A PILOT PROJECT TO DETECT AND FORECAST HARMFUL ALGAL BLOOMS IN THE NORTHERN GULF OF MEXICO

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Abstract. More timely access to data and information on the initiation, evolution and effects of harmful algal blooms can reduce adverse impacts on valued natural resources and human health. To achieve this in the northern Gulf of Mexico, a pilot project was initiated to develop a user-driven, end-to-end (measurements to applications) observing system. A key strategy of the project is to coordinate existing state, federal and academic programs at an unprecedented level of collaboration and partnership. Resource managers charged with protection of public health and aquatic resources require immediate notice of algal events and a forecast of when, where and what adverse effects will likely occur. Further, managers require integrated analyses and interpretations, rather than raw data, to make effective decisions. Consequently, a functional observing system must collect and transform diverse measurements into usable forecasts. Data needed to support development of forecasts will include such properties as sea surface temperature, winds, currents and waves; precipitation and freshwater flows with related discharges of sediment and nutrients; salinity, dissolved oxygen, and chlorophyll concentrations (*in vivo* fluorescence); and remotely-sensed spatial images of sea surface chlorophyll concentrations. These data will be provided via a mixture of discrete and autonomous *in situ* sensing with near real-time data telemetry, and remote sensing from space (SeaWiFS), aircraft (hyperspectral imagery) or land (high-frequency radar). With calibration across these platforms, the project will ultimately provide a 4-dimensional visualization of harmful algae events in a time frame suitable to resource managers.

Keywords: Harmful algal blooms, red tide, observing systems, remote sensing, *in situ* sensing, environmental monitoring

1. Introduction

Approximately 5000 species of microalgae exist world-wide, of which about 100 are toxic. More than half of the toxic species occur in the Gulf of Mexico, each with a potential to create public health risks, cause mortalities of marine organisms, or alter the capacity of coastal ecosystems to support living resources. Toxic algae comprise multiple trophic levels and a variety of taxa (dinoflagellates, diatoms, cyanobacteria), and can create toxic effects at relatively low densities. Nonetheless, such events are recognized by a generic term, harmful algal blooms (HABs), which is widely accepted to represent toxic species as well as species that alter habitat (anoxia, hypoxia, persistent turbidity), create physiological dysfunction (respiratory, reproductive), or perturb community relationships (trophic level domination). HAB events worldwide appear to be increasing in frequency and severity (Smayda, 1989). They may be initiated and sustained by natural environmental conditions (Steidinger and Haddad, 1981; Tester *et al.*, 1991), but have also been

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linked to anthropogenic factors. These include watershed runoff of nutrients that stimulate algal growth (Hallegraeff, 1993; Smayda, 1990) and spread of indigenous and non-indigenous algal species through increased commerce (Hallegraeff and Bolch, 1992; Carlton and Geller, 1993).

Coastal economies are affected by HABs through shellfish closures, fish kills, and beach advisories that reduce tourism and consumer confidence in seafood products. It has been estimated (CENR, 2000) that the annual cost of HABs in the U.S. is $300-700 million. Valued marine resources such as finfish, shellfish, manatees, dolphins, and sea turtles are killed by acute exposure to HAB toxins and may be sublethally affected at lower, chronic exposures. Ecologically important species are also affected, which can lead to degraded water and habitat quality. These effects, coupled with the increasing number, extent and severity of harmful algal blooms in the U.S. (Anderson, 1989; Smayda, 1990; Hallegraeff, 1993; Van Dolah, 2000), mobilized Congress to pass the 1998 Harmful Algal Bloom and Hypoxia Research and Control Act (P.L. 105-383), which specifically calls for the establishment of: (1) an inter-agency task force, (2) a national assessment, and (3) an assessment plan for HABs and hypoxia in the Gulf of Mexico. The latter was in recognition of their high visibility and economic importance to the region.

2. Management of Red Tides in the Gulf of Mexico

Among the most common and deleterious blooms in the Gulf of Mexico are those caused by the dinoflagellate *Gymnodinium breve* (Geesey and Tester, 1993), which has recently been renamed *Karenia brevis* (*K. brevis*) (Daugbjerg *et al.*, 2001). In high concentrations, *K. brevis* imparts a reddish hue to the water, a condition commonly referred to as 'red tide'. Red tides routinely occur along the southwest coast of Florida in the late summer and early fall (Gunter *et al.*, 1948; Gilbes *et al.*, 1996) and may persist for three months (Steidinger and Baden, 1984). Recently, *K. brevis* blooms have become more widely distributed; they have been reported in Texas, Mexico, and as far north as North Carolina (Tester *et al.*, 1991). The first confirmed reports of red tides in Alabama, Mississippi and Louisiana were in 1996, supporting the assertion that red tides are occurring more frequently. In 1986, Texas experienced its first red tide in 30 years. Since then, major events have occurred in 1996, 1997 and 2000.

Karenia brevis produces, under certain (yet unknown) environmental conditions, a neurotoxin (brevetoxin), that paralyzes respiratory function in fish and mammals and can accumulate in edible shellfish. Consequently, blooms of *K. brevis* adversely affect public health, economy, and valued coastal resources. Humans are exposed to brevetoxin by aerosols or through ingestion of shellfish that have accumulated the toxin. Aerosol exposure usually causes mild respiratory irritation that leads to a burning throat, coughing and asthma-like symptoms. Ingestion exposure can cause more severe symptoms, including vomiting, muscle cramps and seizures. The severity is tied to high toxin concentrations that can accumulate in edible bivalves such as eastern oysters, *Crassostrea virginica*. To guard against human ingestion, public health managers close shellfish harvesting when *K. brevis* cell densities in the water reach 5 x 10^3/L and re-open them when oysters contain < 80 µg/100 g shellfish. Consequently, a red tide event may last only a few days but hazardous toxin concentrations can persist for months.

Economic costs of red tide events depend on the severity and location of the bloom. Losses related to public health include wages, workdays and medical treatment. Fisheries incur losses when oyster beds are closed and when fish are killed or impaired by red tide toxins or associated hypoxic conditions. There are costs associated with state responses to fish kills, with cleanup of dead and decaying organisms on beaches, and with rehabilitation of protected species. And, even when events are restricted to only a few locations, media reports can reduce tourism across broad coastal areas. In Florida, a single *K. brevis* event is estimated to cost millions of dollars.

All fish and mammals are susceptible to brevetoxin, but some are less mobile and can be trapped in estuaries. Dolphin can easily elude *K. brevis* in the water column but may eat fish that have accumulated brevetoxin. Manatee appear to get trapped when climatic conditions alter their spring migrations or when the blooms are more extensive along the southwestern Florida coast. Notable manatee mortality events have occurred in 1963 (7), 1982 (39) and 1996 (149 manatee killed), coincident with higher than normal levels of *K. brevis* during those years (Landsberg and Steidinger, 1997).

The health, economic and ecological costs of *K. brevis* blooms compel the application of measures to prevent, control or mitigate their occurrence (CENR, 2000). Any management action will depend upon, or benefit from, an accurate system to detect ongoing events, forecast bloom severity and trajectory, and predict when environmental conditions are susceptible to bloom formation. For example, prior knowledge of an event would allow protection (e.g., baffling) of aquaculture shellfish beds or harvesting of threatened oysters prior to an event. Open seasons and bag limits for commercial fish could be altered. In addition, states and animal rehabilitation organizations could mobilize response and cleanup crews in advance of an event. The tourist industry could better estimate their need for employees and could mitigate losses at the beach by offering alternative activities. Forecasts would be valuable at several time scales. Annual and seasonal forecasts would allow states to better budget resources according to estimated response needs. Forecasts in real-time (nowcasts) would provide local and state resource managers with pre-emptive tools to reduce the effects and costs of an event.

Management of blooms and bloom effects may lie within separate political jurisdictions, but forecasting will be better achieved at a regional scale. Initiation and sustenance of HABs is a consequence of both small and large scale environmental and meteorological conditions; changes in circulation patterns, currents, winds, water temperature, climate, watershed runoff and land-use might all interactively influence *K. brevis* blooms, as might a variety of biological and ecological factors (Tester and Steidinger, 1997). Accurate forecasts will require crossing state and local jurisdictions to collect and assemble data into useful, regionally-integrated information. And, despite the logistical issues, a regional approach offers numerous advantages. Specific expertise or capabilities from different jurisdictions can be applied for the good of all, and redundant efforts can be minimized. Regional information also reaches a broader spectrum of users, and the interactions of these users can establish a framework for greater and more sustained coordination among academic, state and federal programs.

3. Initiation of the Harmful Algal Blooms Observing System

A concept for a regional HAB forecasting system was derived through the U.S. Global Ocean Observing System (GOOS) Program (Malone, 2002). The objective of the international GOOS effort is to develop observing systems to improve the timeliness and accuracy for detecting and predicting global scale weather patterns and climate change. The coastal component of GOOS is under development, but includes goals to: (1) improve local and regional weather forecasts; (2) minimize or eliminate public health risks associated with environmental changes (e.g., coastal flooding) and biological events (e.g., harmful algal blooms); (3) improve predictions of the effects of global weather and climate patterns on coastal populations and the safety and efficiency of marine operations, and (4) improve the efficacy of management actions to control and mitigate effects of human activities and natural hazards on coastal ecosystems and to protect and restore critical habitats and biodiversity.

The Harmful Algal Blooms Observing System (HABSOS) is proposed as a pilot project to formulate and implement a user-driven, end-to-end (measurements-to-applications) observing system for the northern Gulf of Mexico (U.S. portion). It will focus on timely access of data and information on the initiation, evolution, location and effects of *K. brevis* blooms with future potential to include additional bloom types. The project will rely on an unprecedented level of inter-jurisdictional cooperation and collaboration, and will serve as 'proof-of-concept' for data collection, integration, interpretation, distribution and archival for a variety of coastal issues. Red tides were selected to pilot the observing system because of their importance to the region, the relatively strong historical record of red tide blooms and their effects, and the ability to detect red tides from satellite and aerial imaging (chlorophyll *a*). The latter will be integral to the pilot project because a primary goal is to demonstrate integration and management of data from a variety of platforms, including *in situ* and remote monitoring. The design and implementation of a *K. brevis* observing system is a test case for determining the types and quality of data collection and data management infrastructure needed for a single, important coastal issue. Once completed, the subsequent goal is to grow the system into a fully integrated and sustained observing system for the northern Gulf of Mexico. Eventually, similar systems developed for other coastal regions will form a national federation of regional observing systems.

Data relevant to *K. brevis* blooms will vary depending on the status and location of the bloom. Data needed to track and forecast the trajectory of an existing bloom will be different than the data needed to identify new blooms or anticipate new blooms from prevailing environmental conditions. In addition, data requirements will depend on whether the bloom is offshore or nearshore. Even though a major bloom has persisted offshore in southwest Florida for many years, more destructive effects are registered for blooms that originate nearshore and in estuaries, where public health is at greater risk. In all cases, the presence and effects of harmful algae must be documented in the context of changes in the physical and chemical characteristics of the water column (e.g., currents, wind, temperature, salinity, nutrients).

Presence of *K. brevis* is best characterized by direct microscopic identification, sometimes performed in routine monitoring of shellfish beds and intermittently performed during research cruises. Remote sensing of red tide blooms is also possible when *K. brevis* cells reach high densities in the water column. The spectral signature of chlorophyll *a* in high-density blooms can be detected from clear Gulf waters using color sensors in airplanes or satellites (Tester and Stumpf, 1998). The Sea-viewing Wide Field-of-View Sensor (SeaWiFS) satellite commercially launched in 1997 can detect chlorophyll *a* at a 1 km resolution across the entire Gulf of Mexico every 1–2 days (Tester *et al.*, 1998). Accounting for variability, the satellite sensor is valid at *K. brevis* cell densities of 5×10^4/L, which is insufficient to signal shellfish bed closures (5×10^3 cells/L), but quite capable of detecting densities (10^5–10^6/L) that are associated with human respiratory distress and aquatic mortality events. Currently, high chlorophyll measurements must be sampled on site (shipboard) to validate presence and dominance of *K. brevis*. Future remote sensors may use spectral signatures for individual phytoplankton species (Cullen *et al.*, 1997). Also, due to limitations of low resolution satellite imagery, chlorophyll detection is not valid within 2 km of shore where many of the most destructive *K. brevis* events occur.

Until better methods are developed, nearshore detection and tracking of red tides may rely on *in situ* monitoring and responses to mortality events. Much of these data, as well as data to investigate underlying environmental causes of HABs, are collected by different state, federal and academic programs. Yet there is little consistency in the objectives of these programs and no existing strategy for integration of data or effective use of collective resources. Forecasting *K. brevis* will require integration of synoptically-collected remote data (e.g., chlorophyll *a*, sea surface temperatures), data collected *in situ* (e.g., cell counts, nutrients, currents, wind) from monitoring programs and data collected during event responses.

4. Integrating and Delivering Data

A principal component of HABSOS is to demonstrate a capacity to integrate existing data collected from multiple sources at different spatial and temporal scales into a cohesive and useful body of information. Such integration must occur with an issue-relevant objective in mind; in this case, the forecast of *K. brevis* blooms. In early discussions of HABSOS, it was determined that state public health and resource mangers, i.e., those who make decisions to mitigate red tide events, were the end-users of the observing system. In the ensuing workshop, these managers expressed a need for moderately-interpreted information; not raw data (e.g., current vectors, cell counts, nutrients) and not prognostication, but an overview of probabilities similar to the integrated meteorological data provided by the Weather Service. State managers also indicated that the priority products for HABSOS should be: (1) routine early warnings (alerts) of events as they are detected, (2) forecasts for time- and space-dependent trajectories of ongoing events, (3) timely access to information on *K. brevis* events and related environmental variables, and (4) alerts of where and when environmental conditions are favorable for *K. brevis* blooms. Because these priorities rely on an integration of regionally-collected data of different types and from different platforms, their achievement will require a model and a clear vision for iterative development and testing.

In a first iteration, data will be mined from previous events and examined for forecasting utility. Phytoplankton experts from across the Gulf of Mexico have begun to aggregate regional data from 1996 (very high *K. brevis* activity across all five states), 1997 (relatively low activity) and 2000 (high activity) with an initial focus on cell counts, chlorophyll *a* (available for 2000 only), salinity and temperature. A determination will be made as to whether these factors could have been used to project the mortalities and shellfish closures that occurred during those years, and whether they differ between high and low red tide years. More refined models will require additional data and may eventually target data that are not currently collected. Fundamental to this process is continued research to elaborate causes, contributing factors, and consequences of *K. brevis* blooms.

Aggregated information from the case study (described above) and from future observations will be presented through a 'portal' system, similar to that used by the Chesapeake Bay Program (www.chesapeakebay.net/cims/). In this system, user queries result in retrieval of information relevant only to their particular needs. Advantages include flexibility in the type and format of data that are retrieved and the knowledge that information is not only timely, but prepared by a subject area expert.

5. Partners in HABSOS

Implementation of HABSOS will require coordination among numerous state, federal and academic institutions. The Gulf of Mexico Program (GMP) was formed in 1988 to develop and implement voluntary, incentive-based management strategies to protect, restore and maintain the health and productivity of the Gulf of Mexico ecosystem. The program is framed to provide interaction among multiple state, federal, and private entities on issues of environmental importance with clear oversight by all stakeholders. Algal blooms are very important to GMP objectives, playing a role in three of four priority issues. The GMP will provide the organizational infrastructure to transform HABSOS from concept to reality. In so doing, it is anticipated that HABSOS will influence the GMP approach to a variety of other environmental issues that require integration of complex and diverse data.

A number of partners are involved in the collection, integration and presentation of HABSOS data. State agencies and academic researchers across all five coastal states will provide cell count data and *in situ* measurements of salinity, temperature and nutrients. Similarly, state resource managers will provide documentation of responses to mortality events through the GMP's Gulf of Mexico Aquatic Mortality Network (Fisher and Sherman, 1999). Forecasts for ocean and near coastal circulation, waves, tides, sediment transport, and water quality in the coastal regions of all five Gulf States is anticipated through expansion of the Northern Gulf Littoral Initiative of the U.S. Navy, University of Southern Mississippi and the GMP. Integration and interpretation of data will become a project of the LabNet and CastNet programs of the 115-member National Association of Marine Laboratories. These are distributed data communications and management systems that link data bases at participating coastal laboratories via the internet to provide visually integrated environmental data on temporal and geospatial scales. Presentation of information via portals will be a project of the newly formed NOAA National Coastal Data Development Center and archival will be facilitated through coordination with NOAA's National Ocean Data Center. Developing forecast tools depends on timely detection of events and on constructive and timely interactions among research, monitoring, and the users of the data and information generated by research and monitoring programs. It is imperative that HABSOS interacts with existing research programs, such as the national, multi-agency ECOHAB Program, to better understand the types of data and interpretive concepts needed to forecast blooms. In return, researchers are provided information in the context of relatively large scale observations critical to hypothesis-driven research. Environmental research is most valuable when conducted in the context of an integrated observing system that is sustained over sufficiently large areas with sufficient resolution to document patterns of variability and change. The successful observing system will incorporate key environmental variables that span regional and national interests while remaining locally relevant. Development of a strategy that provides this critical perspective will be invaluable to future research on causes of algal blooms and aquatic mortalities in the Gulf of Mexico. Such a system will also contribute to better understanding of other changes in coastal ecosystems such as the development and effects of bottom water hypoxia and anoxia.

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