Models: Tools for Synthesis in International Oceanographic Research Programs

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1. Introduction

Through its promotion of coordinated international research programs, the Intergovernmental Oceanographic Commission (IOC) has facilitated major progress in some of the most challenging problems faced by the field of oceanography. Issues of global significance-such as the general circulation, the carbon cycle, the response of marine ecosystems to climate, and harmful algal blooms—are so large in scope that they require international collaboration to be addressed in a systematic way. Such problems lend themselves not to a single approach, but an entire portfolio of research activities, including global surveys, regional process studies, time-series observations, laboratory-based investigations, and satellite remote sensing. Synthesis of this vast array of results presents its own set of challenges (Hofmann et al., this volume), and models offer an explicit framework for integration of the knowledge gained as well as detailed investigation of the underlying dynamics. Such models help us to understand not only what has happened in the past, but also make predictions of future changes—both aspects of which feed into development of sound policy and decision-making. Herein we review some examples of how models have been used for this suite of purposes, focusing on key areas where IOC coordination played a key role in organization and coordination of the research activities.

2. Ocean Circulation

The vision of ocean state estimation as a means of bringing all ocean observations into a dynamically consistent description of the global time-varying ocean circulation goes back as far as the beginnings of the World Ocean Circulation Experiment (WOCE) era (Munk and Wunsch, 1982). Achieving this vision required a significant development of *in situ* and satellite observing

capabilities, together with improvement of modern ocean models and enhanced computational capabilities. Important milestones in this development included the development of inverse methods (adjoint, Kalman filter, etc.) that can be applied to ocean circulation models using supercomputers. This development required coordinated international activities, to which IOC organizational efforts contributed a great deal (as did the World Climate Research Program (WCRP) and the Global Ocean Data Assimilation Experiment (GODAE)). This undertaking has proven to be a large endeavor that requires international coordination, long-term national financial commitments and the existence of expertise in ocean observations, modeling, and data assimilation, as well as infrastructure for information technology.

One example of a climate oriented, ocean synthesis effort is the Estimation the Circulation and Climate of the Ocean (ECCO, Stammer et al., 2002) effort that began in 1999 with funding provided through the US National Ocean Partnership Program, building on prior work accomplished during the WOCE era. Close to a decade of sustained consortium effort was necessary to develop the ECCO ocean model environment, which encompassed modern primitive equation (PE) models (e.g., the MITgcm: Marshall et al., 1997), the development of adjoint model compilers (Giering and Kaminski, 1998), and their pilot applications to ocean problems (Marotzke et al., 1999). Results of ECCO are especially useful for describing the ocean's transports of heat and freshwater, for estimating unobserved quantities such as the meridional overturning circulation, and for constraining surface fluxes. ECCO is currently oriented toward physical variables, but in principle may encompass many other substances, including CO₂, nutrients, and oxygen. The role of ocean state estimates for providing best possible present-day initial conditions for climate prediction systems is now gaining increasing attention. We can anticipate that 10 years from now, ocean state estimation will be an integral component of an ocean and climate information system for ocean and climate analyses and forecasts.

A quantity of specific concern is sea level and its low-frequency variability, which represents an integral over many individual aspects of the ocean state. Changes in sea level potentially can have a substantial impact on society and understanding ongoing and past changes and their regional character is therefore of considerable interest. ECCO state estimates facilitate explicit distinction between thermosteric and halosteric effects on changes in sea level (Figure 1, left column). Over large parts of the world ocean, ECCO results suggest that observed SSH changes are induced by steric changes in sea level. Changes in heat content and salinity counterbalance each other to some extent, as expected from either advection of water masses along isopycnals (e.g., changes in wind forcing) and/or via the temperature/salinity relationship implicit in the model. Correspondence of the simulated and observed trends during the recent era of sustained altimetric observations (Figure 1, right column) lends credibility to these modelderived diagnostics. Moreover, this demonstration of skill provides confidence in the model's validity for hindcasting and forecasting beyond the data-rich time period (Köhl and Stammer, 2008; Wunsch et al., 2007).

Through the international efforts of IOC/GODAE and WCRP, several global ocean data assimilation products are available for use in climate and ocean services applications. Underlying assimilation schemes range from simple and computationally efficient (e.g., optimal interpolation) to sophisticated and computationally intensive (e.g., adjoint, Kalman filters, and smoothers). Some of the existing assimilation products span the past several decades; others focus on the data-rich period, roughly from 1992 to present. Ongoing applications of those systems include many aspects of operational oceanography and climate research such as sea

level variability and changes (e.g., Carton et al., 2008), water-mass analysis (e.g., Fukumori et al., 2004), and mixed-layer heat balance (e.g., Halkides and Lee, 2009).

An example hindcast performed under the auspices of CLIVAR (Stammer et al., 2010) is shown in Figure 2. Estimates of the heat content of the global ocean suggest an overall increase in the ocean's heat content in the top 700 m during the last 50 years. The increase is clearly not monotonic or smooth—it shows significant variations on a wide range of time scales. As expected, steric anomalies reflect the changes in heat and salt/freshwater content depicted in Figure 1.

Clearly, this intercomparison reveals a large spread in some of the results from ocean syntheses. This spread is due to differences in approaches and the underlying data sets utilized in each case. We note that the spread increases toward the end of the data record characterized by the largest number of observations, suggesting that the syntheses are evolving further from a common state. An optimistic expectation would be that the states for the latter period are more randomly distributed around the truth, and ensemble means are less prone to model bias.

Dynamically self-consistent assimilation approaches can to some degree correct for biases in observations. For example, the increase in heat content during the 1970s has been attributed to systematic errors in XBT data during the time period in which such measurements entered widespread use. Most assimilation results are constrained strongly by those erroneous data. Only the dynamically consistent ECCO results rejected those errors in the observations, thereby yielding heat content estimates consistent with corrected XBT data (Figure 2, left hand panel; see Domingues et al., 2008).

Much needs to be done over the coming decades to improve these ocean state estimates and to characterize their uncertainties. Merging these products in a weighted ensemble mean

will yield better estimates and reduced uncertainties. Future progress will be facilitated by concerted comparison efforts based on assimilation experiments with same data, period, etc., in order to clearly distinguish differences in controls, analyses, and innovations. Such advances will provide an improved scientific basis for ocean state estimation and all of its relevant applications.

3. Carbon Cycle

The ocean plays a pivotal role in the global biogeochemical cycles of carbon, nitrogen, phosphorus, silicon and a host of other biologically active elements such as iron and other trace metals. Ocean carbon dynamics is particularly relevant to current discussions of rising atmospheric carbon dioxide (CO₂) and climate change. Well-tested numerical models are needed to quantify the historical uptake of anthropogenic CO₂ by the ocean and to assess future changes of marine biogeochemistry and carbon storage under a warmer, high-CO₂ world. The development of ocean biogeochemical models is synergistic with laboratory studies and ocean field observations at many levels: experiments and process studies provide the conceptual framework for identifying the key processes that need to be considered in model formulation and in estimating parameter values; process-studies, time-series and survey data provide essential constraints on model dynamics and for evaluating overall performance; models offer a test-bed for exploring hypothesis, quantifying processes that are difficult to observe directly, extrapolating to larger space-scales and longer time-scales, and designing new observation systems.

The field of ocean biogeochemical modeling benefitted greatly from the initiation, in the late 1980s, of the field components of the international Joint Global Ocean Flux Study (JGOFS)

(Fasham et al., 2001). Modeling has also been integral in the rationale for and implementation of subsequent international research programs such as the Surface Ocean Lower Atmosphere Study (SOLAS), the Integrated Marine Biogeochemistry and Ecosystem Research (IMBER), and the CLIVAR/CO2 Repeat Hydrography Program. The IOC has contributed greatly to ocean biogeochemical research through the International Ocean Carbon Coordination Project (IOCCP), which has fostered better integration of sampling programs, data compilation and data synthesis on topics such as temporal changes in ocean carbon inventories and the spatial patterns and variability of surface ocean pCO₂ and air-sea CO₂ flux (Doney et al., 2009), and the coordination of biogeochemical modeling has been led through JGOFS, the Global Analysis, Intercomparison, and Modeling (GAIM) task force, and the Global Carbon Project (GCP). Similar efforts have occurred at the national and multi-national level through programs such as the U.S. JGOFS Synthesis and Modeling Project (Doney and Ducklow, 2006) and the European Union CARBOCEAN Project.

The Ocean Carbon-cycle Model Intercomparison Project (OCMIP) was pivotal in advancing global-scale ocean biogeochemical modeling. Phase 2 of OCMIP brought together about a dozen international modeling groups to conduct a standard suite of ocean simulations for transient tracers, inorganic carbon system variables, and biogeochemical fields. Model results were compared systematically against field data from the WOCE/JGOFS Global CO₂ Survey. OCMIP depended especially on synthesis products created by the GLobal Ocean Data Analysis Project (GLODAP) (Key et al., 2004). OCMIP-2 established a baseline for assessing ocean carbon model skill and in particular identified observation-based tracer metrics (e.g., chlorofluorocarbons and radiocarbon) for evaluating and choosing among different model

estimates of ocean uptake of anthropogenic CO_2 (Matsumoto et al., 2004). Major products from the project included future projections of oceanic anthropogenic CO_2 uptake and the resulting ocean acidification for the 21st century (Orr et al., 2005). Follow-on studies have utilized OCMIP results and new model variants to track horizontal transport and air-sea exchange of natural and anthropogenic CO_2 (Gruber et al., 2009). Analysis of interannual variability and secular trends in net ocean carbon storage suggest the efficiency of ocean removal of anthropogenic CO_2 may be declining with time (Le Quéré et al., 2009).

The OCMIP Phase-2 models used relatively crude representations of ocean biology (Najjar et al., 2007), and parallel research was underway to improve model treatment of primary and new production, phytoplankton-zooplankton dynamics, export flux, and particle sinking and remineralization. The JGOFS process studies and time-series records have been essential in this regard, as has the advent of routine global satellite ocean color observations, beginning with Seaviewing Wide Field-of-view Sensor (SeaWiFS) in 1997. A key technical advance has involved the application of inverse models and data assimilation techniques to marine food-web data. The Regional Test-Bed Project (Friedrichs et al., 2007), for example, created a uniform interface for optimizing parameters for 1-D ecosystem models using time-series observations. By systematic comparison of optimized model results from multiple ecosystem model structures for several sites, Friedrichs et al. (2007) determined that models with multiple phytoplankton groups are more portable across different biogeographic regimes. Simulated plankton species are often aggregated into functional groups distinguished by size class, production of calcified or siliceous shells, and ability to carry out specific biogeochemical processes such as nitrogen fixation or dimethylsulfide production (Hood et al., 2006a).

The newest generation, 3-D ocean biogeochemical models typically incorporate phytoplankton functional groups, multiple limiting nutrients, flexible elemental composition, and iron limitation (e.g., Moore et al., 2004; Le Quéré et al. 2005). Other significant developments involve the application high-resolution, mesoscale eddy simulations for regional coastal domains (Gruber et al., 2006) and ocean basins (Oschlies, 2002; McGillicuddy et al., 2003; Figure 3). For an individual investigator, the task of developing and evaluating these ever more complex simulations is daunting, and international collaborations have sprung-up to facilitate model-data evaluation and speed the model design cycle, an approach encapsulated in the Dynamic Green Ocean Project² and the follow-on MARine Ecosystem Model Intercomparison Project³ (MAREMIP). Such models have great utility for analyzing the seasonal dynamics and interannual variability of ocean biology and chemistry as quantified with the growing capability of ocean observing systems. More sophisticated coupled marine-ecosystem-biogeochemistry models also are increasingly used in future climate and carbon cycle projections to characterize the ocean impacts due to anthropogenic climate change (Sarmiento et al. 2004; Steinacher et al., in press) and possible feedbacks via changes in the air-sea flux of CO₂ and other radiativelyactive trace gases (Friedlingstein et al., 2006).

4. Ecosystem Dynamics

Our ability to model marine ecosystems has advanced substantially in recent years. Some of this progress is the result of technical developments in modeling and computer capabilities, but the most significant impact has been through the numerous interdisciplinary programs that have stimulated ecosystem studies (Barange et al., 2010). In that context, the Global Ecosystem

² <u>http://lgmacweb.env.uea.ac.uk/green_ocean/model/model.shtml</u>

³ <u>http://lgmacweb.env.uea.ac.uk/maremip/index.shtml</u>

Dynamics Program (GLOBEC) has played a central role. GLOBEC was initiated in 1991 by SCOR and the IOC of UNESCO "to understand how global change will affect the abundance, diversity and productivity of marine populations comprising a major component of oceanic ecosystems"⁴.

Three key characteristics have supported the expansion of ecosystem modeling: (i) development of advanced, realistic and computationally achievable hydrodynamic models that describe the circulation fields at the scales needed (ii) coupling of hydrodynamic and biological models and (iii) enhanced complexity and realism of the biological models, building upon laboratory and field studies. It is not simply the quality and realism of the physical modeling that has influenced ecosystem models, it is also the availability of these models through various user-group and public domain initiatives such as that for ROMS⁵, POM⁶, GOTM⁷, ADCIRC⁸, and FVCOM⁹ among others.

The challenge of understanding how organisms disperse in the oceans was first identified by Hjort (1914) almost a century ago in his studies of North Sea fish populations. Most marine organisms undergo a planktonic stage in their life cycles, i.e., they are at the mercy of the circulation field for weeks to months, making quantitative understanding of transport and dispersal an essential component in the study of marine ecosystems. Modeling the Lagrangian character of the flow began with the exploration of the dispersal of particles, i.e., planktonic stages of organisms, by the velocity field through the use of Individual Based Models (IBMs). Early successes establishing the capability of IBMs were demonstrated by modeling the transport

⁴ <u>http://www.globec.org/</u>

⁵ <u>http://www.myroms.org</u>

⁶ http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom

⁷ <u>http://www.gotm.net</u>

⁸ <u>http://www.unc.edu/ims/adcirc/</u>

⁹ http://fvcom.smast.umassd.edu/FVCOM/index.html

of herring (*Clupea harengus*) larvae in the North Sea (Bartsch et al., 1989), cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) larval retention on Georges Bank (Werner et al., 1993), and the movement of anchovy larvae from their spawning sites to nursery areas in the Benguela Current System (Mullon et al., 2003).

While accurate simulations remain a challenge for hydrodynamic models at certain space- and time-scales (Werner et al., 2007), perhaps a greater challenge is the proper representation of behavior. For example, coupled modeling of copepod life history and upwelling dynamics on the Oregon shelf (Batchelder et al., 2002) has revealed how diel vertical migration influences the distribution of copepods across the Shelf (Figure 4). This model explicitly includes vital rates (behavior, growth, reproduction and mortality) so that the life history of the drifting copepod could be tracked through space and time. In the absence of vertical migration, the copepods are much more concentrated in the surface waters, and relatively few large copepods are found at depth on the outer shelf. Coupled biophysical models have been crucial for disentangling the complex dynamics of upwelling systems such as those found off the west coast of southern Africa (Parada et al., 2008). In particular, transport of spawning products to the Agulhas Bank from the spawning grounds is influenced by the strength of the coastal current, upwelling dynamics, and the details of the spawning process itself. Coupled modeling has been used by Mullon et al. (2002) to explore the evolutionary implications of spawning in the Benguela upwelling system.

Integrating across multiple trophic levels and large spatial scales remains one of the challenges for ecosystem dynamics modeling (deYoung et al., 2004). Advances in this area were achieved by researchers working together on the North Pacific (Kishi et al., 2007). They developed a biomass-based model built on a multi-compartment lower trophic level marine

model coupled to a bioenergetic model for two different fish – Pacific saury (*Cololabis saira*) and herring (*Clupea pallasii*) (Rose et al., 2008). Another group (Lehodey et al., 2003), working on Pacific skipjack tuna (*Katsuwonus pelmais*), successfully combined coupled lower and upper level trophic modeling, coupling a prey model for tuna with a biogeochemical model (Chai et al. 2003) embedded within a three-dimensional ocean circulation model.

Population connectivity is the exchange of individuals among geographically separated subpopulations that comprise a metapopulation (Cowen et al., 2007). This topic has become one of the central paradigms for population studies and one of the goals of ecosystem modeling. Physical circulation modeling on ecologically-relevant space and time scales has now moved beyond the continental shelf to the open ocean, enabling and stimulating ecosystem studies at the basin scale (deYoung et al., 2004). The previously mentioned work on tuna in the North Pacific is one example. Another is the work of Speirs et al. (2006) on the copepod *Calanus finmarchicus* in the North Atlantic. Using a model that integrated observational data, biological and physical models structures, Speirs et al. were able to explore the basin-scale connectedness of *Calanus*. They demonstrated the high-level of connectivity over the North Atlantic, showed the dependence of mortality on temperature, and explored different hypotheses underlying the organism's resting state, diapause. Such modeling work has influenced our understanding of the coupling between the shelf and the deep ocean and has shifted our perspective on shelf and open ocean ecosystem dynamics.

Integration of observations and models has advanced our understanding of marine ecosystems, population dynamics, and the connectivity, dispersal and mixing of populations. Models have contributed to the explanation of variability in fisheries, and have led to changes in approaches to fisheries management (Fogarty and Botsford, 2007). The results of the ecological

modeling and genetic studies (Cowen et al., 2007) have shifted our perspective on marine population connectivity suggesting that larval retention near local populations may be more important for maintaining population structure and persistence than was previously believed. The earlier paradigm was that marine populations were quite 'open' and that larvae were plentiful and widely dispersed (Caley et al., 1996). Models linking dispersal and connectivity in systems such as coral reefs have shown the importance of closed population structures at smaller spatial scales (Cowen et al., 2000). These population and dispersal models will prove important for the consideration and design of marine protected areas, which have been suggested as an approach to improve fisheries by enhancing the rebuilding of over-harvested stocks, protecting essential fish habitat and reducing the risk of stock collapses (Gell and Roberts, 2003).

5. Harmful Algal Blooms

Harmful algal blooms (HABs) are those proliferations of algae that can cause fish and shellfish kills, produce toxins harmful to human health, and develop biomass accumulations that can alter ecosystems in other deleterious ways. It is now recognized that HAB events are growing in frequency, extent, and duration throughout the world (e.g., Anderson et al., 2002; Glibert et al., 2005; Heisler et al. 2008). Responding to the urgent need for scientific information on this topic, IOC and SCOR facilitated the development of the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) program in 1998. The goal of GEOHAB is to "foster international co-operative research on HABs in ecosystem types sharing common features, comparing the key species involved and the oceanographic processes that influence their population dynamics."¹⁰

¹⁰ <u>http://www.geohab.info/</u>

HABs produce a wide range of toxins which may accumulate in predators and organisms higher in the food web, ultimately affecting humans when seafood is consumed, when toxinladen aerosols are inhaled, or when contaminated water is consumed. Evidence is also mounting that both direct and indirect or subtle ecosystem effects are also being expressed in response to HABs by fish and wildlife. The direct and indirect effects of these events on human health and ecosystem function are all of concern, and forecasts and predictions are needed to understand when and how they may occur or how such patterns may change in the future. To address these needs, the HAB modeling community is engaging internationally with climate scientists, marine ecologists, invasive species experts, watershed modelers and hydrologists, social scientists, economists, managers and policy makers (Glibert et al., 2010). Herein we provide some examples, focusing on HABs associated with eutrophication. An overview of other types of HABs is provided by Anderson et al. (this volume).

While there are many reasons that contribute to the global spread of HAB events, there is a growing appreciation that eutrophication is one of the major reasons why such blooms are now being found with increasing frequency (Anderson et al., 2002; Glibert et al., 2005; Glibert and Burkholder, 2006). In order to relate HABs to nutrient loading— and thus to establish the extent to which eutrophication may be a contributing factor— models of nutrient export are required. Nutrient loads, which reflect a rate of delivery of nutrients from water- and air-sheds, cannot be estimated from nutrient *concentration* data alone: the nutrient *flux* is needed. There are many types of models that are in use for estimating the rate of nutrient loading from land to coastal waters. However, at global scales there are very real challenges: for many regions of the world, data on nutrient export and loading are either not available or not easy to obtain. Dispersal of nutrients and the interaction with the receiving waters are also difficult to quantify.

Spatially explicit models are helping to advance our understanding of nutrient loads. One such effort is the Global Nutrient Export from Watersheds (NEWS) program, an activity fostered directly by IOC. The NEWS system of models is used to estimate magnitude and sources of different elements (C, N, and P) and different forms (particulate, dissolved inorganic and organic). This suite of models, based on data from more than 5,000 exoreic basins, includes natural processes such as N₂ fixation and P weathering, as well as anthropogenic sources (Figure 5; also see Dumont et al., 2005, Seitzinger et al., 2005). The models also account for hydrological factors including water runoff, precipitation intensity, land use and slope, as well as in-water removal processes such as dams and reservoirs and consumptive water use. These models have been compared with the distribution of several HAB species. For example, the models have shown how the HAB dinoflagellate *Prorocentrum minimum* is associated with regions of high dissolved inorganic nitrogen (DIN) and phosphorus (DIP) exports that are strongly influenced by anthropogenic sources (Figure 6).

Different types of algae respond differently to nutrient loads and/or variations in the relative proportion of various nutrients. To capture these differences, models require physiological or process-oriented details. Process-oriented models contain explicit descriptions of biochemical processes, such as the rate of nutrient uptake, but many such processes are poorly characterized under different growth conditions (Glibert and Burkholder, 2006). For most HABs, quantitative data on the full range of nutritional pathways are lacking. A few models are beginning to incorporate the breadth of nutritional flexibility observed for many HABs – that is, the ability to use complex organic nutrient or to eat other cells (e.g., Hood et al., 2006b). Some process models are based on a single nutrient, such as N, although multi-element models provide

a more complete approach, as many HABs occur in nutrient regimes for which the major nutrients are not in stoichiometric balance.

Blooms associated with eutrophication result not only from the availability of sufficient nutrients, but also from a combination of physical, chemical and biological mechanisms and their interactions with other components of the food web. Many of these processes and interactions are not well understood, thus making it challenging to capture these interactions accurately in a model. Organism behavior also needs to be captured in models that attempt to explain why one species – a HAB – may bloom when another does not. Some behaviors, such as swimming for mating, diel vertical migration, or formation of temporary or long-term cyst stages may be associated with nutritional triggers but have not been well characterized in eutrophic systems. In this context, it is also important to understand why micro- or macrozooplankton fail to control the phytoplankton population when blooms develop (Irigoien et al., 2005). Understanding top-down control is as important as understanding factors relieving bottom-up control for HAB development (Stoecker et al., 2008).

The time scales of HAB forecasts range from short- (days to seasons) to long-term (years to decades). Both types of forecasts provide a bridge between research and management, linking research on HAB causes and impacts to applications that can lead to improved management outcomes. Short-term predictions provide advance warnings that can alert local, state and federal agencies and individuals to prepare for and respond to HABs in a timely fashion, as well as provide a means to assess the effectiveness of alternative management strategies on HAB prevention. HAB forecast systems in the U.S. are in various phases of development (Stumpf, 2008). One for *Karenia brevis* in the Eastern Gulf of Mexico is in operational status¹¹. The

¹¹ <u>http://www.csc.noaa.gov/crs/habf/</u>

HAB prediction system in the Chesapeake Bay¹² uses or will use real-time and forecast data acquired and derived from a variety of sources to drive multi-variate, habitat suitability models of HAB species, such as *Karlodinium veneficum* and *Prorocentrum minimum*, in order to generate daily nowcasts and 3-day forecasts of their relative abundance and bloom probability.

Longer-term projections offer a tool to evaluate the response of HABs to proposed management and land-use/land-change policies and climate change. Projecting the long-term effects of nutrient loading on HABs will enable management actions to reduce loads and minimize HABs, leading to multiple benefits, such as planning for restoration and aquaculture facilities, the reduction in drinking water contamination, and a reduction in monitoring burden on state and local agencies. There is an ongoing quest for better models of nutrient loading, transport and mixing. Present models are adequate for many applications, but our needs are for higher resolution nutrient loading models and hydrodynamic models and for better coupling between the two. On multi-year scales, there is much to be learned from the interactions of nutrient loading and other environmental factors, such as changes in temperature and precipitation that may occur due to regime shifts and/or climate change (Najjar et al., 2000; Howarth, 2008). Ultimately, forecast models must be robust but also simple enough to be operational and affordable to managers. Ensembles of models and integrated ecosystem models that couple the atmosphere, land, and coastal ocean are required to investigate ecosystem response to climate change and to further explore the changes in HABs that are to be expected in the future as eutrophication impacts increase.

¹² http://155.206.18.162/cbay_hab/index.php

6. Conclusions

With our growing dependence on the ocean for natural resources, transportation, and recreation, society's need to know about the ocean continues to increase. As such, expanding international cooperation will be required to integrate the data from sophisticated observing networks emerging throughout the global ocean. The need to address longer time-scales, larger spatial-scales and more interdisciplinary questions will require more diverse multi-national teams of investigators both to develop and to implement future models. Such models will continue to serve as focal points for synthesis of observations into useful estimates of the physical, biological, and chemical state of the ocean, as well as predictions about the future. Societal need for the latter is becoming ever more pressing as we face the challenges inherent in a changing climate. To meet that need, continued IOC leadership and international coordination is critical.

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References

Anderson, D.A. and others. This Volume.

Anderson, D.A., P.M. Glibert, and J.M. Burkholder. 2002. Harmful algal blooms and eutrophication: Nutrient sources, composition, and consequences. *Estuaries* 25: 562-584.

Barange, M., J.G. Field, R.H. Harris, E. Hofmann, R.I. Perry, and F.E. Werner, eds. 2010. *Global Change and Marine Ecosystems*. Oxford University Press, City, in press.

Bartsch, J., K. Brander, M. Heath, P. Munk, K. Richardson, and E. Svendsen, 1989. Modelling the advection of herring larvae in the North Sea. *Nature* 340:632-636.

Batchelder, H.P., C.A. Edwards and T.M. Powell. 2002. Individual-based models of copepod populations in coastal upwelling regions: implications of physiologically and environmental influenced diel vertical migration on demographic success and nearshore retention. *Progress in Oceanography* 53:307-333

Caley, M.J., M.H. Carr, M.A. Hixon, T.P. Hughes, G.P. Jones, and B.A. Menge. 1996. Recruitment and the local dynamics of open marine populations. *Annual Review of Ecology and Systematics* 27:477-500.

Carton, J.A. and B.S. Giese. 2008. A reanalysis of ocean climate using Simple Ocean Data Assimilation (SODA). *Monthly Weather Review* 136:2999-3017.

Chai, F., M. Jiang, R.T. Barber, R.C. Dugdale, and Y. Chao. 2003. Interdecadal variation of the transition zone chlorophyll front, a physical-biological model simulation between 1960 and 1990. *Journal of Oceanography* 59:461-75.

Cowen, R.K., K.M.M. Lwiza, S. Sponaugle, C.B. Paris, and D.B. Olson 2000. Connectivity of marine populations: Open or closed? *Science* 287:857–859.

Cowen, R.K., S. Thorrold, J. Pineda, G. Gawarkiewicz, and F. Werner. 2007. Population connectivity in marine systems: an overview. *Oceanography* 20(3):16-23.

deYoung, B., M. Heath, F. Werner, F. Chai, B. Megrey, and P. Monfray. 2004. Challenges of modeling ocean basin ecosystems. *Science* 304:1463-1466.

Domingues, C.M., J.A. Church, N.J. White, P.J. Gleckler, S.E Wijffels, P.M. Barker, and J.R. Dunn. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. *Nature* 453:1090–1093.

Doney, S.C. and H.W. Ducklow. 2006. A decade of synthesis and modeling in the U.S. Joint Global Ocean Flux Study. *Deep-Sea Research II* 53(5-7):451-458.

Doney, S.C., B. Tilbrook, S. Roy, N. Metzl, C. Le Quéré, M. Hood, R.A. Feely, and D. Bakker. 2009. Surface ocean CO₂ variability and vulnerability. *Deep-Sea Research II* 56:504-511.

Dumont, E., J.H. Harrison, C. Kroeze, E.J. Bakker, and S.P. Seitzinger. 2005. Global distribution and sources of dissolved inorganic nitrogen export to the coastal zone: Results from a spatially explicit, global model. *Global Biogeochemical Cycles* 19(4): doi:10.1029/2005GB002488, 1-14.

Fasham, M.J.R., B.M. Balino, M.C. Bowles, R. Anderson, D. Archer, U. Bathmann, P. Boyd,K. Buesseler, P. Burkill, A. Bychkov, and others. 2001. A new vision of oceanbiogeochemistry after a decade of the Joint Global Ocean Flux Study (JGOFS). *AMBIO*,*Special Issue* 10:4-31.

Fogarty, M.J., and L.W. Botsford. 2007. Population connectivity and spatial management of marine fisheries. *Oceanography* 20(3):112-123.

Friedlingstein, P., P. Cox, R. Betts, L. Bopp, W. von Bloh, V. Brovkin, P. Cadule, S. Doney, M. Eby, I. Fung, and others. 2006. Climate–carbon cycle feedback analysis: Results from the C^4 MIP model intercomparison. *Journal of Climate* 19(14):3337-3353.

Friedrichs, M.A.M., J.A. Dusenberry, L.A. Anderson, R. Armstrong, F. Chai, J.R. Christian, S.C. Doney, J. Dunne, M. Fujii, R. Hood, and others. 2007. Assessment of skill and portability in regional marine biogeochemical models: The role of multiple planktonic groups. *Journal of Geophysical Research- Oceans*. 112(C08001):doi:10.1029/2006JC003852.

Fukumori, I., T. Lee, B. Cheng, and D. Menemenlis. 2004. The origin, pathway, and destination of NINO3 water estimated by a simulated passive tracer and its adjoint. *Journal of Physical Oceanography* 34:582-604.

Gell, F.R. and C.M. Roberts. 2003. Benefits beyond boundaries: the fishery effects of marine reserves. *Trends in Ecology and Evolution* 18:448-55

Giering, R. and T. Kaminski. 1998. Recipes for adjoint code construction. *ACM Transactions* on *Mathmatical Software* 24:437-474.

Glibert, P.M., S. Seitzinger, C.A. Heil, J.M. Burkholder, M.W. Parrow, L.A. Codispoti, and V. Kelly. 2005. The role of eutrophication in the global proliferation of harmful algal blooms: New perspectives and new approaches. *Oceanography* 18(2): 198-209.

Glibert, P.M. and J.M. Burkholder. 2006. The complex relationships between increasing fertilization of the earth, coastal eutrophication and proliferation of harmful algal blooms. Pp. 341-354 in *Ecology of Harmful Algae*. E. Graneli and J. Turner, eds, Springer, Netherlands.

Glibert, P.M., E. Mayorga, and S. Seitzinger. 2008. Prorocentrum minimum tracks anthropogenic nitrogen and phosphorus inputs on a global basis: Application of spatially explicit nutrient export models. *Harmful Algae* 8(10):33-38

Glibert, P.M., J.I. Allen, L. Bouwman, C. Brown, K.J. Flynn, A. Lewitus, and C. Madden. In press. Modeling of HABs and eutrophication: Status, advances, challenges. *Journal of Marine Systems*.

Gruber, N., H. Frenzel, S.C. Doney, P. Marchesiello, J.C. McWilliams, J.R. Moisan, J.J. Oram, G.-K. Plattner, and K.D. Stolzenbach. 2006. Eddy-resolving simulation of plankton ecosystem dynamics in the California current system. *Deep-Sea Research I* 53(1483-1516):doi:10.1016/j.dsr.2006.06.005.

Gruber, N., M. Gloor, S.E. Mikaloff, S.C. Fletcher, S. Doney, S. Dutkiewicz, M.J. Follows, M. Gerber, A.R. Jacobson, F. Joos, and others. 2009. Oceanic sources, sinks, and transport of atmospheric CO₂. *Global Biogeochemical Cycles* 23(GB1005):doi:10.1029/2008GB003349.

Halkides, D., and T. Lee. 2009. Mechanisms controlling seasonal-to-interannual mixed-layer temperature variability in the southeastern tropical Indian Ocean. Journal *of Geophysical Research* 114.

Heisler, J., P.M. Glibert, J.M. Burkholder, D.M. Anderson, W. Cochlan, W.C. Dennison, Q. Dortch, C.J. Gobler, C.A. Heil, E. Humphries, and others. 2008. Eutrophication and harmful algal blooms: A scientific consensus. *Harmful Algae* 8:3-13.

Hjort, J. 1914. Fluctuations in the great fisheries of northern Europe. *Rapports et Procès-Verbaux des Réunions du Conseil International pour l'Exploration de la Mer* 20:1-228.

Hood, R.R., E.A. Laws, R.A. Armstrong, N.R. Bates, C.W. Brown, C.A. Carlson, F. Chai, S.C. Doney, P.G. Falkowski, R.A. Feely, and others. 2006a. Pelagic functional group modeling: Progress, challenges and prospects. *Deep-Sea Research II* 53(5-7):459-512.

Hood, R.R., X. Zhang, P.M. Glibert, M.R. Roman and D. Stoecker. 2006b. Modeling the influence of nutrients, turbulence and grazing on *Pfiesteria* dynamics. *Harmful Algae* 5: 459-479.

Hofmann et al., this volume.

Howarth, R.W. 2008. Coastal nitrogen pollution: A review of sources and trends globally and regionally. *Harmful Algae* 8:14-20.

Irigoien, X., K.J. Flynn, and R.P. Harris. 2005. Phytoplankton blooms: A 'loophole' in microzooplankton grazing impact? *Journal of Plankton Research* 27:313-321.

Key, R.M., Kozyr, A., Sabine, C.L., Lee, K., Wanninkhof, R., Bullister, J., Feely, R.A., Millero, F., Mordy, C., Peng. T.-H., 2004. A global ocean carbon climatology: Results from GLODAP. *Global Biogeochemical Cycles*, 18, GB4031.

Kishi, M. J., M. Kashiwai, D.M. Ware, B.A. Megrey, D. L. Eslinger, F.E. Werner, M.N. Aita, T. Azumaya, M. Fujii, S. Hashimoto, and others. 2007. NEMURO - A lower trophic level model for the North Pacific marine ecosystem. *Ecological Modelling* 202(1-2):12-25.

Köhl, A. and D. Stammer. 2008. Variability of the meridional overturning in the North Atlantic from 50-year GECCO state estimation. *Journal of Physical Oceanography* 38:1913-1930.

Lehodey P., F. Chai, and J. Hampton. 2003. Modelling climate-related variability of tuna populations from a coupled ocean-biogeochemical-populations dynamics model. *Fisheries Oceanography* 12:483-494

Le Quéré, C., S.P. Harrison, I.C. Prentice, E.T. Buitenhuis, O. Aumont, L. Bopp, H. Claustre, L.C. Da Cunha, R. Geider, X. Giraud, and others. 2005. Ecosystem dynamics based on plankton functional types for global ocean biogeochemistry models. *Global Change Biology* 11:2016-2040.

Le Quéré, C., M.R. Raupach, J.G. Canadell, G. Marland, L. Bopp, P. Ciais, T.J. Conway, S.C. Doney, R.A. Feely, P. Foster, and others. 2009. Trends in the sources and sinks carbon dioxide. *Nature Geoscience* 2(831-836):doi:10.1038/ngeo689.

Marotzke, J., R. Giering, Q.K. Zhang, D. Stammer, C.N. Hill, and T. Lee. 1999. Construction of the adjoint MIT ocean general circulation model and application to Atlantic heat transport sensitivity. *Journal of Geophysical Research* 104:29,529-29,548.

Marshall, J., A. Adcroft, C. Hill, L. Perelman, and C. Heisey. 1997. A finite-volume, incompressible Navier-Stokes model for studies of the ocean on parallel computers. *Journal of Geophysical Research* 102:5753-5766.

Matsumoto, K., J.L. Sarmiento, R.M. Key, J.L. Bullister, K. Caldeira, J.M. Campin, S.C. Doney, H. Drange, J.C. Dutay, M. Follows, and others. 2004. Evaluation of ocean carbon cycle models with data-based metrics. *Geophysical Research Letters* 31(L07303):doi:10.1029/2003GL018970.

McGillicuddy, D.J., Anderson, L.A., Doney, S.C., and M.E. Maltrud, 2003. Eddy-driven sources and sinks of nutrients in the upper ocean: results from a 0.1 degree resolution model of the North Atlantic. *Global Biogeochemical Cycles* 17(2): 1035, doi:10.1029/2002GB001987.

Moore, J.K., S.C. Doney, and K. Lindsay. 2004. Upper ocean ecosystem dynamics and iron cycling in a global 3-D model. *Global Biogeochemical Cycles* 18(GB4028): doi:10.1029/2004GB002220.

Mullon, C., P. Cury, and P. Penven. 2002. Evolutionary individual-based model for the recruitment of anchovy (*Engraulis capensis*) in the southern Benguela. *Canadian Journal of Fisheries and Aquatic Science* 59:910–922.

Mullon, C., P. Fréon, C. Parada, C. van der Lingen, and J. Huggett. 2003. From particles to individuals: modeling the early stages of anchovy in the Southern Benguela. *Fisheries Oceanography* 12(4):396-406.

Munk, W., and C. Wunsch. 1982. Observing the ocean in the 1990s. *Philosophical Transactions of the Royal Society London* A307:439-464.

Najjar R.G., H.A.Walker, P.J. Anderson, E.J. Barron, R.J. Bord, J.R.Gibson, V.S. Kennedy, C.G. Knight, J.P. Megonigal, R.E. O'Connor, and others. 2000. The potential impacts of climate change on the mid-Atlantic coastal region. *Climate Research* 14:219–233.

Najjar, R.G., X. Jin, F. Louanchi, O. Aumont, K. Caldeira, S.C. Doney, J.C. Dutay, M. Follows, N. Gruber, F. Joos, and others. 2007. Impact of circulation on export production, dissolved organic matter and dissolved oxygen in the ocean: Results from phase II of the Ocean Carbon-cycle Model Intercomparison Project (OCMIP-2). *Global Biogeochemical Cycles*. 21(GB3007):doi:10.1029/2006GB002857.

Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, and others. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on marine calcifying organisms. *Nature* 437(681-686):doi:10.1038/nature04095.

Oschlies, A. 2002. Can eddies make ocean deserts bloom? *Global Biogeochemical Cycles* 16(4): 1106, doi:10.1029/2001GB001830.

Parada, C., Mullon, C., Roy, C., Freon, P., Hutchings, L., and C. van der Lingen. 2008. Does vertical migratory behaviour retain fish larvae inshore in upwelling ecosystems? A modeling study of anchovy in the southern Benguela. *African Journal of Marine Science* 18(3):437-452.

Rose, K.A., B.A. Megrey, D. Hay, F. Werner, and J. Schweigert. 2008. Climate regime effects on Pacific herring growth using coupled nutrient-phytoplankton-zooplankton and bioenergetics models. *Transactions of the American Fisheries Society* 137:278-297.

Sarmiento, J., R. Slater, R. Barber, L. Bopp, S.C. Doney, A.C. Hirst, J. Kleypas, R. Matear, U. Mikolajewicz, P. Monfray, and others. 2004. Response of ocean ecosystems to climate warming. *Global Biogeochemical Cycles* 18(GB3003):doi:10.1029/2003GB002134.

Seitzinger, S.P., J.A. Harrison, E. Dumont, A.H.W. Beusen, and A.F. Bouwman. 2005. Sources and delivery of carbon, nitrogen and phosphorous to the coastal zone: An overview of global nutrient export from watersheds (NEWS) models and their application. *Global Biogeochemical Cycles* 19(4): doi:10.1029/2005GB002606.

Seitzinger, S.P., E. Mayorga, C. Kroeze, A.F. Bouwman, A.H.W. Beusen, G. Billen, G. Van Drecht, E. Dumont, B.M. Fekete, J. Garnier, J. Harrison, D. Wisser, and W.M. Wollheim.

2009. Global nutrient river export trajectories 1970-2050: A Millennium Ecosystem Assessment scenario analysis. *Global Biogeochemical Cycles*, 2009GB003587.

Smith, R., M. Maltrud, F. Bryan, and M. Hecht. 2000. Numerical simulation of the North Atlantic Ocean at 1/10°. *Journal of Physical Oceanography* 30:1532–1561.

Speirs, D.C., W.S.C. Gurney, M.R. Heath, W. Horbelt, S.N. Wood, and B.A. de Cuevas. 2006. Ocean-scale modelling of the distribution, abundance, and seasonal dynamics of the copepod *Calanus finmarchicus*. *Marine Ecology Progress Series* 313:173-192.

Stammer, D., C. Wunsch, I. Fukumori, and J. Marshall. 2002. State estimation improves prospects for ocean research. *EOS, Transactions, American Geophysical Union* 83(27):294-295.

Stammer, D. and co-authors. 2010. Ocean Information Provided through Ensemble Ocean Syntheses. In: *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society* (Vol. 2), Venice, Italy, 21-25 September 2009, Hall, J., D.E. Harrison, and D. Stammer, Eds., ESA Publication WPP-306.

Steinacher, M., F. Joos, T.L. Frölicher, L. Bopp, P. Cadule, V. Cocco, S.C. Doney, M. Gehlen, K. Lindsay, J.K. Moore, and others. 2010. Projected 21st century decrease in marine productivity: A multi-model analysis. *Biogeosciences* 7:979-1005.

Stoecker, D.K., A.E. Thessen, and D.E. Gustafson. 2008. "Windows of opportunity" for dinoflagellate blooms: Reduced microzooplankton net growth coupled to eutrophication. *Harmful Algae* 8:140-151.

Stumpf, R.P., 2008. Developing operational capabilities for nowcasts and forecasts of harmful algal blooms. In: O. Moestrup, ed., *Proceedings XII International Conference on Harmful Algae*. IOC of UNESCO, Copenhagen, pp. 96-98.

Werner, F.E., F.H. Page, D.R. Lynch, J.W. Loder, R.G. Lough, R.I. Perry, D.A. Greenberg, and M.M. Sinclair. 1993. Influence of mean 3-D advection and simple behavior on the distribution of cod and haddock early life history stages on Georges Bank. *Fisheries Oceanography* 2:43-64.

Werner, F.E., R.K. Cowen, and C.B. Paris. 2007. Coupled biological and physical models: Present capabilities and necessary developments for future studies of population connectivity. *Oceanography* 20(3):54-69

Wunsch, C., R.M. Ponte, and P. Heimbach. 2007. Decadal trends in sea level patterns: 1993-2004. *Journal of Climate* 20:5889-5911.

Figure Captions

Figure 1. Left column: estimates of local thermosteric (top) and halosteric (bottom) sea level trends from the Global ECCO (GECCO) state estimate 1992-2001. Right column: observed trends (top) compared with simulated ECCO trends (bottom) over the period 1992–2001.

Figure 2. Global heat (left) and steric surface height anomalies (right). Note that the three estimates showing a significant thermosteric increase during the 1990s (GECCO, ECMWF, and Mercator/OPAVAR/CERFACS) make significant direct use of satellite altimeter measurements.

Figure 3. Simulated surface chlorophyll concentration (mg Chl m⁻³) from a 0.1-degree resolution model of the North Atlantic, consisting of a primitive equation physical model (Smith et al., 2000) and a 24-box ecosystem model (Moore et al., 2004) that includes three phytoplankton groups.

Figure 4. Two different model simulation results for a coastal upwelling simulation. The upper panel shows the copepod distributions after 40 days for a simulation in which the copepods do not undergo diel vertical migration. In the lower panel, the copepods undergo vertical migrations where the speed is dependent on light, food concentration and the individual's weight, and hunger. The size of the bubbles is related to the weight of the individual (from Batchelder et al. 2002).

Figure 5. Conceptual diagram of the Global NEWS model construction, submodels and parameters used in developing the spatially explicit Global NEWS nutrient maps. Redrawn from Seitzinger et al. (2009).

Figure 6. Global distribution of the HAB dinoflagellate *Prorocentrum minimum* in relation to export of inorganic nitrogen by dominant form. The base map is a Global NEWS model (from Dumont et al., 2005), reproduced with permission of the American Geophysical Union; the overall figure is reproduced from Glibert et al. (2008) with permission of Elsevier.

McGillicuddy et al., Figure 1.



McGillicuddy et al., Figure 2.



McGillicuddy et al., Figure 3.



McGillicuddy et al., Figure 4.







McGillicuddy et al., Figure 6.

