PARADIGM: The Partnership for Advancing Interdisciplinary Global Modeling – Year 3 Annual Report

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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.

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 third year of the program. Because of space limitations imposed upon this report, we can only summarize our progress towards one of our six themes, the Global Scale Modeling theme, which is effectively the synthesis theme for all of our activities. Annual reports for all other PARADIGM themes are available upon request.

Four major global scale modeling tasks were completed in 2004. 1) We completed a first set of global solutions for the new multi-functional group ocean ecosystem model at coarse resolution (~3 deg. global); an initial paper (Moore et al., 2004) was submitted and published. 2) We conducted a series of historical reconstruction experiments (1958-2000) using the coarse resolution version. 3) We ported the ecosystem model into a high-resolution (0.4 deg. global) version of the Parallel Ocean Program (POP) model, carried out preliminary testing and spin-up, and started a companion historical simulation to the low-resolution suite. 4) We submitted and had published a paper (Doney et al., 2004) that reviews the present state of marine microbial genomics and outlines the synergy of the emerging molecular work with new ocean observing systems and numerical models.

RESULTS

<u>*The "Ocean Genome"*</u>. The application of new molecular and genomic techniques to the ocean is driving a scientific revolution in marine microbiology. Discoveries range from previously unknown groups of organisms and novel metabolic pathways to a deeper appreciation of the fundamental genetic and functional diversity of oceanic microbes. The "oceanic genotype" represents only the potential biological capacity and sets an upper constraint on possible pathways and ecosystem rates. The realized structure and functioning of marine ecosystems, the "oceanic phenotype", reflects the complex interactions of individuals and populations with their physical and chemical environment and with each other. A comprehensive exploitation of the wealth of new genomic data therefore requires a close synergy with interdisciplinary ocean research. Incorporating the information from environmental genomics, targeted process studies, and ocean observing systems (Figure 1) into numerical models will improve predictions of the ocean's response to environmental perturbations. Integrating information from genes, populations, and ecosystems is the next great challenge for oceanography.

(a) (b) (c)

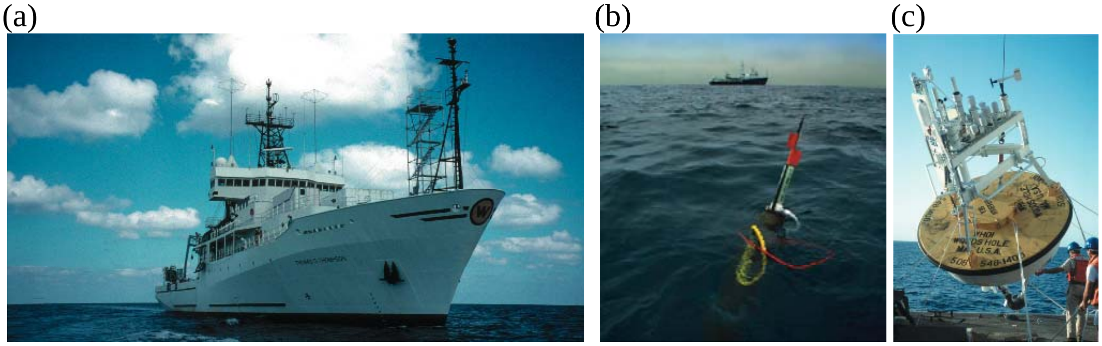

Figure 1. Elements of an interdisciplinary ocean observing system include: (a) commercial and research ship-based surveys and time series; (b) moorings and coastal and regional cabled networks (e.g. ORION http://www.orion.org); and (c) autonomous drifters, floats and gliders, and aircraft and satellite remote sensing.

<u>*Global Model Simulation.*</u> A global three-dimensional marine ecosystem model with several key phytoplankton functional groups, multiple limiting nutrients, explicit iron cycling, and a mineral ballast/organic matter parameterization is run within a global ocean circulation model. The coupled

biogeochemistry/ecosystem/circulation (BEC) model reproduces known basin-scale patterns of primary and export production, biogenic silica production, calcification, chlorophyll, macronutrient and dissolved iron concentrations. The model captures observed high nitrate, low chlorophyll (HNLC) conditions in the Southern Ocean, subarctic and equatorial Pacific (for figures, please see www.whoi.edu/science/MCG/doneylab/data/eco_ccsm_log.html). Spatial distributions of nitrogen fixation are in general agreement with field data, with total N-fixation of 55 Tg N. Diazotrophs directly account for a small fraction of primary production (0.5%) but indirectly support 10% of primary production and 8% of sinking particulate organic carbon (POC) export. Diatoms disproportionately contribute to export of POC out of surface waters, but CaCO3 from the coccolithophores is the key driver of POC flux to the deep ocean in the model. An iron source from shallow ocean sediments is found critical in preventing iron limitation in shelf regions, most notably in the Arctic Ocean, but has a relatively localized impact. In contrast, global-scale primary production, export production, and nitrogen fixation are all sensitive to variations in atmospheric mineral dust inputs. The residence time for dissolved iron in the upper ocean is estimated to be a few years to a decade. Most of the iron utilized by phytoplankton is from subsurface sources supplied by mixing, entrainment, and ocean circulation. However, owing to the short residence time of iron in the upper ocean, this subsurface iron pool is critically dependent on continual replenishment from atmospheric dust deposition and, to a lesser extent, lateral transport from shelf regions.

IMPACT AND APPLICATIONS

PARADIGM is 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 is being used to improve model formulation and to validate model performance. New approaches to software development are employed to simplify the addition of new ocean processes. Some models are capable of emergent behavior, testing the hypothesis that fundamental domain shifts occur in response to climate change.

PARADIGM improves 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 serves 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 enable the study of complex, global-scale processes in a rigorous open manner.

TRANSITIONS

To benefit from relationships outside our consortium, a fundamental objective will be *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). An important event that will begin to take shape this coming year (a special issue of Progress in Oceanography devoted to PARADIGM and PARADIGM-related research) demonstrate how seriously we take this objective. This responsibility will also include the distribution of forward model and data assimilation products, computational algorithms, etc. through workshops, summer schools, etc. For that, we have established a PARADIGM web site (http://www.gso.uri.edu/paradigm/).

PARADIGM PUBLICATIONS – YEAR 3

Cullen, J. J. “Observation and prediction of harmful algal blooms.” 2005. 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. and H W Ducklow, 2004. Food web structure and biogeochemical processes during phytoplankton blooms: An inverse model analysis. Deep-Sea Res II (submitted and in review).

Denman, K.L., 2003. Modelling planktonic ecosystems: parameterizing complexity, Progress in Oceanography, 57, 429-452.

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 Ecology Environ., 2, 457-466.

Dutkiewicz, S.W., M.J. Follows, and P. Parekh (2005) Interactions of the iron and phosphorus cycles: A modelling study. Submitted to *Global Biogeochem. Cycles.* (Revised version returned).

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. (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 (in revision)

Follows, M.J., S. Dutkiewicz, and T. Ito (2005) Solving the carbonate system in ocean biogeochemistry models. Submitted to *Ocean Modelling.* (Under revision).

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. (in press).

Lehmann, M.K., R.F. Davis, Y. Huot, and J.J. Cullen. 2004. Spectrally weighted transparency in models of water-column photosynthesis and its inhibition by ultraviolet radiation. Mar. Ecol. Prog. Ser. 269:101-110.

Monahan, A.H., and K.L. Denman, 2004. Impacts of atmospheric variability on a coupled upper ocean/ecosystem model of the subarctic Northeast Pacific , Global Biogeochemical Cycles, 18, GB2010, doi: 10.1029/2003GB002100.

SELECTED MEETING PRESENTATIONS

Cullen, J.J. Evolution of a real-time, physical-biological coastal observation and prediction system. Bedford Institute of Oceanography, Dartmouth, NS. November 2004. **(Invited)**

Cullen, J.J., C. Brown, R.F. Davis, M. Dowd, Y. Huot, S. Kirchhoff, M.K. Lehmann, C. Normandeau and C. Schallenberg. Optical proxies of biological properties for assimilation into models of ecosystem dynamics. Oral presentation, ASLO/TOS Ocean Research Conference, Honolulu, February, 2004.

Denman, K., Invited Plenary talk: "Modelling marine ecosystems: Why do we need models and where are we going?", American Geophysical Union, Ocean Sciences Meeting, Portland USA, January, 2004.

Denman, K., Invited Plenary talk: "Modelling the planktonic community response to iron fertilization", International SOLAS Open Science Conference, Halifax, Canada, October, 2004.

Huot, Y. C.A. Brown and J.J. Cullen. Variability in sun-induced chlorophyll fluorescence in surface waters: Physiology or biomass? Oral presentation, ASLO/TOS Ocean Research Conference, Honolulu, February, 2004.

Huot, Y. and J.J. Cullen. Observing regulation and acclimation using fluorescence: a model. Workshop: Modelling autotrophic growth. Villefranche sur Mer, March 24-26,2004.

Lehmann, M.K., A.M. Edwards, W. Gentleman, J.J. Cullen. 2004. Dynamics of a size-structured model of plankton ecosystems with fluctuating environmental forcing. Oral presentation, ASLO/TOS Ocean Research Conference, Honolulu, February, 2004.

Lavoie, D., K. Denman and C. Michel, Poster: "Modelling the biological CO_2 pump in seasonally ice covered regions of the Arctic Ocean", International SOLAS Open Science Conference, Halifax, Canada, October, 2004.

Voelker, C., and K. Denman, Contributed talk: "Modelling silicon dynamics at station P in the subarctic Pacific", ASLO-TOS Aquatic Sciences Meeting, Honolulu, February 2004.

Wiggert, J.D., A.G.E. Haskell, G.-A. Paffenhöfer, E.E. Hofmann, J.M. Klinck, Sustaining Copepod Populations Under Oligotrophy: The Role of Feeding Behavior, 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, Sustaining Copepod Populations Under Oligotrophy: The Role of Feeding Behavior, Advances in Marine Ecosystem Modeling 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. (Note: This manuscript will be submitted to the special issue of *Journal of Marine Systems* that is devoted to the proceedings of the Advances in Marine Ecosystem Modeling Research Symposium.)

Ph.D. THESIS COMPLETED

Huot, Y. Sun-induced fluorescence of phytoplankton in the ocean: linking physiology and remote sensing. Dalhousie University. December 2004.