Title	On modelling harmful algal blooms
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Citation	
Date	2005
URL	http://hdl.handle.net/10220/7143
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On Modelling Harmful Algal Blooms

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A short running title: Modelling HAB

Key words: **Modelling Harmful Algal Blooms.**

ABSTRACT

Numerical analysis has been shown as an important tool in studying the dynamics of harmful algal blooms, exploring the causes, mechanism and prediction of red tides. In this paper, various multivariate statistical methods and biophysical models are reviewed in examining the roles of biological, chemical, physical factors and biological-physical interactions in red tides. These models have achieved some degrees of success in describing the underlying dynamical processes. However, relatively poor knowledge about physiological responses of bloom species to the physical field has greatly limited the predictive ability of existing models. The improvement of existing models will depend on a better understanding of the physical, physiological, and ecological processes and their interactions.

ADDITIONAL INDEX WORDS: Numerical Analysis, Harmful Algal Blooms.

INTRODUCTION

Harmful algal blooms (HAB), also referred to as "red tides" in the older literature, have been observed frequently and globally (Anderson 1989). The important aspects for HAB research are how to reveal the causes of their outbreaks, analyze their formative mechanisms and describe the dynamics underlying biological and physical processes. Large amounts of *in situ* data have been accumulated over past decades. However, it is not enough to explore individual environmental factors in laboratory or field qualitative analysis of blooms. Numerical analysis has been used more widely in the last twenty years as an important tool in studying dynamic process of HAB. However, the lack of knowledge in identifying the influence of various physical, chemical and biological factors and their complex interactions on the appropriate temporal and spatial scales has prevented the quantitative assessment of the importance of these factors in causing HAB and the development of predictive models (ECOHAB 1995). Until now, statistical models have mainly been used to analyze some limiting factors causing the HAB. Better physical and biological models are still being developed.

MULTIVARIATE STATISTICAL ANALYSIS

Since the 1970's, multivariate statistical methods have been applied in HAB studies in order to decrease the dimensionality of problems. Popular multivariate methods are principal component analysis, regression analysis, interpretative structural modeling, cluster analysis, discriminant analysis and time series analysis.

Principal Component Analysis (PCA)

In order to assess the importance of external environmental factors, principal component analysis has been adopted to transform a set of correlated information into some lumped and defined parameters that can directly describe the characteristics of HAB. One of the earliest applications was that of Quchi and Takayama (1981), who considered six environmental factors including temperature, salinity, organic nitrogen, and organic phosphorus as well as inorganic nitrogen and inorganic phosphorus. A three-dimensional "red tide map" was plotted in terms of three principal components in *PCA* and used to predict that *Gymnodinium mikimotoi* bloom would not occur in 1982 (Quchi and Takayama 1984). In another effort, Huang *et al.* (1997) used fourteen variables to examine relationships between *Skeletonema costatum* and environmental factors in Dapeng Bay of the South China Sea. Results showed that the main factors affecting the amount of *S. costatum* were nitrogen, silicate, and water temperature.

Regression Analysis (RA)

A simple equation of *RA* is

$$P = \beta X^{n} + \varepsilon$$

where P, X, β and ε are the phytoplankton concentrations, environmental factors, regression coefficients and error terms respectively, and n is the index term. Quchi (1986) made a multiple linear regression model of *G. mikimotoi* blooms, from August of 1979 and 1983 in the northern part of Hiroshima Bay. Among various *RA* methods, a popular method is the stepwise regression that removes unimportant variables. A model of multinomial stepwise regression (Huang *et al.*, 1994) was applied to analyze the relationship between chlorophyll *a* and environmental factors and results indicated that the soluble iron, chemical oxygen demand (COD), and salinity were the most important factors influencing variations of chlorophyll *a*. In some cases, a curve more suitably describes the relationship between biomass and environmental factors than a simple straight line. Zheng and Yuan

(1991) derived an exponential relationship for a model of chlorophyll *a*, salinity, and COD in an enclosed ecosystem. However, in most cases, it is difficult to select a suitable curvilinear equation and calculation is also very complicated; as a result, it is scarcely used now.

Interpretative Structural Modeling (ISM)

As an auxiliary tool to examine system structures, *ISM* modelling was applied to HAB analysis in the middle of the 1980s. Its main purpose is to derive interpretable figures. Based on literature for *Noctiluca scintillans* blooms in the South China Sea, Wang *et al.* (1994) selected 22 basic environmental factors associated with the blooms from different aspects of meteorology, oceanography, chemistry, and biology. The relationships suggested for this kind of bloom involved six levels. *ISM* is useful as a "conceptual model" for developing dynamic models of HAB. However, it cannot provide quantitative assessment on the factors responsible for the formation of the HAB.

Cluster Analysis (CA)

According to a certain resemble standard, a cluster dendrogram of HAB samples can be gained through *CA*. Further, a factor can be indicated important according to the change of the cluster dendrogram on elimination of the factor. One example using *CA* is provided by Qi *et al.* (1994) where a dynamic fuzzy cluster was used to analyze *Chattonella marina* blooms from 1991 in the South China Sea. Results indicated that iron ions and wind velocity were decisive factors for the initiation of the blooms. Although *CA* can be used to analyze complicated structures, different cluster criteria can bring about quite distinct results that cause some uncertainty in explaining the dendrogram.

Discriminant Analysis (DA)

DA can also be used to classify HAB. A discriminant function can be constructed based on historical HAB data and using collected monitoring information, used to predict whether HAB will develop. Therefore, it is a useful tool in predicting the possibility for HAB in an area (Quchi 1984; Kato *et al.* 1985). For instance, Huang *et al.* (1997) constructed three discriminant equations for *S. costatum* blooms, for an initial period, bloom period, and normal period based on data acquired during 1990 spring blooms in the South China Sea. In order to examine the validity of their resultant discriminant functions, comparisons between predictive results and observed data were made for 1991 spring blooms. The corrective rate for the blooms was only 64 percent. Huang *et al*. (1997) found that the accuracy of prediction would be improved with the increasing numbers of data used to construct the *DA* model.

Time Series Analysis (TSA)

The quantity of an HAB organism fluctuates with time and the variation of biomass forms a series of counts in relation to temporal processes. The key of *TSA* is to set up a stable autoregressive model, such as the autoregressive moving average method. Qi *et al.* (1991) applied a random *TSA* to analyze the dynamics of a *N. scintillans* population and found a critical density of the population for both surface and bottom water, what if not reached, no bloom would occur. In fact, however, it is technically difficult to monitor the population density of all causative species in real time.

COUPLED DYNAMIC MODELS OF HAB

In recent years, the dynamics of marine ecosystems have been one of the most studied areas by global oceanic researchers. Usually these dynamics include key physical oceanographic forcing functions that play significant roles in both HAB dynamics and the patterns of toxicity or adverse impacts (Aksnes *et al.* 1995; Baretta *et al.* 1995). Furthermore, interplay or coupling between physical and biological behaviors, such as swimming, vertical migration, or physiological adaptation, holds a key for understanding many HAB phenomena (Donaghay and Osborn 1997). However, the mechanism governing interactions of physical systems with biological components is ignored in traditional statistical models. In order to understand these interactions, a new program, *i.e.*, the ecology and oceanography of harmful algal blooms (ECOHAB) has been put forward (ECOHAB 1995). One of its major aims is to identify, measure, and model the underlying biological and physical processes and their interactions.

Since Kierstead and Slobodkin (1953) proposed the first model to examine the opposing effects of growth and diffusion in the formation of HAB, many models have been developed to explore the dynamics of bloom species. These models can be divided into various types in accordance with different classification. For instance, according to expiated complexity, there are aggregated biological models (Truscott 1995), multispecies biological models (Kishimoto 1990), and biological models coupled with simple physics (Yoshimori *et al.* 1995; Carlos *et al.* 1999) or detailed physics (Yanagi *et al.* 1993, 1995; Allen *et al.* 1998).

Modeling HAB ecosystems demands abundant knowledge of chemical and biological interactions operating within the physical environment and must be formulated by a multidisciplinary team. Over the past four decades, studies of HAB in laboratory, field, and theoretical work have greatly contributed to the theory of how biological and physical processes and their interactions affect the dynamics of HAB. The European Regional Seas Ecosystem Model (*ERSEM*), proposed in the early 1990s, is hitherto one of the most successful ecosystem models and has been used in HAB simulation.

The ecosystem described in *ERSEM* is considered to be a series of interacting physical, chemical, and biological processes, which together exhibit a coherent system behavior (Baretta *et al.* 1995). Almost all the biota, important elements, and physical processes are included in a bulk model. It is very promising for predicting long-time effects of anthropogenic inputs of nutrients on marine systems, but fails to reproduce a scenario when a bloom is collapsing (Allen *et al.* 1998).

A relatively simple model was proposed by Xia *et al.* (1997) to describe the dynamics of *N. scintillans* blooms. The model used two-dimensional physical dynamics coupled with the biological dynamics.

$$\frac{\partial D}{\partial t} + u\frac{\partial D}{\partial x} + v\frac{\partial D}{\partial y} = A_h\frac{\partial^2 D}{\partial x^2} + A_h\frac{\partial^2 D}{\partial y^2} + S_D$$

where u and v are the seawater velocities, A_h is the diffusion coefficient, D represents the nutrient concentration E, and the biomass N in seawater, respectively. S_D is a biological term.

$$S_E = H\left[C_1(E_0 - E) - a\frac{E}{E_m + E}N\right]E,$$

$$S_N = H\left[-C_2 + b\frac{E}{E_m + E}N\right]N$$

where H is the water depth, C_1, C_2, a, and b are the rates of nutrient consumption, algal death, maximum photosynthesis, and nutrient weight conversion, respectively. E_0 is the initial nutrient concentration and E_m is the nutrient half saturation constant.

Although the model is fairly simple, the results show a good agreement between numerical simulation and observation. It can be considered as a basis for developing more complex models.

DISCUSSION

Nearly all-dynamic models stem from a similar framework of physical and biological equations (Kishi, 1986). Differences between models are parameterization and initialization of processes.

Variable selection

Numerous studies have shown that every causative alga responsible for HAB grow and reproduce at special optimum conditions. All possible factors affecting the formation of HAB can be monitored, but not all factors are equally significant. Therefore, it should be possible to obtain an acceptable result by restricting parameters by some amount. First, every area has characteristics of temperature, salinity, current, tide, topography, and meteorology. The selection of parameters can be site-specific through the analysis of historical HAB events. Secondly, parameters entering the model should be as uncorrelated as possible. For example, in the study of necessary conditions for *Chattonella antiqua* red tide outbreaks, the model was expressed as a set of equations for inorganic phosphate, nitrate, ammonia, P cell quota (organic phosphate), N cell quota (organic nitrogen), temperature, and salinity (Amano *et al*. 1998).

Data assimilation

Models of HAB are very sensitive to initial and boundary conditions. Slightly different initial conditions can lead to widely different results. The accuracy of results is also affected by inaccurate and inconsistent data from different meteorological, hydrological, chemical, and biological measurements. Moreover, HAB generally lasts for less than a week and presents irregular spatial patterns as a function of turbulence, internal waves, and sharp fronts (Franks 1997). Insufficient *in situ* sampling performed temporally and spatially prevents models from providing adequate insights into HAB dynamics.

An assimilation technique has been developed to obviate the effects of inaccurate initial conditions and the inescapable chaotic divergence of model and reality (Brasseur and Nihoul 1994). Some models that incorporate data obtained by remote sensing techniques have been proposed (Armstrong *et al.* 1995). Data assimilation can greatly improve the agreement between model simulation and observation.

Dimensional selection

Models of HAB can be classified as one, two, and three-dimensional. Most flagellates swim to surface waters during the day and sink at night, so a one-dimensional model often depicts the vertical migration of flagellates. A two-dimensional model usually describes the effects of wind forcing and vertical migration upon the formation of the HAB. A three-dimensional model might include diel vertical migration, spatially variable steady wind, and tides. Three-dimensional simulations have already been proposed by Pinazo *et al.* (1996) and Hoch and Garreau (1998). Models become more complex as the model dimension increases. Suitable dimensions should be chosen in accordance with species of algae, the features of current, such as tide, upwelling, and the prevalence of wind.

Model coupling

An ecosystem with HAB can be considered to be a series of interacting complex physical, chemical, and biological processes, which together exhibit a coherently systematic behavior. Thus, a HAB model underlying bloom dynamics usually consists of biological, chemical, and physical submodels. Detailed descriptions of biological submodels can be found for a population growth model of algae (Wyatt and Horwood 1973) and multispecies models (Montealegre *et al*. 1995). Wang *et al*. (1997) and Lee and Arega (1999) proposed chemical dynamics of nitrogen, phosphate, and silicate. Hydrodynamic models have been well documented to determine watermass movements such as river inflows (Allen 1997), windforced upwelling (Carbonel 1998), and advection (Anderson 1984).

It is difficult to integrate biological submodels with physical submodels due to numerous variables varying in time and space. Comparative studies between model simulations and experiments show that relatively simple reliable modules or compartments may have better results in some cases because errors caused by inserting certain unreliable submodels may spoil the larger model simulations (Eigenheer *et al.* 1996). Nonetheless, fine interdisciplinary models with interaction among different compartments reveal a great deal and make predictions of HAB possible.

CONCLUSIONS

The ultimate goal of HAB models is prediction. However, many parameters and linkages, such as poor knowledge of competition of multispecies and life-historic strategies of causative species, limit predictive ability. Before models of HAB act as a useful tool like weather forecasts, the following efforts will be required in the future:

(a) To improve algal fundamental physiological and ecological knowledge;

(b) To investigate and explore dynamic processes underlying HAB formation both in laboratory and in field, especially biological and physiological responses to physical forcing;

(c) To apply newly developed techniques such as remote sensing and DCMU techniques in HAB observation so as to gain detailed sets of spatial and temporal data; and

(d) To develop better parameterization and data assimilation in order to improve predictive power of models.

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