochemical + general circulation models: Start with a model aimed at improving our understanding, depicted by the solid line with arrows. ‘Iterate’ denotes the many times through this loop of developing, testing, comparing with observations. Eventually modelers will step into the loop with the dashed line where the objective is to forecast the future. Again ‘iterate’ indicates traveling around this loop many times evaluating where the forecasts fail, identifying the weakness(es) in the model, then stepping back into the first loop to add complexity to address the weakness(es) that have been identified.

If the model development is problem-driven then we might expect application of these principles to allow two streams of ecosystem model development in the ocean: one stream for biogeochemical or carbon cycle models, and one stream for fisheries foodweb models. This dual stream development may not be desirable, but it has evolved over the last decade.

Genomics: Where Ocean Ecosystem Modeling May Need to Go

Genomics is the study of whole genomes of organisms. This field has been revolutionized in the past two decades by a battery of molecular techniques including gene insertion and cloning, DNA sequencing and the polymerase chain reaction (PCR) that recovers both common and rare genomes from the environment, even when organisms cannot be grown in the lab. The field has made revolutionary contributions to ocean ecology (Doney et al. 2004; DeLong and Karl 2005). The importance of genomic discoveries for ocean modelers is that these new approaches are telling us about new aspects of previously modeled processes or organisms and also about previously unknown organisms and processes that need to be modeled. Two examples illustrate the challenges presented.

Genome-based probes were used to enumerate planktonic archaea in the mesopelagic water column in the North Central Pacific Gyre and off the West Antarctic Peninsula (Karner et al. 2001; Church et al. 2003). Archaea are structurally similar to bacteria (they are both prokaryotes) but are genetically distinct. With the *Bacteria* and *Eukarya*, the *Archaea* form the three fundamental domains of life. They may be numerically dominant in a large part of all ocean waters, but we are still not certain of what they do: current evidence suggests they are chemoautotrophs, possibly nitrifiers (Francis et al. 2005). Models of nitrogen cycling and material fluxes in mesopelagic systems need to address these organisms.

Another example concerns dinitrogen fixation, the ultimate process supplying fixed nitrogen to the ocean over long timescales. The principal nitrogen-fixing organism in the central gyres has been assumed to be the large filamentous cyanobacterium *Trichodesmium* (Karl et al. 1997). This organism exists as large bundles of filaments a few mm long, is favored in warm, calm seas, lives mostly at the surface, where irradiance is greatest, and is resistant to grazing. *Trichodesmium* is now represented in several models. For this sea-surface-dwelling organism, the main challenges for modelers are high light tolerance and mechanisms for acquiring iron and

phosphorus in nutrient-depleted waters (Hood et al. 2004; Fennel et al. 2002; Neumann 2000). Recently genomic probing for the gene that expresses the nitrogen-fixing nitrogenase enzyme has revealed that there are also abundant, small unicellular N-fixers (Zehr et al. 2001), and that these are sufficiently abundant to be a significant source of fixed nitrogen (Montoya et al 2004). Indeed, Montoya et al (2004) concluded that they may fix as much or more nitrogen than *Trichodesmium* in the North Pacific gyre. Unicellular N-fixers are found deeper in the water column and so must be less vulnerable to turbulence and can tolerate low light. Because they are small, they are probably vulnerable to microzooplankton grazers. It follows from these observations that the population dynamics and distributions of the unicellular N-fixers may be quite distinct from *Trichodesmium*. Future models of oceanic N dynamics must address the diversity of N-fixing organisms and their dynamics in order to represent the N-fixation process correctly (Arrigo 2005). Furthermore, inclusion of both classes of N-fixers is probably also critical if we are to predict the response of the ocean nitrogen fixation system to regime shifts and climate change.

IMPACT AND APPLICATIONS

PARADIGM scientists are developing new community models of ocean biogeochemistry and ecology on global scales, comprising complex ecosystem dynamics based on functional groups (e.g., *Archaea*, diatoms, copepods, gelatinous predators), individual keystone species (e.g., *Trichodesmium*, *Euphausia superba*) and multi-element limitation and cycling (e.g., C, N, P, Si, Fe). These models include new parameterizations of mesoscale and submesoscale processes that are especially important in biological/physical coupling. Data assimilation and data fusion are being used to improve model formulation and to validate model performance. New approaches to software development are being used to simplify the addition of new ocean processes. The models we are developing are capable of emergent behavior, testing the hypothesis that fundamental domain shifts occur in response to climate change.

PARADIGM research is improving the linkages between modelers and field oceanographers by creating an environment where model assumptions can be explored, model performance rigorously evaluated, and new ideas and hypotheses formulated and tested. Through regular interactions, data visualization, and focused workshops, PARADIGM is serving as an intellectual hub for the study of ocean ecology and biogeochemistry with numerical models as the tool. By making such models more transparent to the non-modeler, we are enabling the study of complex, global-scale processes in a rigorous open manner. In one specific example, our development of an open biogeochemical modeling tool as part of the MITgcm (<http://mitgcm.org>) provides a tool for the wider community which will also encourage scientific communication within the community of MIT model users.

TRANSITIONS

To benefit from relationships outside our consortium, a fundamental objective is *to make all of our research widely available to the scientific community*, both through traditional mechanisms (e.g. workshops) and innovative modes of communication (web-based interactive exchanges). Continuing in the PARADIGM tradition of writing overview articles that reach the broader scientific community, “Modeling Ocean Ecosystems: The PARADIGM Program” will be published in Oceanography Magazine in March 2006. In addition, we will be updating our website for the formal distribution of forward model and data assimilation products, computational algorithms, etc. (<http://www.gso.uri.edu/paradigm/>).

RELATED PROJECTS

A sub-set of the NOPP investigators (e.g., Hofmann, McClain, Haidvogel, Yoder) along with other investigators developed a proposal that was funded as part of the NASA Interdisciplinary Science initiative. This project started in late summer 2004 and is intended to augment the coastal component of the PARADIGM. The overall goal of the project is to develop carbon budgets for continental shelf waters of the Mid-Atlantic Bight (MAB) and South Atlantic Bight (SAB) along the east coast of the United States. This goal is addressed through five specific research questions:

1. What are the relative carbon inputs to the MAB and SAB from terrestrial run-off and *in situ* biological processes?
2. What is the fate of dissolved organic carbon (DOC) input to the continental shelf from estuarine and riverine systems?
3. What are the dominant food web pathways that control carbon cycling and flux in this region?
4. Are there fundamental differences in the manner in which carbon is cycled on the continental shelves of the MAB and SAB?
5. Is the carbon cycle of the MAB and SAB sensitive to climate change?

To date, excellent progress has been made on developing coupled circulation-biogeochemical-carbon models for the MAB and SAB. Progress has also been made in analyses of satellite-derived data sets (e.g. ocean color) and historical hydrographic measurements (e.g. salinity and oxygen) from the two regions, development of data assimilative biological models, and interfacing the MAB and SAB coupled models with climate models developed for the U.S. mid-Atlantic region. The NASA IDS program also includes a limited field component that is providing measurements of many of the quantities and variables included in the biogeochemical and carbon models. Several papers describing results from the modeling, data analyses and field measurement activities are now in preparation. As part of the NASA IDS program, we organized a special session on carbon cycling in continental shelf systems for the 2006 Ocean Sciences Meeting. For more information on the NASA IDS program please visit the project web site: <http://www.ccpo.odu.edu/Research/US-ECOS/index.html>.

REFERENCES

- Arrigo, K. R. 2005. Marine microorganisms and global nutrient cycles. *Nature (London)*, **437**, 349-355.
- Church, M. J., E. F. DeLong, H. W. Ducklow, M. B. Karner, C. M. Preston and D. M. Karl. 2003. Abundance and distribution of planktonic Archaea and Bacteria in the waters west of the Antarctic Peninsula. *Limnology and Oceanography*, **48**, 1893-1902.
- Cullen, J.J., Franks, P.J.S., Karl, D.M. and Longhurst, A., 2002. Physical influences on marine ecosystem dynamics. In: A.R. Robinson, J.J. McCarthy and B.J. Rothschild (Editors), *The Sea: Biological-Physical Interactions in the Ocean*. John Wiley and Sons, pp. 297-335
- Denman, K.L., C. Voelker, M.A. Peña, and R. Rivkin, Modelling the ecosystem response to iron fertilization in the subarctic NE Pacific: The influence of grazing, and Si and N cycling on CO₂ drawdown, Deep-Sea Research II, in press.
- Doney, S.C., M.R. Abbott, J.J. Cullen, D.M. Karl, and L. Rothstein, 2004: From genes to ecosystems: the ocean's new frontier. *Frontiers In Ecology And The Environment*, **2**(9), 457-466.
- Edwards, A.M., and A. Yool (2000). The role of higher predation in plankton population models. *Journal of Plankton Research*, **22**(6):1085-1112.
- Fasham, M.J.R., H.W Ducklow, and S.M. McKelvie, 1990: A nitrogen-based model of plankton dynamics in the oceanic mixed layer. *J. Mar. Res.*, **48**, 591-639.
- Fennel, K., Spitz, Y.H., Letelier, R.M., Abbott, M.R. and Karl, D.M, 2002. A deterministic model for N₂ fixation at stn. ALOHA in the subtropical North Pacific Ocean. *Deep-Sea Research II* **49**, 149-174.
- Ferris, M.J., and B. Palenik (1998) Niche adaptation in ocean cyanobacteria. *Nature*, **396**, 226-228.
- Francis, C. A., K. J. Roberts, J. M. Beman, A. E. Santoro and B. B. Oakley. 2005. Ubiquity and diversity of ammonia-oxidizing archaea in water columns and sediments of the ocean. *PNAS*, **102**, 14683-14688.
- Frost, B.W., and N.C. Franzen, 1992. Grazing and iron limitation in the control of phytoplankton stock and nutrient concentration: a chemostat analogue of the Pacific equatorial upwelling zone, *Marine Ecology Progress Series*, **83**, 291-303.
- Hood, R.R., Coles, V.J. and Capone, D.G., 2004. Modeling the distribution of *Trichodesmium* and nitrogen fixation in the Atlantic Ocean. *Journal of Geophysical Research* **109**, C06006, doi:10.1029/2002JC001753.

- Johnson, Z.I., E.R. Zinser, A. Coe, N.P. McNulty, E. Malcolm, S. Woodward and S.W. Chisholm. Niche Partitioning among *Prochlorococcus* ecotypes along ocean-scale environmental gradients. Submitted to *Science*.
- Karl, D., R. Letelier, L. Tupas, J. Dore, J. Christian and D. Hebel. 1997. The role of nitrogen fixation in biogeochemical cycling in the subtropical North Pacific Ocean. *Nature*, **388**, 533-538.
- Karner, M. B., E. F. DeLong and D. M. Karl. 2001. Archaeal dominance in the mesopelagic zone of the Pacific Ocean. *Nature*, **409**, 507-510.
- Laws, E.A., P.G. Falkowski, W.O. Smith, Jr., H. Ducklow, and J.J. McCarthy, 2000. Temperature effects on export production in the open ocean, *Global Biogeochemical Cycles*, **14**, 1231-1246.
- Mazzocchi, M.G., and G.A. Paffenhöfer, Swimming and feeding behaviour of the planktonic copepod *Clausocalanus furcatus*, *J. Plankton Res.*, **21** (8), 18, 1999.
- Montoya, J. P. 2004. High rates of N₂ fixation by unicellular diazotrophs in the oligotrophic Pacific Ocean. *Nature*, **430**, 1027-1032.
- Neumann, T., 2000. Towards a 3D-ecosystem model of the Baltic Sea. *Journal of Marine Systems* **25** (3-4), 405-419.
- Paffenhöfer, G.A., Does *Paracalanus* feed with a leaky sieve?, *Limnol. Oceanogr.*, **29** (1), 155-160, 1984.
- Paffenhöfer, G.A., On the relation of structure, perception and activity in marine planktonic copepods, *J. Mar. Sys.*, **15** (1-4), 457-473, 1998.
- Paffenhöfer, G.A., and M.G. Mazzocchi, On some aspects of the behaviour of *Oithona plumifera* (Copepoda: Cyclopoida), *J. Plankton Res.*, **24** (2), 7, 2002.
- Paffenhöfer, G.A., M. Tzeng, R. Hristov, C.L. Smith, and M.G. Mazzocchi, Abundance and distribution of nanoplankton in the epipelagic subtropical/tropical open Atlantic Ocean, *J. Plankton Res.*, **25** (12), 1535-1549, 2003.
- Steele, J.H., and E.W. Henderson, 1992. The role of predation in plankton models, *Journal of Plankton Research*, **14**, 157-172.
- Svensen, C., and T. Kiørboe, Remote prey detection in *Oithona similis*: hydromechanical versus chemical cues, *J. Plankton Res.*, **22** (6), 1155-1166, 2000.
- Tilman, D. 1977. Resource competition between planktonic algae: An experimental and theoretical approach. *Ecology* **58**:338-348.
- Tozzi, S., O. Schofield, P. Falkowski (2004) Historical climate change and ocean turbulence as selective agents for two key phytoplankton functional groups. *Marine Ecol. Prog. Series.*, **274**, 123-132.
- Wiggert, J. D., A. G. E. Haskell, G.-A. Paffenhöfer, E. E. Hofmann, and J. M. Klinck, 2005. The role of feeding behavior in sustaining copepod populations in the tropical ocean, *J. Plankton Res.*, **27**, 1013-1031.
- Zehr, J. P., J. B. Waterbury, P. J. Turner, J. P. Montoya, E. Omoregie, G. F. Steward, A. Hansen and D. M. Karl. 2001. Unicellular cyanobacteria fix N₂ in the subtropical North Pacific Ocean. *Nature*, **412**, 635-638.

PARADIGM PUBLICATIONS – YEAR 4

- Babin, M., J.J. Cullen, C.S. Roesler, P.L. Donaghay, G.J. Doucette, M. Kahru, M.R. Lewis, C.A. Scholin, M.E. Sieracki, H.M. Sosik. 2005. New approaches and technologies for observing harmful algal blooms. *Oceanogr. Mag.* **18**(2): 210-227.
- Berman-Frank, I., Chen, Y., Gao, Y., Fennel, K., Follows, M., Milligan, A., Falkowski, P.G. (2005) Feedbacks Between the Nitrogen, Carbon and Oxygen Cycles. (submitted as chapter for “Nitrogen in the Marine Environment”, eds.: E. Carpenter and D. Capone, 2nd edition)
- Cullen, J.J. “Observation and prediction of harmful algal blooms.” In: “Real-Time Coastal Observing Systems for Ecosystems Dynamics and Harmful Algal Blooms.” M. Babin, J.J. Cullen and C.S. Roesler, eds. UNESCO (in press).
- Daniels, R. M., H. W. Ducklow and T. L. Richardson. Food web structure and biogeochemical processes during oceanic phytoplankton blooms: An inverse model analysis. *Deep-Sea Research II* (in press).

- Denman, K.L., C. Voelker, M.A. Peña, and R.B. Rivkin, Modelling the ecosystem response to iron fertilization in the subarctic NE Pacific: The influence of grazing, and Si and N cycling on CO₂ drawdown, Submitted to Deep-Sea Research II, revised, Nov. 2005.
- Ducklow, H. W. and R. M. Daniels. Water column processes in the West Antarctic Peninsula and the Ross Sea: interannual variations and foodweb structure. Deep-Sea Research II, (accepted). (Daniels received his MSc degree in 2004 with PARADIGM support).
- Dutkiewicz, S.W., P. Parekh, T. Ito and M.J. Follows (2005) Interactions of the iron and phosphorus cycles: A modelling study. *Global Biogeochem. Cycles*. **19**, GB1021, doi:10.1029/2004GB002342.
- Fennel, K., Wilkin, J., Levin, J., Moisan, J., O'Reilly, J., Haidvogel, D. (2005a) Nitrogen cycling in the Mid Atlantic Bight and implications for the North Atlantic nitrogen budget: Results from a three-dimensional model. (revised version submitted to *Global Biogeochemical Cycles*).
- Fennel, K., Follows, M., Falkowski, P.G. (2005b) The Co-evolution of the nitrogen, carbon and oxygen cycles in the Proterozoic Ocean. *American Journal of Science* **305**:526-545.
- Follows, M.J., S. Dutkiewicz, and T. Ito (2006) On the solution of the carbonate system in ocean biogeochemistry models. *Ocean Modelling*, **12**, 290-301.
- Hill, H., C.N. Hill, M.J. Follows, S. Dutkiewicz (2005) Is there a computational advantage to offline tracer modelling at very high resolution? Submitted to *Ocean Modelling*.
- Huot, Y., C.A. Brown and J.J. Cullen. 2004. New algorithms for MODIS sun-induced chlorophyll fluorescence and a comparison with present data products. *Limnol. Oceanogr.*: Methods 3: 108-130.
- Ito, T., P. Parekh, S. Dutkiewicz and M.J. Follows (2005) The Antarctic Circumpolar Productivity Belt. *Geophys. Res. Lett.*, **32(13)**, L13604, 10.1029/2005GL023021
- Katz, M.E., Wright, J.D., Miller, K.G., Cramer, B.S., Fennel, K., Falkowski P.G. (2005) Biological Overprint of the Geological Carbon Cycle. *Marine Geology* **217**(3-4):323-338
- Lavoie, D., K. Denman, and C. Michel (2005), Modeling ice algal growth and decline in a seasonally ice-covered region of the Arctic (Resolute Passage, Canadian Archipelago), *J. Geophys. Res.*, **110**, C11009, doi:10.1029/2005JC002922.
- McKinley, G.A., T. Takahashi, E. Butenhuis, F. Chai, J.R. Christian, S.C. Doney, C. Le Quere, I. Lima, R. Murtugudde, L. Shi, and P. Wetzel, North Pacific carbon cycle response to climate variability on seasonal to decadal timescales, *J. Geophys. Res. Oceans*, submitted.
- Parekh, P., M.J. Follows, and E.A. Boyle (2005) Decoupling of iron and phosphate in the global ocean. *Global Biogeochem. Cycles*. **19**, GB2020, 10.1029/2004GB002280
- Parekh, P., M.J. Follows, S. Dutkiewicz and T. Ito (2005) Atmospheric carbon dioxide in a less dusty world. In press, *Geophys. Res. Lett.*
- Richman, J.G., R.N. Miller and Y.H. Spitz, 2005. Error estimates for assimilation of satellite SST data in ocean climate models. *Geophys. Res. Lett.* DOI 10.1029/ 2005GL023591, in press
- Rothstein, L.M., M. Abbott, E. Chassignet, J. Cullen, K. Denman, S. Doney, H. Ducklow, K.Fennel, M.Follows, D. Haidvogel, E. Hofmann, D. Karl, J. Kindle, I. Lima, M. Maltrud, C. McClain, D. McGillicuddy, J. Olascoaga, Y. Spitz, J. Wiggert, James Yoder. 2006. Modeling Ocean Ecosystems: The PARADIGM Program. *Oceanography Mag.* (Accepted).
- Steiner, N., K. Denman, N. McFarlane, and L. Solheim, Simulating the atmosphere-ocean physical conditions and planktonic ecosystem response during SERIES, submitted to Deep-Sea Research II, in press.
- White, A.E., Y.H. Spitz and R.M. Letelier, 2005a. Flexible elemental stoichiometry in *Trichodesmium* spp. and its ecological implications. *Limnology and Oceanography*, in revision.
- White, A.E., Y.H. Spitz, D. Karl and R.M. Letelier, 2005b. Modeling carbohydrate ballasting by *Trichodesmium* spp. at Station ALOHA. *Marine Ecology Progress Series*, submitted.
- Wiggert, J.D., A.G.E. Haskell, G.-A. Paffenhöfer, E.E. Hofmann, J.M. Klinck, 2005, The role of feeding behavior in sustaining copepod populations in the tropical ocean, *Journal Plankton Research*, **27**, 1013-1032.

SELECTED MEETING PRESENTATIONS

INVITED

- Cullen, J.J. 2005. Workshop on the Applications of in situ Fluorometers in Nearshore Waters, Cape Elizabeth, Maine, February. Keynote presentation: "In situ fluorometers for coastal management applications: salvation or curse?"
- Cullen, J.J. 2005. Cullen, J.J. Special panel at the 8th International Conference on Remote Sensing for Marine and Coastal Environments, Halifax, NS: "The role of remote sensing in providing inputs for operational coastal management needs." May.
- Cullen, J.J. 2005. SOLAS Mesoscale Iron Fertilization Workshop, Wellington, New Zealand. Thoughts on co-limitation of planktonic processes in the ocean. October.
- Denman, K. "The impact of climate change on the oceans", in 'Changing Currents – Charting a course of action for the future of the Oceans', Morris Wosk Centre for Dialogue, Simon Fraser University, Vancouver, February, 2005. Plenary.
- Denman, K., "Fertilizing the oceans with iron – can it reverse the buildup of CO₂ in the atmosphere?", Department of Earth and Ocean Sciences, UBC, Vancouver, January, 2005.
- K. Denman, G. Flato, and N. Roulet: "The Canadian Global Coupled Carbon Climate Model - CGC³M" , Canadian Meteorological and Oceanographic Society Annual Congress, Vancouver, Canada, June, 2005.

REGULAR

- Barnett, A.B., C. Normandeau, C. Ryan, J.J. and Cullen. 2005. The influence of nutrition and light history on nonphotochemical quenching of fluorescence in a marine diatom. ASLO Aquatic Sciences Meeting, Salt Lake City, February 2005.
- Cullen, J.J., Dowd, M., Guarracino, M., Hannah, C., Laurent, A., Sheng, J., Vezina, A.F., Wang, L., Evolution of a real-time, physical-biological coastal observation and prediction system. ASLO Winter Meeting, Salt Lake City, Feb. 2005.
- Cullen, John J., Richard F. Davis, Michael Dowd, Yannick Huot, Diego Ibarra, Chris Jones, Stephane Kirchhoff. Using optical measurements in ocean observatories to describe biological variability in coastal ecosystems. 2005 International Ocean Research Conference, Paris, June.
- Fennel, K., Wilkin, J. (OS33D-05) A Biogeochemical Model for the Northwestern Atlantic Continental Shelf, 2006 Ocean Sciences Meeting
- Ianson, D., C. Voelker, and K. Denman: "A biogeochemical patch model of the NE Pacific SERIES in situ manipulation experiment", Canadian Meteorological and Oceanographic Society Annual Congress, Vancouver, Canada, June, 2005.
- Lavoie, D., and K. Denman: "Climate variability, primary productivity and export fluxes in the Beaufort Sea: a modelling study", International GLOBEC-PICES Symposium on Climate Variability and Sub-Arctic Ecosystems, Victoria, Canada, May, 2005.
- Peña, A., K. Denman, C. Voelker and R. Rivkin: "Modelling the ecosystem response to iron fertilization during SERIES", Canadian Meteorological and Oceanographic Society Annual Congress, Vancouver, Canada, June, 2005.
- Steiner N., K. Denman, N. McFarlane, and L. Solheim: "Canadian SOLAS experiments simulated in a 1-D coupled atmosphere-ocean-biogeochemical model", Canadian Meteorological and Oceanographic Society Annual Congress, Vancouver, Canada, June, 2005.
- Wiggert, J.D., A.G.E. Haskell, G.-A. Paffenhöfer, E.E. Hofmann, J.M. Klinck, The role of feeding behavior in sustaining copepod populations in the tropical ocean, oral presentation, ASLO Aquatic Sciences Meeting, Salt Lake City, UT, 20-25 February 2005.
- Wiggert, J.D., A.G.E. Haskell, G.-A. Paffenhöfer, E.E. Hofmann, J.M. Klinck, The role of feeding behavior in sustaining copepod populations in the tropical ocean, oral presentation, Advances in Marine Ecosystem Modelling Research Symposium, Plymouth, England, 27-29 June 2005.
- Wiggert, J.D., A.G.E. Haskell, G.-A. Paffenhöfer, E.E. Hofmann, J.M. Klinck, The role of feeding behavior in sustaining copepod populations in the tropical ocean, poster presentation, The Ocean Carbon System:

Recent Advances and Future Opportunities, An Ocean Carbon and Climate Change (OCCC) Workshop, Woods Hole Oceanographic Institution, Woods Hole, MA, 1-4 August 2005.

Zaharieva, K., K. Denman, and J. Christian: "The Canadian Model of Ocean Carbon and its equilibrium carbon climate", Canadian Meteorological and Oceanographic Society Annual Congress, Vancouver, Canada, June, 2005.

DOCTORAL THESIS

Cahill, B. A Regional Intercomparison Between the Seasonal Cycles of the Georges Bank, Gulf Of Maine and Irish Shelf Ecosystems: The Impact of Physical Variability. University of Rhode Island.

MASTERS THESIS

Barnett, A. Nonphotochemical Quenching Of Fluorescence as a Diagnostic of Light History and Nutrient Stress in the Diatom *Thalassiosira pseudonana*. Dalhousie University.