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Preface

Models of harmful algal blooms: Conceptual, empirical, and numerical approaches

Now is a historic time in the field of harmful algal bloom (HAB) science. HAB problems are growing worldwide, and society's need for understanding these phenomena is more pressing than ever. Technological advances have expanded our capabilities for observing the ocean, providing unprecedented opportunities not only for the detection of blooms, but also for the physical, chemical, and biological factors that trigger their initiation, development, and ultimate demise. However, despite these rapidly expanding observational capabilities, HAB processes will continue to be undersampled for the foreseeable future, owing to the wide range of space and time scales relevant to these oceanographic phenomena. As such, we must rely on models to help interpret our necessarily sparse observations. Such models can take many forms, ranging from conceptual models, to simple analytic formulae, to complex numerical models that assimilate data (Franks, 1997). Of course, the topic of HAB modeling is embedded within, and benefits from, the accomplishments of the broader field of physical–biological interactions generally (Franks, 1995; Hofmann and Friedrichs, 2002; Blackford et al., 2007; Lynch et al., 2009).

In June 2009, a workshop was convened under the auspices of the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) program to develop strategies for using observations and models to address the science questions articulated in the Open Science Meeting Reports for each of the GEOHAB Core Research Projects (Cembella et al., 2010; Gentien et al., 2008; Glibert, 2006; Pitcher et al., 2005). A total of 80 participants from 26 nations, including 20 students and postdocs met for one week at the National University of Ireland Galway (McGillicuddy et al., in preparation). This volume is comprised of a set of papers conceived at the Galway workshop. Collectively, these contributions illustrate the wide variety of approaches being brought to bear on harmful algal bloom phenomena, spanning conceptual, empirical, and numerical approaches.

Conceptual models are not only useful in their own right, but also form the foundation of all other types of models. As such, conceptual models figure prominently into each of the papers contained herein. One paper in particular provides a pedagogical guide to conceptualization of phytoplankton life cycles in both Eulerian and Lagrangian frameworks (Hense, 2010-this issue). Because many HAB species have complex life cycles that can include resting stages, vegetative growth, and sexual reproduction, explicit representation of these biological aspects can be essential to accurate modeling of their bloom dynamics.

Empirically-based algorithms are playing an increasingly important role in HAB modeling, providing an important link between conceptual and dynamical modeling approaches. For example, Blauw et al. (2010-this issue) use fuzzy logic to relate nuisance foam events in Dutch coastal waters to *Phaeocystis globosa* blooms, quantifying their relationships with environmental parameters such as mixed layer irradiance and nutrient availability. Anderson et al. (2010-this issue) adopt a different mathematical framework – a logistic Generalized Linear Model (GLM) – to predict potentially toxigenic *Pseudo-nitzschia* blooms in the Chesapeake Bay as a function of time of year, location, temperature, salinity, light, nutrients, and freshwater discharge. Yet another analytical approach is offered by Wang and Tang (2010-this issue), who use Empirical Orthogonal Function analysis on satellite-based ocean color data to identify winter phytoplankton blooms south of Luzon Strait, relating their causes to subsurface upwelling and mixed layer entrainment via statistical analysis of both remotely sensed and *in situ* observations. Raine et al. (2010-this issue) identify a chain of observable events that lead to HAB outbreaks in a coastal embayment in southwestern Ireland: easterly winds tend to accelerate the coastal current, delivering *Dinophysis acuminata* blooms from the continental shelf to the mouth of Bantry Bay; subsequent southwest winds can then transport the blooms into the Bay. By encapsulating this sequence of wind forcing conditions into a single index, Raine et al. evaluate the skill of harmful algal event predictions in both hindcast and forecast modes. Each of these examples illustrates how empirically-based approaches provide a valuable framework for formulating and refining conceptual models underpinning HAB phenomena, setting the stage for future development of dynamical models. In some cases, such advances have turned out to be surprisingly useful and practical for prediction purposes.

Aggregated box models, sometimes referred to as zero-dimensional models, have tremendous utility for a variety of purposes, ranging from exploratory theoretical and conceptual model development to applications in real systems with HAB phenomena. Flynn and Mitra (2010-this issue) provide an excellent example of the former in their investigation of mixotrophy. Although few data are available to test such models, their numerical simulations offer a framework for initial evaluation of various mixotrophic formulations. Their findings could help inform the design of future experimental work to be used in more rigorous testing of such models. Similarly, Flynn (2010-this issue) uses detailed physiological models to examine how internal cellular nutrient stores respond to external nutrient availability, illustrating the complex nonlinear processes involved in phytoplankton response to varying environmental conditions. Such information is directly relevant to devising effective management strategies for HABs and eutrophication. Chapelle et al. (2010-this issue) describe species-specific physiological models for phosphorus-limited growth of *Alexandrium minutum* and *Heterocapsa triquetra*, testing them with laboratory experiments comprised of both pure and mixed semicontinuous culture. Such models yield insight into nutritional regulation of blooms of these harmful species, which is of course

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useful information in and of itself. In addition, such physiological formulations set the stage for more complete models of bloom dynamics that include controls such as light, temperature, predation, etc.

One framework in which to synthesize such a vast array of processes is provided by planktonic ecosystem models. Llebot et al. (2010-this issue) implement a zero-dimensional ecosystem model to explore nutrient supply processes fueling blooms in a Mediterranean coastal embayment. By comparing carefully constructed sensitivity experiments with available observations, they are able to assess the plausibility of a variety of nutrient sources and mechanisms for delivery. The results demonstrate the importance of dissolved organic phosphorus to bloom nutrition, despite the hydrodynamic simplifications inherent in the zero-dimensional formulation. In many cases, such models lend themselves to incorporation in three-dimensional circulation models, and Roiha et al. (2010-this issue) provide a striking example of how an ecosystem model with multiple phytoplankton functional types can be used to predict cyanobacterial blooms in the Black Sea. This is one of the first, if not the first, documented uses of ensemble methods of HAB forecasting. Such ensembles provide valuable information about forecast uncertainty and sensitivity, which are crucial in interpreting the results for use in management decisions. Moreover, ensemble forecasts can also be used to assess and refine observing systems used to drive HAB predictions. Another novel application of ecosystem models builds on the seminal work of Follows et al. (2007), who introduced the process of selection into such formulations. Simulations described by Goebel et al. (2010-this issue) start with a large number (78) of phytoplankton types for which physiological traits are randomly chosen. The plankton model is integrated forward in time within a high-resolution three-dimensional model of the California Current System, and this simulation of the natural selection process yields an autotrophic community with recognizable phytoplankton functional groupings, as evidenced by detailed comparisons with observations.

Three-dimensional models need not necessarily include complex biological components in order to be useful for HAB studies. Velo-Suárez et al. (2010-this issue) use particle tracking techniques to explain the disappearance of a *Dinophysis acuminata* bloom in the Bay of Biscay. Although biological processes may have contributed to the decline of the bloom, results from a three-dimensional model seeded with passive particles suggest advection and dispersion processes were sufficient to provide a hydrodynamic termination mechanism. Doan et al. (2010-this issue) apply a similar approach to a *Phaeocystis globosa* bloom in the upwelling waters of south central coast of Viet Nam. Under strong southwest monsoonal winds, the population tended to be advected offshore, whereas in the absence of wind forcing the bloom was transported northward in the coastal current. These numerical experiments clearly illustrate the importance of wind forcing in determining transport pathways and exposure of HABs to coastal habitats.

Another major contributor to HABs in coastal environments is the process of eutrophication, which is a growing problem globally (Glibert et al., 2010-this issue). As with HABs in general, modeling approaches to HABs in eutrophic systems are quite diverse. For example, Xu et al. (2010-this issue) use primarily conceptual models to interpret time series data in two Hong Kong harbors to determine that differences in hydrodynamic circulation and mixing are the primary causes for differences in eutrophication impacts in those particular systems. At the other end of the spectrum of complexity lie global eutrophication models, which couple land use information with representations of the coastal ocean to assess the connection between nutrient loading and HAB occurrence (Glibert et al., 2010-this issue). A grand challenge for future progress in this area is the integration of fully dynamic models of land use, watershed and coastal hydrodynamics, and HAB biology into a "system of systems."

This volume concludes with a review of rheological properties in marine systems (Jenkinson and Sun, 2010-this issue). The potential importance of this topic to HAB studies stems from organic exopolymeric substances exuded by phytoplankton, which can have an impact on seawater viscosity. In turn, this could constitute a feedback mechanism relevant to thin layers of plankton in stratified systems.

The sixteen papers contained herein thus comprise a broad but incomplete survey of the field of HAB modeling. Future progress in this field depends heavily not only on the creativity and innovation of individual investigators developing new models and new approaches, but also on integration with the broader community of researchers dealing with physical–biological interactions of plankton populations. Interestingly, it was a HAB problem (on the west Florida shelf) that inspired one of the earliest coupled physical–biological models of plankton dynamics, which dealt with the competing effects of growth and diffusion (Kierstead and Slobodkin, 1953; Skellam, 1951). Other key opportunities for this field abound in partnership with the emergent global ocean observing system, which has been in part justified by the need to observe, understand, and predict HABs in the coastal ocean (Nowlin et al., 1997).

Dedication

It was with great sorrow that our community learned of the death of Patrick Gentien on May 9, 2010. His sharp intellect and keen intuition afforded him a deep understanding of oceanic plankton populations, and his curiosity about marine systems was infectious. Patrick's generosity with ideas and keen sense of humor made him a wonderful collaborator. He was exceptionally dedicated to advancing the field, having served as chair of the ICES-IOC Working Group on HAB Dynamics (1996–1998), and French delegate at the Intergovernmental Panel on Harmful Algal Blooms (IPHAB). He was involved with the GEOHAB program from its inception, serving as the first chair (1999). Patrick played a major role in the organization, execution, and follow-up to the Galway modeling workshop. For all of these reasons, we dedicate this volume to our treasured colleague and friend.

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