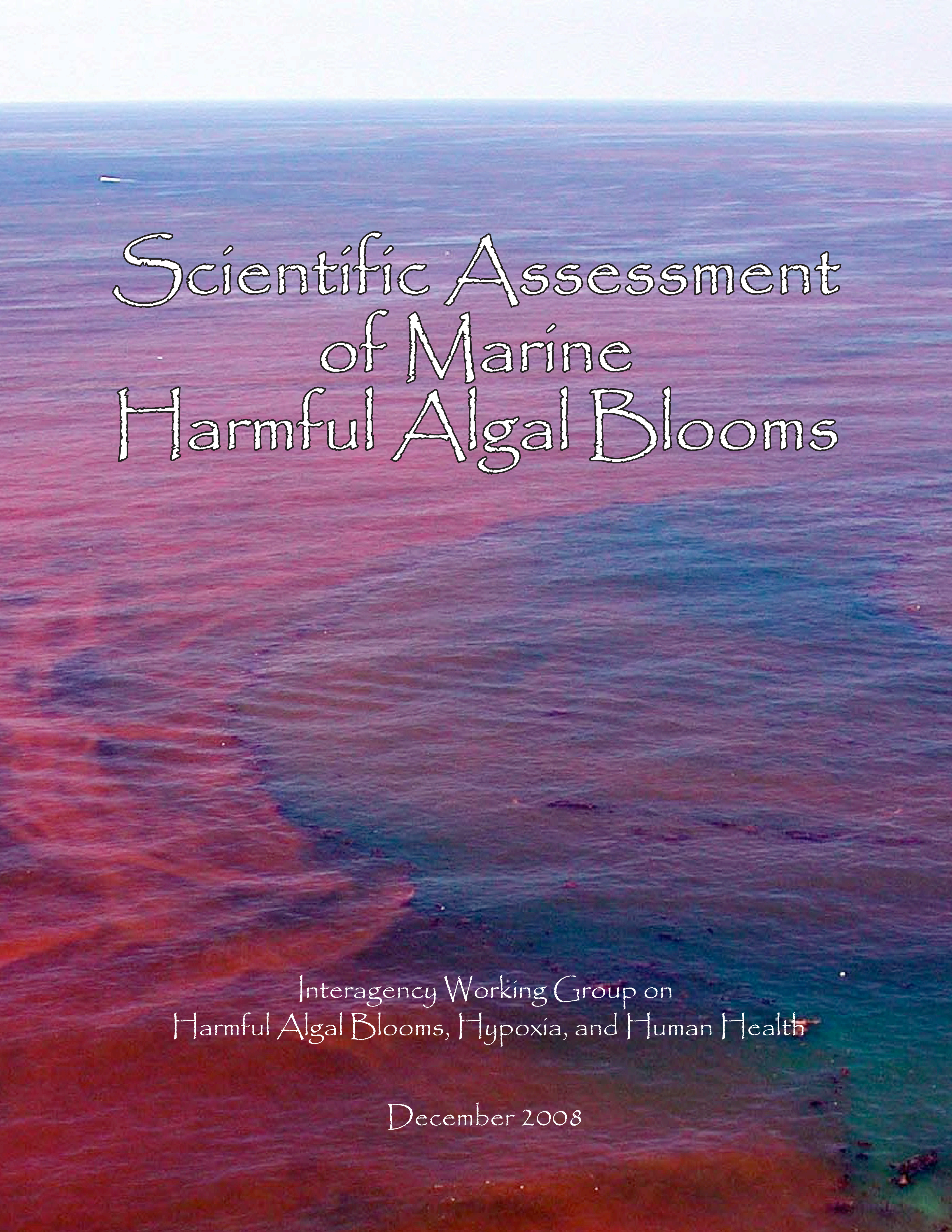


Scientific Assessment of Marine Harmful Algal Blooms

Interagency Working Group on
Harmful Algal Blooms, Hypoxia, and Human Health

December 2008

This document should be cited as follows:

Lopez, C.B., Dortch, Q., Jewett, E.B., Garrison, D. 2008. Scientific Assessment of Marine Harmful Algal Blooms. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Washington, D.C.

Acknowledgements:

Many scientists and managers from Federal and state agencies, universities, and research institutions contributed to the knowledge base upon which this assessment depends. Thank you to all those who contributed to this report, including Lynn Dancy of NOAA National Centers for Coastal Ocean Science who provided a thorough copy editing.

Cover and Sidebar Photo Credits:

Cover: A bloom of the nontoxic dinoflagellate *Lingulodinium polyedrum* along the coast of La Jolla, San Diego County, Kai Schumann (see p. 2 for the entire photo).

Sidebars: Red drift algae on Sanibel Island, Florida, Mike Valiquette (see p. 17 for entire photo).

Council on Environmental Quality
Office of Science and Technology Policy
Executive Office of the President
November 13, 2008

Dear Members of Congress:

We are pleased to transmit this report, a ***Scientific Assessment of Marine Harmful Algal Blooms***. This document assesses the problem of harmful algal blooms (HABs) in our Nation's coastal ocean and estuarine waters and describes recent advances made by Federal agencies to improve scientific understanding of HABs and our ability to manage them.

In December 2004, Congress reauthorized the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA) by passing the Harmful Algal Bloom and Hypoxia Amendments Act of 2004 (HABHRCA 2004). The reauthorization of HABHRCA acknowledged that HABs are one of the most scientifically complex and economically damaging issues challenging our ability to safeguard the health of our Nation's aquatic and marine ecosystems. The Administration further recognized the importance of HABs as a high priority national issue by specifically calling for the implementation of HABHRCA in the President's U.S. Ocean Action Plan.

This report is the last of four reports required by HABHRCA 2004 to address various aspects of HABs in U.S. waters. It was prepared by the Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health, which was chartered through the Joint Subcommittee on Ocean Science and Technology of the National Science and Technology Council and the Interagency Committee on Ocean Science and Resource Management Integration. This report highlights a number of research advances relevant to the HAB-related priorities identified in *Charting the Course for Ocean Science in the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy*, recently released by the Joint Subcommittee on Ocean Science and Technology. The assessment draws from direct contributions of Federal agencies as well as previous reporting efforts that involved numerous experts and stakeholders from Federal, state, and local governments, and academia, industry, and non-governmental organizations.

As the U.S. Commission on Ocean Policy points out, our Nation's coastal ocean, estuaries, and inland waters are vital to our quality of life, our culture, and the economy. This report is an effort to assess the problem of HABs, specifically in our coastal ocean and estuarine waters, and to highlight research advances over the last decade. Activities highlighted here have improved our ability to minimize human health, economic, and environmental impacts from marine HABs. We hope it will be useful to the Congress and a broad range of interested parties.

Sincerely,

James L. Connaughton
Chair, Committee on Ocean Policy
Chair, Council on Environmental Quality

John H. Marburger III
Director
Office of Science and Technology Policy

Joint Subcommittee on Ocean Science and Technology (JSOST)

Richard Spinrad, DOC/NOAA, Co-Chair
Dan Walker, OSTP, Co-Chair
Julie Morris, NSF, Acting Co-Chair

Arctic Research Commission
John Farrell

Department of Agriculture
Louie Tupas

Department of Commerce
National Oceanic and Atmospheric Administration
Richard Spinrad
Steve Murawski
Marie Colton

Department of Defense
U.S. Army Corps of Engineers
Charles Chesnutt
Joan Pope

Department of Defense
Office of Naval Research
Linwood Vincent
James Eckman

Department of Energy
Office of Science
Julie Carruthers
James Ahlgrimm

Department of Health and Human Services
Centers for Disease Control and Prevention
Lorraine Backer
G. David Williamson

Department of Health and Human Services
Food and Drug Administration
Robert Dickey
William Jones

Department of Health and Human Services
National Institutes of Health
Allen Dearry

Department of Homeland Security
U.S. Coast Guard
Jonathan Berkson

Department of the Interior
Kameran Onley
Tim Petty

Department of the Interior
Minerals Management Service
James Kendall
Walter Johnson

Department of the Interior
United States Geological Survey
Linda Gunderson
John Haines

Department of Justice
Bradford McLane

Department of State
David Balton
Liz Tirpak

Department of Transportation
Maritime Administration
Richard Corley

U.S. Environmental Protection Agency
George Gray
Steven Hedtke

Executive Office of the President
Council on Environmental Quality
Gerhard Kuska

Executive Office of the President
Domestic Policy Council
Paul Skoczylas

Executive Office of the President
Office of Management and Budget
Stuart Levenbach
Kimberly Miller

Executive Office of the President
Office of Science and Technology Policy
Dan Walker

Joint Chiefs of Staff
Robert Winokur
James Kraska
Nadeem Ahmad

National Aeronautics and Space Administration
Jack Kaye
Eric Lindstrom

National Science Foundation
Margaret Leinen
Julie Morris

Marine Mammal Commission
Robert Gisiner

Smithsonian Institution
Leonard Hirsch

JSOST Interagency Working Group on Harmful Algal Blooms, Hypoxia and Human Health (IWG-4H)

Lorraine C. Backer (Co-Chair)
Centers for Disease Control and Prevention

Paul A. Sandifer (Co-Chair)
National Oceanic and Atmospheric Administration

Paula Bontempi
Alternate: John A. Haynes
National Aeronautics and Space Administration

Herbert T. Buxton
United States Geological Survey

Stacey M. Etheridge
U.S. Food and Drug Administration

David Garrison
National Science Foundation

Sherwood Hall
U.S. Food and Drug Administration

Rob Magnien
Alternate: Quay Dortch
National Oceanic and Atmospheric Administration

Tim Ragen
Alternate: Mike Simpkins
Marine Mammal Commission

Teri Rowles
National Oceanic and Atmospheric Administration

Juli Trtanj
National Oceanic and Atmospheric Administration

Frederick L. Tyson
National Institute of Environmental Health Sciences

Usha Varanasi
Alternate: Walton Dickhoff
National Oceanic and Atmospheric Administration

William Russo
U.S. Environmental Protection Agency

Mark Weltz
Alternate: Mike O'Neill
Department of Agriculture

Scientific support staff:

Elizabeth B. Jewett
Cary B. Lopez
Carolyn Sotka
Virginia Fay
National Oceanic and Atmospheric Administration

Cheryl L. Fossani
National Science Foundation

Primary Authors

Cary B. Lopez
National Oceanic and Atmospheric Administration

Elizabeth B. Jewett
National Oceanic and Atmospheric Administration

Quay Dortch
National Oceanic and Atmospheric Administration

David Garrison
National Science Foundation

Other Contributors

Rachel Jakuba
Environmental Protection Agency

Tiffany Moisan
National Aeronautics and Space Administration

John Schwab
National Institute of General Medical Sciences

Kevin Chu, Kelly Goodwin, Greg Doucette, Steve Morton, John Ramsdell, Marc Suddleson, Pat Tester, Michelle Tomlinson, Vera Trainer, Dwight Trublood, Frances VanDolah, Gary Wikfors
National Oceanic and Atmospheric Administration

Mark Poli
United States Army Medical Research Institute of Infectious Diseases

Table of Contents

List of Boxes

List of Figures

List of Tables

List of Acronyms

AOAC Association of Analytical Communities

ASP amnesic shellfish poisoning

CCEHBR NCCOS Center for Coastal Environmental Health and Biomolecular Research, NOAA

CCFHR NCCOS Center for Coastal Fisheries and Habitat Research, NOAA

CCMA NCCOS Center for Coastal Monitoring and Assessment, NOAA

CDC Centers for Disease Control and Prevention, Department of Human and Health Services

CFP ciguatera fish poisoning

CICEET Cooperative Institute for Coastal and Estuarine Environmental Technology

COHH Centers for Oceans and Human Health, NSF/NIEHS

CSCOR NCCOS Center for Sponsored Coastal Ocean Research, NOAA

DSP diarrhetic shellfish poisoning

ECOHAB Ecology and Oceanography of Harmful Algal Blooms Program

ELISA enzyme-linked immunosorbent assay

EMCC Eastern Maine Coastal Current

EPA U.S. Environmental Protection Agency

FDA U.S. Food and Drug Administration, Department of Human and Health Services

GEOHAB Global Ecology and Oceanography of Harmful Algal Bloom Program

GEOSS Global Earth Observation System of Systems

GLERL Great Lakes Environmental Research Laboratory, NOAA

GOOS Global Ocean Observing System

HAB harmful algal bloom

HABHRCA Harmful Algal Bloom and Hypoxia Research and Control Act

HABISS Harmful Algal Bloom-related Illness Surveillance System

HARR-HD Harmful Algal Research and Response: A Human Dimensions Strategy

HARRNESS Harmful Algal Research and Response: A National Environmental Science Strategy 2005–2015

HPLC high performance liquid chromatography

IEOS U.S. Integrated Earth Observing System

IOC Intergovernmental Oceanographic Commission

IOOS Integrated Ocean Observing System

ISSC Interstate Shellfish Sanitation Conference

ISSHA International Society for the Study of Harmful Algae

IWG-4H Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health

JSOST Joint Subcommittee on Ocean Science and Technology

LCMS liquid chromatography mass spectrometry

MERHAB Monitoring and Event Response for Harmful Algal Blooms Program, NOAA

MMC Marine Mammal Commission

NASA National Aeronautics and Space Administration

NCCOS National Centers for Coastal Ocean Science, NOAA

NCEH National Center for Environmental Health, CDC

NEFSC Northeast Fisheries Science Center, NOAA

NESDIS National Environmental Satellite, Data, and Information Service, NOAA

NERRS National Estuarine Research Reserve System

NHC National HAB Committee

NIEHS National Institute of Environmental Health Sciences, NIH

NIGMS National Institute of General Medical Sciences, NIH

NIH National Institutes of Health, Department of Human and Health Services

NMFS National Marine Fisheries Service, NOAA

NOAA National Oceanic and Atmospheric Administration, Department of Commerce

NSF National Science Foundation

NSP neurotoxic shellfish poisoning

NWFSC Northwest Fisheries Science Center, NOAA

OAR Office of Oceanic and Atmospheric Research, NOAA

OHH Oceans and Human Health

OHHI Oceans and Human Health Initiative, NOAA

ONR Office of Naval Research, U.S. Department of Defense

ORHAB Olympic Region HAB Monitoring Program

PICES North Pacific Marine Science Organization

PSP paralytic shellfish poisoning

RDDTT Research Development Demonstration and Technology Transfer

UME unusual mortality event

USAMRIID U.S. Army Medical Research Institute of Infectious Diseases

USDA U.S. Department of Agriculture

USFWS U.S. Fish and Wildlife Service, U.S. Department of the Interior

USGS U.S. Geological Survey, U.S. Department of the Interior

Executive Summary

Algae are the most abundant photosynthetic organisms in marine ecosystems and are essential components of marine food webs. Harmful algal bloom or "HAB" species are a small subset of algal species that negatively impact humans or the environment. HABs can pose health hazards for humans or animals through the production of toxins or bioactive compounds. They also can cause deterioration of water quality through the buildup of high biomass, which degrades aesthetic, ecological, and recreational values.

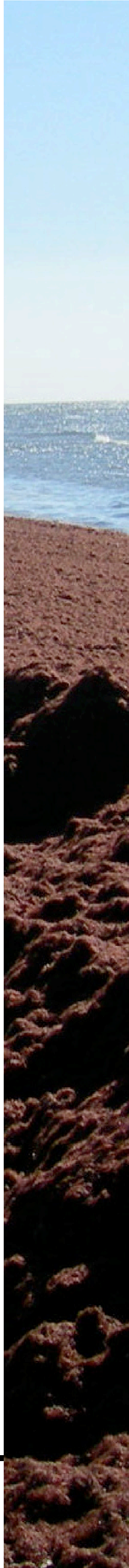
Humans and animals can be exposed to marine algal toxins through their food, the water in which they swim, or sea spray. Symptoms from toxin exposure range from neurological impairment to gastrointestinal upset to respiratory irritation, in some cases resulting in severe illness and even death. HABs can also result in lost revenue for coastal economies dependent on seafood harvest or tourism, disruption of subsistence activities, loss of community identity tied to coastal resource use, and disruption of social and cultural practices. Although economic impact assessments to date have been limited in scope, it has been estimated that the economic effects of marine HABs in U.S. communities amount to at least $82 million per year including lost income for fisheries, lost recreational opportunities, decreased business in tourism industries, public health costs of illness, and expenses for monitoring and management. As reviewed in the report, *Harmful Algal Research and Response: A Human Dimensions Strategy*[1], the sociocultural impacts of HABs may be significant, but remain mostly undocumented.

It is widely believed that the frequency and geographic distribution of marine HABs have been increasing worldwide. All U.S. coastal states have experienced HABs over the last decade, and new species have emerged in some locations that were not previously known to have problems. While marine HABs occur naturally, human actions that disturb ecosystems in the form of increased nutrient loadings and pollution, food web alterations, introduced species, and water flow modifications have been linked to the increased occurrence of some HAB species.

Efforts to address the HAB problem at the Federal level began with the first HAB National Plan in 1993, followed by the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA) of 1998. In 2004, Congress reauthorized HABHRCA with the Harmful Algal Bloom and Hypoxia Amendments Act (HABHRCA 2004). The 2004 legislation required the generation of five reports (see Box 1.1), including this *Scientific Assessment of Marine Harmful Algal Blooms*. HABHRCA 2004 stipulates that this report: 1) examine the causes, consequences, and economic costs of marine HABs, 2) describe the potential ecological and economic costs and benefits of possible actions for preventing, controlling, and mitigating HABs, 3) evaluate progress made by Federal research programs, and 4) make recommendations to improve coordination among Federal agencies with respect to research on marine HABs. The primary focus of this report is the fundamental scientific research that is the basis for improving HAB management and response. It is based, in part, on the new national plan, *Harmful Algal Research and Response: A National Environmental Science Strategy 2005-2015* (*HARRNESS*)[2].

State of the Science: Research Advances by Federal Programs

Many advances in understanding marine HABs have occurred in recent years in the United States, due in large part to Federal investments in marine HAB research. This research has been conducted through national research programs focused on HAB research and as part of other more general research programs. The two national, extramural HAB funding programs, Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) Program and Monitoring and Event Response for Harmful Algal Blooms (MERHAB) Program, have together funded approximately $100 million in marine HAB research since the programs began in 1996 and 2000, respectively. In addition,



at least 13 Federal agencies conduct significant marine HAB research as part of other research programs.

Major accomplishments of these research efforts fall into the five categories discussed below. Research accomplishments in HAB prevention, control, and mitigation are discussed briefly in this report and are covered in more detail in *HAB Management and Response: Assessment and Plan*[3] (Box 1.1).

Understanding HAB Causes and Controls and Developing Predictive Models

Research on HAB causes and controls, also referred to as 'bloom ecology and dynamics,' encompasses research aimed at understanding the biological, physical, and chemical factors that control HAB initiation, maintenance, transport, and decline. The ultimate products of research on HAB causes and controls are models of population growth and mortality and, potentially, predictive models of bloom dynamics and impacts. Much research has focused on this topic and, as a result, significant advances have been realized.

Cell physiology, organism life cycle, and genetic research has led to better understanding of how cells function, effective tools for detection (see next section), identification of known species in new areas, and discovery of new species. The linkages between cell physiology and toxicity have become clearer for some organisms, helping to explain why cells are more toxic at certain times. In addition, a better understanding of the role of resting stages in bloom initiation has improved predictive models. Tools have been developed for controlled testing of environmental factors that regulate growth and toxin production of the Florida red tide alga. Genetic research has also led to insight into harmful algal genes and their regulation, serving as a springboard for research to refine understanding of the biological aspects of bloom development.

Knowledge of historical bloom patterns has been gained from long-term monitoring* data sets. These data are revealing shifts in phytoplankton communities and occurrence of exceptional events. Long-term data are also being used to explore natural or human-induced drivers of this change.

Research on the role of nutrients has revealed relationships between increased anthropogenic nutrient loadings and prevalence of some species, such as *Pfiesteria* spp., some macroalgae, and *Pseudo-nitzschia* in the Gulf of Mexico. Other

A nontoxic bloom of the dinoflagellate *Lingulodinium polyedrum* along the coast of La Jolla, San Diego County. *Photo: Kai Schumann*

**The term monitoring as used in this document is not meant to convey requirements under regulation unless specified.*

research has shown that changes in nutrient quality (e.g., organic versus inorganic nutrients), not quantity, may favor proliferation of some harmful algal species.

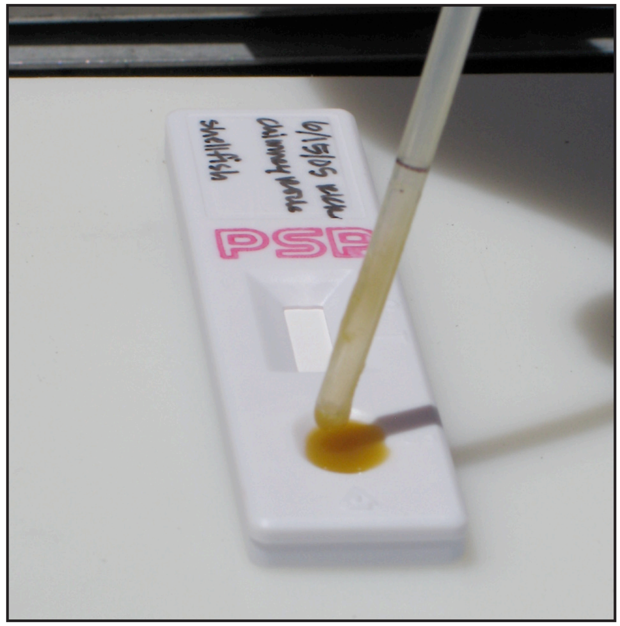
As a result of years of research, models that incorporate biological and physical data have been developed for specific HAB species prevalent in New England, Florida, and the Pacific Northwest. In New England, the model has explained patterns and variations in shellfish toxicity and has been used in demonstration mode to give weekly predictions of bloom status to resource managers since 2005. These model predictions have allowed managers to design more precise and selective shellfish harvesting closures, thereby minimizing economic impacts on local communities while protecting human health. Forecasts based on simpler models are also now operational in the Chesapeake Bay and in Florida.

Developing Detection Methods for Cells and Toxins

Managers rely on the ability to detect HAB cells and toxins to mitigate bloom impacts, and multiple methods are often needed because no method fulfills all purposes. Many new technologies for detecting HAB cells have emerged from studies on HAB physiology and molecular biology. New molecular-based assays have been and are continuing to be developed. In several regions of the country, these tools are used routinely for HAB detection and have led to better understanding of species distributions and identification of new species of concern. Deployable instruments for real-time, in-water detection of HABs have been developed as well. The ‘brevebuster’ optically detects the Florida red tide species (*Karenia brevis*) and can be deployed on automated underwater vehicles or on stationary platforms. The ‘environmental sample processor’, another deployable instrument that can detect several HAB species, was successfully deployed in Monterey Bay, California, where it detected the harmful diatom (*Pseudo-nitzschia*) and its toxin, domoic acid, in real-time.

A range of analytical methods for toxin detection—from very accurate and expensive laboratory analytical techniques to quick and easy screening methods for the field—are used to minimize the impacts of toxic outbreaks. Many agencies have been involved in improving toxin detection methods. As a result, there are newly developed methods being considered for regulatory testing of the toxins that cause paralytic and neurotoxic shellfish poisoning syndromes. These tests are more rapid, reliable, and efficient than the currently approved regulatory method. Other quick and easy toxin tests are being developed for rapid initial screening in the field. These tests reduce the number of samples taken for laboratory analysis, thereby saving time and money as components of tiered monitoring protocols.

Applying a shellfish sample to a qualitative field test for the PSP toxins (Jellett Rapid testing Systems, Ltd.)
Photo: Gregg Langlois, California Department of Health Services



Characterizing Toxins and Toxin Impacts

New instrumental techniques have been applied to the determination of both toxin chemical structures and their metabolites, and advances in chemical instrumentation have enabled chemists to determine toxin structures on smaller quantities of toxins. Several new marine toxins or metabolites have been characterized and more are being investigated. Newly identified compounds include the free radical-forming metal complex produced by *Pfiesteria* and the fish-killing karlotoxins.

The primary site of action of most of the major toxins has been established. Animal models have improved understanding of acute and chronic effects, including developmental effects of domoic acid, brevetoxins, and ciguatoxins. It is now known, for example, that domoic acid exposure can cause reproductive failure in California sea lions as well as behavior and memory impairment in rats. Human and wildlife case studies have helped define acute impacts, such as respiratory effects from aerosolized brevetoxins. Knowledge of effects from long-term, low-level exposures is still being established, but research with California sea lions suggests chronic effects, such as epilepsy and behavioral changes, occur with repeated, sub-lethal exposure to domoic acid.

Toxin detection in clinical matrices, such as blood and urine, is necessary to confirm and investigate toxin exposure and effects during outbreaks. Diagnostic tests are being developed for ciguatera toxin exposure in humans and other toxins in marine mammals. More accurate assessments of exposures will benefit studies of toxin occurrence and impacts.

Several promising therapeutic approaches to remediate HAB toxin exposure are also being explored, including the use of brevenal, a compound that counteracts the effects of brevetoxin.

Digging for clams is a tradition for many families in the Pacific Northwest.
Photo: Vera Trainer, NOAA

HAB impacts on food webs and fisheries

Research in this area has received less attention in the past than some of the other HAB-related issues. In addition to impacts on animal health (discussed in previous section), research to date has focused on changes in food web structure, transfer of toxins through the food web, and accumulation and elimination of toxin in food web components. Recent advances include identification of 'new' pathways for toxin entry into food webs, such as zooplankton, fish, and seagrass leaves for brevetoxins, which serve as additional modes of toxin transfer to marine mammals.

Understanding shellfish toxin accumulation and elimination will improve prediction and management of shellfish toxicity. Much of this work is ongoing. Some commercial bivalves have been shown to have saxitoxin resistance, which allows more rapid toxin accumulation, due to a genetic mutation. Genetic markers are in development to distinguish such toxin resistance. Furthermore, a model for domoic acid elimination in razor clams and crabs, which will be useful to predict how long it takes for contaminated shellfish to become safe for human consumption, is in development.

Assessing Public Health, Economic, and Sociocultural Impacts

The major acute seafood poisoning syndromes caused by HABs are well-defined. The geographic areas impacted by these syndromes are also well-known, but recent work has identified public health issues emerging in new areas, such as saxitoxin puffer fish poisoning in Florida and, potentially, ciguatera-producing organisms in the Northwestern Gulf of Mexico. A majority of the current public health surveillance efforts grew from the Centers' for Disease Control and Prevention initial response to the *Pfiesteria*-related outbreak in the late 1990s. For example, the Harmful Algal Bloom-related Illness Surveillance System has been developed and is being used in some states to capture human and animal health data as well as environmental data during HAB events.

Epidemiological studies on specific populations (cohort-based) have been limited, but one is currently underway in the Pacific Northwest with Native American infants, children, and adults who may be exposed to domoic acid through razor clam consumption. This research is making headway for identifying populations most at-risk for exposure and effects from toxic HABs.

In the last decade, several thorough, yet conservative, assessments of the economic impacts of marine HABs in the United States have been conducted. Additionally, assessments of individual events have been supported by Federal and state agencies and illustrate well the large economic impact that just one event can have on local communities. Cost/benefit studies of HAB management strategies and assessments of sociocultural impacts are new areas that are just starting to be addressed.

Coordination for Future Progress

Research advances over the last decade have been considerable and the benefits have been observed in improved management of the Nation's resources and better protection of humans and ecosystems. Federal involvement in and coordination of marine HAB research are important for continued progress and to meet common goals to protect human health, economies, communities, ecosystems, and fisheries. Opportunities for improved synergy and success of HAB research programs recur in a number of recent HAB reports, including *HARRNESS* [2] and the recent HABHRCA report, *Harmful Algal Bloom Management and Response: Assessment and Plan* [3] and can be categorized into the following four general themes:

1) basic research provides new understanding that feeds into developing strategies and tools for improved HAB management,

2) coordination between programs that perform HAB research in the environment and those that study human and community impacts is important,

3) programs dedicated to moving new information and technologies to operational use by managers will advance HAB response, and

4) a combination of extramural and intramural competitive and noncompetitive research is best able to meet the multiple goals for improving management of HABs and their impacts.

The Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health (IWG-4H), as the body fulfilling the role of the Interagency Task Force on HABs and Hypoxia, provides Federal coordination for HAB research and response. The IWG-4H may also cultivate Federal coordination through interaction with the HAB research and management communities via the U.S. National Office for HABs, the National HAB Committee, the Interstate Shellfish Sanitation Commission, the Working Group on Unusual Marine Mammal Mortality Events, the National Water Quality Monitoring Council, and various regional activities. Coordination at the international level, such as through participation in national and international meetings, will also be important for continuing progress and avoiding duplication of effort.

Chapter 1

Legislative Background and Report Process

1.1 Legislative Background

The Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 (HABHRCA, Public Law 105-383) was reauthorized by the Harmful Algal Bloom and Hypoxia Amendments Act of 2004 (HABHRCA 2004, Public Law 108-456). HABHRCA 2004 reconstituted the Interagency Task Force on Harmful Algal Blooms and Hypoxia, and required five reports to assess and recommend research programs on harmful algal blooms (HABs) and hypoxia in U.S. waters, including this *Scientific Assessment of Marine Harmful Algal Blooms* (Box 1.1). The Interagency Task Force on HABs and Hypoxia was incorporated into the Interagency Working Group on HABs, Hypoxia, and Human Health (IWG-4H, see page iii) of the Joint Subcommittee on Ocean Science and Technology (JSOST). The IWG-4H was tasked with implementing the requirements of both HABHRCA 2004 and the Interagency Oceans and Human Health Research Program established in the Oceans and Human Health (OHH) Act of 2004 (Public Law 1088-447; Box 1.2).

HABHRCA 2004 stipulates that this report 1) examine the causes, consequences, and economic costs of marine HABs (see Chapter 2), 2) describe the potential ecological and economic costs and benefits of possible actions for preventing, controlling, and mitigating HABs (see Chapters 2 and 3), 3) evaluate progress made by Federal research programs (see Chapter 3), and 4) make recommendations to improve coordination among Federal agencies with respect to research on marine HABs (see Chapter 4). The mandate to include information on efforts to prevent, control, and mitigate marine HABs (#2 above) is covered in more detail by the report *Harmful Algal Bloom Management and Response: Assessment and Plan*[3] (Box 1.3).

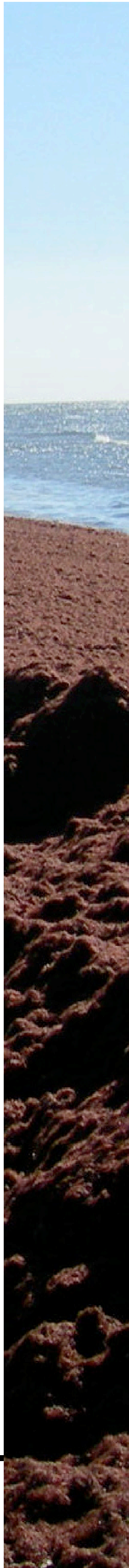
1.2 Report Process

The first marine HAB assessment, the *National Assessment of Harmful Algal Blooms in U.S. Waters*[6], was completed for Congress in 2000 in response to the original HABHRCA legislation. The current report builds on the earlier report to assess the U.S. HAB problem, but also takes an extra step to provide analysis of major research advances made by Federal agencies. Research covered goes back as far as 1996 to include projects that were precursors to the interagency Ecology and Oceanography for Harmful Algal Blooms (ECOHAB) Program, which began in 1997.

The primary focus of this report is the fundamental scientific research that is the basis for improving HAB management and response. Focus areas were derived from the report, *Harmful Algal Research and Response:*

Box 1.1. HABHRCA 2004 Reports and Assessments

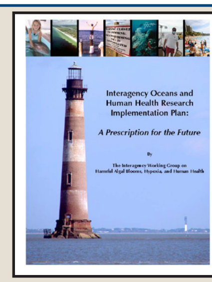
- Harmful Algal Bloom Management and Response: Assessment and Plan
  - National Assessment of Efforts to Predict and Respond to Harmful Algal Blooms in U.S. Waters (Prediction and Response Report)
  - National Scientific Research, Development, Demonstration, and Technology Transfer Plan for Reducing HAB Impacts (RDDTT Plan)
- Scientific Assessment of Freshwater Harmful Algal Blooms
- **Scientific Assessment of Marine Harmful Algal Blooms**
- Scientific Assessment of Hypoxia



A National Environmental Science Strategy 2005–2015 (*HARRNESS*)[2], which represents an intense multiyear collaboration among the HAB community to assess the state of HAB research and chart a way forward. The focus areas include bloom ecology and dynamics, food webs and fisheries, toxins and their effects, and public health and socioeconomic studies. However, a brief overview of prevention, control, and mitigation activities, based on the *Harmful Algal Bloom Management and Response: Assessment and Plan*[3] is also given. Social science research directions are considered in more detail in the report, *Harmful Algal Research and Response: A Human Dimensions Strategy* (*HARR-HD*)[1].

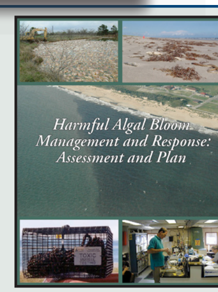
Information for this report was synthesized from several sources. This assessment draws strongly from the *HARRNESS* report[2], which was developed by the HAB research and management community using an open forum discussion of 200 participants at the second U.S. National HAB Symposium in 2003, a detailed web-based questionnaire yielding more than 1000 targeted responses, a workshop of 50 U.S. HAB experts in 2004, an advisory committee with Federal and management representatives, and a steering committee to assemble and review the most current information available for use in developing the document. White papers, written by members of the HARRNESS Steering Committee on the state of the science in preparation for the HARRNESS workshop, along with more recent scientific publications and reports, were used to develop this assessment. In addition, Federal agencies involved in marine HAB research provided information, drawing from project progress reports, about current research and accomplishments.

Box 1.2. Oceans and Human Health Act 2004



The OHH Act requires the National Science and Technology Council to establish an Interagency Oceans and Human Health Research Program to improve understanding of the role of the oceans in human health and establishes the National Oceanic and Atmospheric Association (NOAA) Oceans and Human Health Initiative as part of this interagency program. The JSOST IWG-4H, in addition to serving as the Interagency Taskforce on HABs and Hypoxia as called for in HABHRCA, was charged with the responsibility for coordinating the interagency OHH program and producing both the HAB-related and OHH-related reports to Congress. HABs are included as part of the OHH program scope, but the OHH Act specifically states that "nothing in this subsection is intended to duplicate or supersede the activities of the Inter-Agency Task Force on Harmful Algal Blooms and Hypoxia." The IWG-4H has prepared a 10-year Interagency OHH Implementation Plan[4], which was called for by the OHH Act. Coordination with HABHRCA activities is provided through the IWG-4H since it has responsibilities for OHH, HABs, and hypoxia.

Box 1.3. *Harmful Algal Bloom Management and Response: Assessment and Plan*



Two reports mandated by HABHRCA 2004, the Prediction and Response Report[5] and the RDDTT Plan (Box 1.1), were combined into one final report that addresses HAB prediction and response in the United States: the *Harmful Algal Bloom Management and Response: Assessment and Plan*[3]. The Prediction and Response Report reviewed and evaluated existing prediction and response programs and activities and highlighted options for improving those efforts. This assessment was made available for public comment via the Federal Register in fall of 2006. A workshop with participants from the HAB community (both management and research representatives from Federal, state, local, and tribal organizations and private industry) was held in June 2007 to address opportunities for advancement identified in the report and in the public comment period. The RDDTT Plan was then developed by drawing from the workshop results. The final combined report comprises a comprehensive evaluation and strategy developed with input by multiple stakeholders to improve the national and local response to HABs in U.S. waters.

Chapter 2

State of the Marine HAB Problem in the United States

Algae, in general, are beneficial because they provide the main source of energy that sustains marine life. However, a small percentage of algal species cause harm to humans, animals, and the environment through toxin production or excessive growth. The majority of these HAB species are phytoplankton, which are microalgae (microscopic, single-celled algae), that live suspended in the water. "Harmful algae" also include some microalgae that live attached to plants or other substrates as well as some species of macroalgae (i.e., seaweeds). Marine HABs refer to harmful blooms that occur in oceans, coastal waters, and estuaries. Major algal groups that cause problems in the United States are listed in Table 2.1. Freshwater and other inland HABs, including those that occur in the Great Lakes and upper reaches of estuaries, are covered in the HABHRCA report, the *Scientific Assessment of Freshwater Harmful Algal Blooms* [8] (Box 1.1).

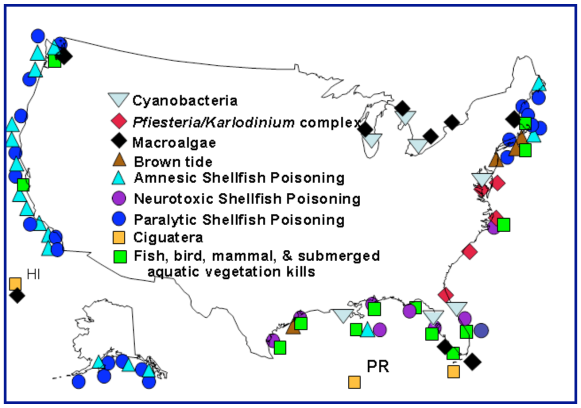


Figure 2.1. HAB events in the United States.

Although only a small percentage of the world's algal species are considered harmful, the geographic distribution of HAB events is broad with pervasive impacts. All coastal states in the United States have experienced HAB events over the last decade (Figure 2.1), and it is generally believed that the frequency and distribution of HABs and their impacts have increased considerably in recent years in the United States and globally[9,10,11,12,13,14]. Causes and consequences of HABs in the United States are discussed in general below. Specific HAB problems and impacts are discussed in more detail in the regional boxes throughout this chapter.

2.1. Causes

HABs are a natural phenomenon in coastal ecosystems, but human activities are thought to contribute to the increased frequency of some HABs. For example, although not all HABs occur in high nutrient environments, increased nutrient loading has been acknowledged as a likely factor contributing to the increased occurrence of high biomass HABs[13,14]. Other human-induced environmental changes that may foster development of certain HABs include changes in nutrient regimes[14], alteration of food webs by overfishing[15], introductions of nonindigenous species[16,17], and modifications to water flow[18]. It should also be noted that climate change will almost certainly influence HAB dynamics in some way since many critical processes governing HAB dynamics—such as temperature, stratification, upwelling and ocean circulation patterns, and freshwater and land-derived nutrient inputs—are influenced by climate[19,20]. The interactive role of climate change with the other factors driving the frequency and severity of HABs is an important topic currently in the early stages of research.

The specific causes of HABs are complex, vary between species and locations, and are not all well understood. In general, algal species proliferate

Table 2.1. Major HAB organisms causing problems in U.S. marine systems, their major toxins (if characterized), their direct acute impacts to humans and ecosystem health, and regions of the United States that have been impacted by these HAB organisms. 'Not characterized' indicates that toxins have been implicated but not characterized.

HAB Organism	Toxins	Acute Human Illness*	Direct Ecosystem Impacts	Impacted regions of the United States
Alexandrium spp.	Saxitoxins	Paralytic Shellfish Poisoning	Marine mammal mortalities	Northeast, Pacific Coast, Alaska
Aureococcus anophagefferens (Long Island Brown Tide)	Not characterized	--	Shellfish mortality, seagrass die-off	Northeast, Mid-Atlantic Coast
Aureoumbra lagunensis (Texas Brown Tide)	Not characterized	--	Seagrass die-off	Gulf of Mexico (Texas)
Dinophysis spp.	Okadaic Acid	Diarrhetic Shellfish Poisoning	--	New England, Gulf of Mexico, Pacific Coast
Gambierdiscus spp., *Prorocentrum* spp., *Ostreopsis* spp.	Ciguatoxin, Gambiertoxin, and Maitotoxin	Ciguatera Fish Poisoning	--	Gulf of Mexico (Florida, Texas), Hawaii, Pacific Islands, Puerto Rico and U.S. Virgin Islands
High biomass bloom formers	†	--	Low dissolved oxygen, Food web disruption	All regions
Karenia spp.	Brevetoxins	Neurotoxic Shellfish Poisoning, Acute respiratory illness	Fish kills, mortalities of other marine animals	Gulf of Mexico, South-Atlantic Coast
Karlodinium spp.	Karlotoxins	--	Fish kills	Mid- and South- Atlantic Coast, Gulf of Mexico (Alabama, Florida)
Macroalgae	‡	--	Low dissolved oxygen, seagrass and coral overgrowth and die-off, beach fouling	All regions
Marine Cyanobacteria (CyanoHABs) (*Lyngbya* spp.)	Lyngbyatoxins	Dermatitis	Seagrass and coral overgrowth and die-off, beach fouling	Gulf of Mexico and South-Atlantic Coast (Florida), Hawaii and Pacific Territories
Pfiesteria spp.	Free radical toxin, others not characterized	--	Fish kills	Mid- and South-Atlantic Coast
Pseudo-nitzschia spp.	Domoic Acid	Amnesic Shellfish Poisoning	Mortality of seabirds and marine mammals	Pacific Coast, Alaska, Gulf of Mexico, Northeast, Mid-Atlantic Coast
Pyrodinium bahamense	Saxitoxins	Puffer Fish Poisoning	--	South-Atlantic Coast (Florida)
Some raphidophytes (e.g., *Heterosigma akashiwo*, *Chattonella* spp.)	Brevetoxins (*Chattonella*), other icthyotoxins not characterized	--	Fish kills	Pacific Coast (Washington), Mid-Atlantic Coast

*This table only captures the major acute human illnesses associated with these HAB species. Other, less severe acute health effects, such as skin irritation, may occur with some of these HAB groups. Chronic effects, such as tumor promotion, can also occur. A table of short- and long-term health effects is given in *HARRNESS* [2].
†Some high biomass bloom formers may produce toxins.
‡Some macroalgae have been shown to produce bioactive compounds, such as dopamine and dimethylsulfoniopropionate (DMSP), which may have direct ecosystem effects[7].

when environmental conditions (e.g., nutrient and light availability, temperature, and salinity) are optimal for cell growth. Other biological (e.g., vertical migration, grazing, viral infection, and parasitism) and physical (e.g., transport) processes determine if enhanced cell growth will result in biomass accumulation. The challenge for understanding the causes of HABs stems from the complexity of these biological, chemical, and physical interactions and their variable influence on growth and bloom development among different species[21]. Further, environmental control and genetic variation of toxin production, vertical migration, life cycles, and cell physiology add to the challenge of understanding HAB dynamics. The complexity of interactions between HABs, the environment, and other plankton complicate the predictions of when and where HAB events will occur. Knowledge of how all these factors control HAB initiation, maintenance, and decline is the subject of much research highlighted in this report. This knowledge is a critical precursor for advancing HAB management[3].

2.2. Consequences

HAB impacts are variable in their scope and severity and depend on the causative species. Some harmful microalgae produce potent toxins which cause illness or death in humans and other organisms, including endangered species. Humans, wildlife, and domestic animals can be exposed to algal toxins via contaminated food, water, or aerosols, depending on the toxin. Other HAB species are nontoxic to humans and wildlife but degrade ecosystems by forming such large blooms that they alter habitat quality through overgrowth, shading, or oxygen depletion (hypoxia), thus adversely affecting corals, seagrasses, and bottom-dwelling organisms. High biomass blooms of certain nontoxic harmful algae can also harm fish and invertebrates by damaging gills or by causing starvation or low reproduction due to poor food quality. Human health and ecosystem impacts of HABs can, in turn, have significant economic and sociocultural ramifications. Some economic impacts on coastal communities have been studied[22], but assessments of sociocultural consequences and community vulnerabilities are also needed to understand the full range of HAB impacts and to devise strategies to mitigate them[1]. The general impacts of HABs on human health, ecosystems, economies, and coastal communities are reviewed in the following sections. Regional impacts are highlighted in Boxes 2.2-2.6.

Human Health Impacts

The most severe human health impacts occur from consumption of shellfish or fish contaminated with HAB toxins. Shellfish, such as clams, mussels, and oysters, pose a particular threat to human consumers because these organisms filter large volumes of water as they feed and, as a result, can rapidly concentrate algal toxins in their tissues. Shellfish poisonings that are a threat in the United States include neurotoxic shellfish poisoning (NSP), paralytic shellfish poisoning (PSP), amnesic shellfish poisoning (ASP), and diarrhetic shellfish poisoning (DSP). Finfish can also accumulate toxins to harmful levels by feeding directly on toxic algae or feeding on grazers of toxic algae. Ciguatera fish poisoning (CFP) occurs in sub-tropical and tropical waters and is the most common finfish poisoning, with more than 400 fish species implicated as potential vectors[2] (http://www.whoi.edu/redtide/page.do?pid=14276). Saxitoxin puffer fish poisoning is a type of finfish poisoning posing an emerging threat in Florida[23]. In addition to the human health effects from eating contaminated seafood, acute human health impacts may occur following contact with water or breathing aerosolized toxin.

The effects of chronic or repeated, low-level HAB toxin exposure are also of concern. Cultural traditions, like harvesting marine mammals for subsistence or consuming more seafood, may place certain populations at increased risk for recurring exposure to toxins at low levels. The potential public health impacts of these exposures are unknown.

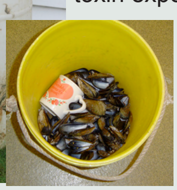
The risk of human illness from algal toxin exposure can be dramatically reduced or prevented through harvesting closures and beach warnings, which are issued based on data provided through rigorous state monitoring programs. Several human poisonings in 2007 (Box 2.1) due to harvesting by individuals from unregulated locations highlight the necessity of these monitoring programs. Illnesses are likely underreported, especially in cases where symptoms are non-specific and potentially attributed to other causes.

Ecosystem Impacts

Massive fish kills are perhaps the most commonly observed impact of HABs on wildlife, but HABs can detrimentally affect many aspects of marine ecosystems. Algal toxins have caused deaths of whales, sea lions, dolphins, manatees, sea turtles, birds, and wild and cultured fish and invertebrates[24]. An increasing number of marine mammal unusual mortality events (UMEs) are being linked to HAB toxins, which is suggested to be a reflection of the increasing occurrence of HABs in the United States[25].

Box 2.1. Human Poisonings in 2007 Highlight Importance of Monitoring and Outreach Programs

In 2007, severe cases of human illness in Maine and Alaska occurred as a result of individuals harvesting shellfish from unmonitored locations. In Maine, four people were hospitalized within hours of eating saxitoxin-contaminated shellfish harvested from a barrel floating off the coast of Maine. The barrel was thought to have been transported from an area where the toxic alga, *Alexandrium*, was in high concentrations. In Alaska, one individual became ill after consuming butter clams recreationally-harvested from an unregulated area. Because of the difficulty and high cost of sampling the Alaska coastline, the Alaska Department of Environmental Conservation can only test recreational beaches on a random basis and discourages recreational harvesting by instructing that no noncommercial, recreational beaches are safe for clamming. These illnesses reiterate the dangers of harvesting shellfish from unmonitored locations and stress the importance of monitoring and outreach programs for reducing risks of human illness from algal toxin exposure.



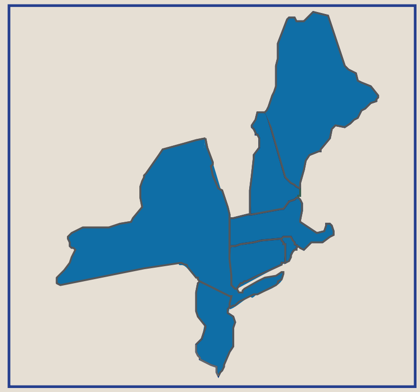
Saxitoxin contaminated mussels (right) harvested from a floating barrel (left) in the Gulf of Maine resulted in hospitalization of four individuals.
Photos: Maine Department of Marine Resources

The pathways by which toxins are transferred to higher trophic level animals are often unknown. Although filter-feeding fish provide one direct link[26], other pathways are suspected—including inhalation of aerosolized toxin by marine mammals breathing at the surface in the midst of a bloom. Furthermore, recent manatee deaths in Florida have been ascribed to brevetoxin accumulation in layers on the outside of aquatic plants[27]. In addition, dungeness crabs on the U.S. west coast can accumulate domoic acid from razor clams on which they prey[28]. Sometimes a HAB toxin is found to be the cause of a mortality event, but there is no immediately obvious source of the toxin, suggesting that bloom impacts may be temporally or spatially separated from the causative bloom or that the pathways of exposure are unknown.

Moreover, algal toxins can exacerbate the impacts of other stressors and indirectly lead to wildlife mortalities. Sick or dying animals are often the first indicators of a toxic bloom and may serve as sentinels for potential harmful effects in other species. In addition to causing acute mortality via toxin production, HABs can also release compounds or have defensive cell wall structures that impair normal functions of fish and invertebrates and lead to harm and death of these organisms.

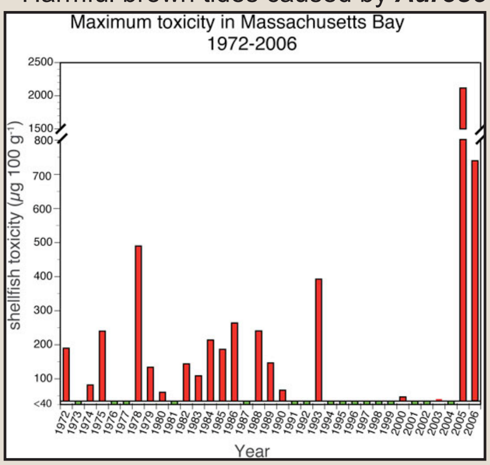
Degraded habitat quality is another ecosystem impact of toxic and nontoxic HAB species. High biomass blooms are a common type of event that can cause hypoxia or anoxia (low or no dissolved oxygen), which suffocates fish and bottom-dwelling organisms and can sometimes lead to hydrogen sulfide poisoning. High biomass blooms can also directly inhibit growth of beneficial vegetation by blocking sunlight penetration into the water column[29]. Macroalgal blooms also reduce sunlight penetration and can overgrow or displace seagrasses and corals[30] as well as foul beaches. Finally, HAB-inflicted mortalities can degrade habitat quality indirectly through altered food webs or hypoxic events caused by the decay of dead animals.

Box 2.2. HABs and HAB Impacts in the Northeastern United States



Blooms of the saxitoxin-producing alga, ***Alexandrium fundyense***, are a recurrent problem in the Northeastern United States. Shellfish closures to protect humans from paralytic shellfish poisoning (caused by exposure to saxitoxin) have occurred every year for the past three decades with significant economic impacts to fishers and businesses in the region. In 2005 and 2006, *A. fundyense* blooms were the worst the region had experienced since 1972. Direct economic impacts on the shellfish industry from inshore shellfish closures in 2005 were estimated to be as high as $18 million in Massachusetts alone[33]. In addition, most molluscan shellfisheries on Georges Bank in the Gulf of Maine have been closed since 1989. Other parts of the ecosystem are affected by these blooms as well. For example, saxitoxins were found in fecal samples from endangered North Atlantic Right Whales and in their zooplankton food, leading to the hypothesis that algal toxin exposure via zooplankton may be a contributing factor to the population's failure to recover[34]. Much has been learned about *A. fundyense* ecology and bloom dynamics over the last decade[35] (see Chapter 3), which has been critical for improving management and lessening HAB impacts in the region.

Harmful brown tides caused by ***Aureococcus anophagefferens***, often called the "Long Island Brown Tide," have occurred in estuaries along the East Coast since the mid 1980's, resulting in significant ecosystem and socioeconomic impacts in the region. Brown tides devastated the Long Island scallop industry, with an estimated $3.8 million per year monetary loss (2006 dollars)[36], and caused a significant decline in eelgrass habitat. Blooms of *A. anophagefferens* have been shown to cause recruitment failure of other commercially important bivalves as well, such as mussels and hard clams. *A. anophagefferens* may also be a poor nutritional source for zooplankton, thus inhibiting their growth and survival during large blooms. *A. anophagefferens* brown tides seem to grow well in environments with high organic and low inorganic nutrients, so these blooms are not a direct response to increased nutrients, but rather may result from a change in the ratio of inorganic and organic nutrients[37,38]. Research has shown that mortality from grazing and viruses is also important.

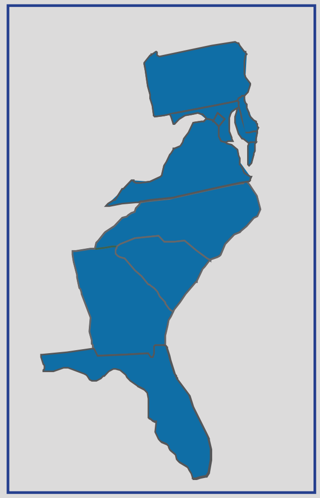


Long-term cycles are apparent in shellfish toxicity associated with *Alexandrium*. Following a major regional bloom in 1972, Massachusetts Bay had frequent outbreaks of toxicity for the next 20 years (shown here), presumably due to the introduction of resting cysts in the western Gulf of Maine and their persistence as a result of cyst deposition during subsequent blooms. Following a 10-year interval with no toxicity in the bay, another major bloom occurred in 2005. History would suggest that the region may have entered another high toxicity phase of the cycle, signaling a decade or more of frequent and intense toxicity. *Graphic: Don Anderson, WHOI*

Domoic acid-producing ***Pseudo-nitzschia*** spp. are also found in New England waters where managers now monitor shellfish for presence of the toxin. Other less-severe or less-persistent marine HAB problems in the Northeast include macroalgal blooms and fish-killing raphidophyte blooms.

Diarrhetic shellfish Poisoning (DSP) could also be a potential problem in the future because the species that produce the toxins associated with this illness occur in the Gulf of Maine[39]. In 1984, one shellfish sample from Narragansett Bay, Rhode Island, was found positive for DSP toxins at time when the ***Dinophysis acuminata***, a known producer of DSP toxins, was relatively abundant[40].

Box 2.3. HABs and HAB Impacts along the Mid- and South-Atlantic Coasts



As discussed in Box 2.2, harmful brown tides caused by ***Aureococcus anophagefferens*** occur in estuaries all along the East Coast, including Delaware, Maryland, and Virginia waters. Studies indicate that *A. anophagefferens* was present in Maryland and Virginia waters as early as 1993, but that there may be a trend of increasing frequency and magnitude of blooms in the region[41]. A reduction in growth of hard clams due to brown tide has been observed in Mid-Atlantic coastal bays[42]; other general impacts of east coast brown tides are discussed in more detail in Box 2.2.

North Carolina was the first state to report fish kills associated with an outbreak of ***Pfiesteria*** spp.[43]. Since then, *Pfiesteria* has been implicated throughout the region and much has been learned about its ecology and toxicity[44,45,46]. Fish kills attributed to ***Karlodinium veneficum*** have also occurred annually since 1998 along the Atlantic Coast, and karlotoxins have been found in samples taken from Delaware, Maryland, North Carolina, South Carolina, Georgia, and Florida[47]. In Maryland, the *Pfiesteria* event in 1997 resulted in about $43 million (or $53 million in 2006 dollars) in lost seafood sales in just a four month period, primarily due to consumer fears[32].

Chattonella* cf. *verruculosa has been associated with fish kills and brevetoxins in Maryland and Delaware[48]. Other potentially toxic **raphidophytes** (***Chattonella*** sp., ***Fibrocapsa*** sp. and ***Heterosigma*** sp.) have been identified in Mid-Atlantic waters, including retention ponds in South Carolina[49] (see Box 2.6 for more about *Heterosigma* impacts).

Cochlodinium polykrikoides bloom in Chesapeake Bay tributary.
Photo: Christy Everett, Chesapeake Bay Foundation

In Maryland's Chesapeake Bay and oastal bays, there has been a problem for years with **high biomass HABs**, comprising numerous algal species, due to nutrient over-enrichment in the region[44]. For example, in late summer of 2007, a putatively toxic, high-biomass bloom of ***Cochlodinium polykrikoides*** in the James River, Virginia, spread into the Chesapeake Bay and caused fish kills, beach closures, and public alarm. In addition, the Chesapeake Bay experiences blooms of ***Prorocentrum minimum*** annually, which have been associated with reduced growth of shellfish and seagrass declines within bloom areas[50]. These blooms can also lead to low dissolved oxygen, which can result in fish and shellfish kills.

In 2002, researchers discovered that the Atlantic strain of ***Pyrodinium bahamense,*** found in Florida's Indian River Lagoon and Banana River, produced saxitoxin and was associated with the first incidence of saxitoxin in puffer fish in the United States. Since 2002, 28 cases of illness associated with eating puffer fish from Indian River Lagoon, Florida have been reported (http://research.myfwc.com/features/view_article.asp?id=18918), resulting in an indefinite ban on recreational fishing of all puffer fish species[23].

Coral reefs in southeast Florida have been devastated by overgrowth of an invasive green **macroalga**, ***Codium isthmocladum***, which has also been linked to increasing land-based nutrient pollution[51] (also see Box 2.4 for more on macroalgal blooms in Florida).

Blooms of ***Karenia*** spp. (see Box 2.4 for more on *Karenia* and its impacts) occur occasionally along the southeast Atlantic Coast[52,53]. Additionally, ***Pseudo-nitzschia*** spp. and domoic acid have been detected in North Carolina waters, and domoic acid-producing *Pseudo-nitzschia* spp. have been isolated from the Chesapeake Bay[54].

Economic Impacts

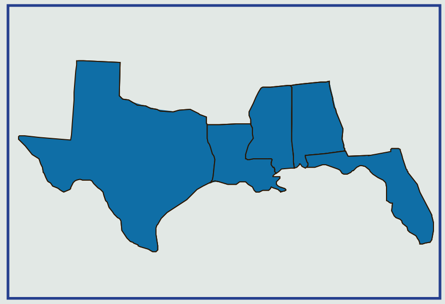
HAB events impact a variety of economic sectors in a manner that can have serious and significant negative effects on local economies[31]. Human poisonings due to HABs can lead to lost wages and work days as well as costs associated with medical treatment. The impact of HABs is felt in various components of the commercial fishing industry from loss of product (e.g., direct fish mortalities, harvesting closures), higher processing costs, and decreased consumer demand. Even when parts of the commercial fishing industry are insulated from the biological effects of a HAB event, indirect or "halo" effects can result in losses due to public fear. For example, it is estimated that $43 million (which would be approximately $56 million in 2007 dollars) in seafood sales were lost in the state of Maryland as a result of halo effects following the 1997 *Pfiesteria* bloom[32]. Other important economic considerations associated with HABs include lost revenue from tourism and recreation as well as expenses associated with monitoring and management. Hoagland and Scatasta[22] estimated that the annual economic impact due to marine HAB events in the United States averages $82 million per year. Given that documentation is sparse on overall impacts from individual events, these estimates are likely conservative. Surplus losses (i.e., changes in economic value) and factors with uncertain monetary values (e.g., wild fish kills) were not considered. Estimates of lost revenue from individual events (Boxes 2.2-2.7) highlight that this annual average for the Nation may be too conservative.

The industry vessel *Misty Dawn* collecting ocean quahogs for toxicity testing.
Photo: FDA

Sociocultural Impacts

Social impacts encompass changes to "the ways in which people live, work, play, relate to one another, organize to meet their needs, and generally cope as members of a society"[81]. The public health, ecosystem, and economic impacts discussed above can all have sociocultural consequences. Direct sociocultural impacts of HABs, other than those to human health and the economy, have not been systematically documented but have been described in some cases. For example, along the Washington and Oregon coasts, tens of thousands of people visit to harvest razor clams recreationally, but due to high levels of the HAB toxin domoic acid, there have been a number of closures to the recreational fishery since 1991, including three year-long closures[2]. These closures have not only resulted in economic losses but also in an erosion of community identity, community recreation, and the traditional way of living for native coastal cultures[1] (Box 2.5). In Florida, aerosolized toxins from *Karenia brevis* blooms can cause respiratory distress and prevent susceptible individuals from visiting the beach or participating in nearby outdoor activities (Box 2.4). Prolonged harvesting closures or noxious HAB events can also lead local residents to mistrust seafood and water safety[1]. Furthermore, the *HARRNESS* report[2] recognized that there are many groups whose lifestyles can be affected indirectly, such as veterinarians when animals become ill or environmental advocates and community volunteers when natural resources are degraded. The need for better assessments of social impacts is highlighted in the *HARR-HD* report[1] and in the *Harmful Algal Bloom Management and Response: Assessment and Plan*[3].

Box 2.4. HABs and HAB Impacts in the Gulf of Mexico



Karenia brevis, the Florida Red Tide and Texas Red Tide organism, is an alga that produces potent toxins that can cause human respiratory distress, toxic shellfish, animal mortality, and water discoloration. *K. brevis* was first identified in Florida in 1947, but anecdotal reports in the Gulf of Mexico date back to the 1530s. Blooms form in the Gulf of Mexico almost every year, most often off the west coast of Florida and generally beginning in the late summer and fall. They also occur, although less frequently, along the Texas and Mexican coasts[55] and even less frequently off of Alabama, Mississippi, and Louisiana[56]. Blooms have recently been discovered to be a mixture of *Karenia* species, although *K. brevis* usually dominates[57].

Several *Karenia* species, including *K. brevis*, produce brevetoxins, which can kill fish, birds, and marine mammals and are a threat to human health. Beachgoers and people working or living near the water can be exposed via sea spray aerosols to these neurotoxins, resulting in respiratory irritation in healthy people and potentially debilitating acute events in people with underlying respiratory illnesses such as asthma. The long-term consequences of recurrent exposure to these toxic aerosols are unknown. Furthermore, there have been dramatic impacts to the environment, including massive fish and invertebrate kills, sea bird die offs, and marine mammal unusual mortality events which have impacted endangered manatees as well as bottlenose dolphins. Steidinger et al.[58] estimated economic impacts in Florida from *K. brevis* blooms to be at least $15-25 million per year (which would be $18-30 million per year in 2006 dollars). Further, economic impacts from a red tide in Texas in 2000 were estimated to be at least $9.9 million (or $11.6 million in 2006 dollars) in Galveston County alone due to commercial oyster fishery closures (to protect against neurotoxic shellfish poisoning), lost tourism, and costs of beach cleanup[59].

Dead fish on Texas Coast caused by *Karenia* bloom.
Photo: The Facts, Brazoria County, Texas.

Most cases of **ciguatera fish poisoning** (CFP) on the U.S. mainland are reported from Florida, but several recent cases of CFP have been associated with eating reef fish caught in the northwestern Gulf of Mexico, resulting in an advisory letter from FDA (http://www.fda.gov/bbs/topics/NEWS/2008/NEW01790.html). In general, the soft bottom environment of northwestern Gulf of Mexico provides poor habitat for ***Gambierdiscus*** spp., some of which are known to produce ciguatoxin. *G. toxicus*, the dominant species of concern, has been found in the Flower Garden Banks National Marine Sanctuary and in the northwestern Gulf of Mexico associated with petroleum production platforms which provide hard substrate. It is not yet clear if the ciguatoxin in fish is coming from the local *G. toxicus* or if the fish transport the toxin in from some other place[60]. Ciguatera in U.S. territorial waters, including Puerto Rico and the U.S. Virgin Islands, account for the majority of public health costs associated with marine HABs[31].

The Texas brown tide organism, ***Aureoumbra lagunensis***, causes brown tides similar to *Aureococcus anophagefferens* (Boxes 2.2 and 2.3) but is unique to the Gulf of Mexico. *A. lagunensis* was first documented in Laguna Madre, a hypersaline bay in Texas. It has since been found in Florida and Mexico. Texas brown tide resulted in the loss of over 2,000 acres of shoalgrass habitat in Laguna Madre, Texas due to long-term light limitation during a bloom that lasted from 1989-1997[29].

Species of ***Pseudo-nitzschia*** are present in coastal waters of the Gulf of Mexico, and isolates from the region have been shown to produce the neurotoxin, domoic acid. Domoic acid has been detected in plankton samples, but no human illnesses have been reported. Domoic acid has also been found at low levels in the urine and stomachs of dolphins during marine mammal mortality investigations in Florida, but the role of domoic acid in the mortalities in unclear (http://www.nmfs.noaa.gov/pr/pdfs/health/ume_bottlenose_2004.pdf). There is evidence that *Pseudo-nitzschia* abundance in the Gulf has increased as a result of eutrophication[61,62], which suggests a potential for increased risks in areas of the Gulf where nutrient inputs may be increasing.

Macroalgal blooms, often comprising multiple species, have become a large problem in southwest Florida. In Lee County, Florida, large red drift algal blooms wash ashore, making beaches unsuitable for recreation. These blooms have been linked to land-based sources of nutrient inputs in the region[63]. Also see Box 2.3 for information on macroalgal blooms on the east coast of Florida.

Red drift algae: Red drift algae on Sanibel Island, Florida, in January 2007.
Photo: Mike Valiquette, PURRE Water Coalition

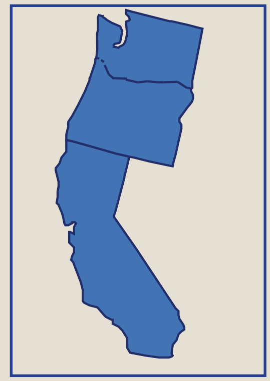
Lyngbya, a filamentous, nitrogen-fixing cyanobacteria that can form large mats and overgrow coral reefs, is responsible for large nuisance blooms in some Florida estuaries and bays, including Tampa Bay, nearshore coral reef environments of the Florida Keys, and reefs off the southeastern coast of Florida. Some marine species of *Lyngbya* are a public health concern because they produce toxins that can cause dermal lesions[64] and are tumor promoters[65].

Dinophysis acumita, which produces toxins that cause diarrhetic shellfish poisoning, bloomed along the Texas coast in March 2008 and resulted in shellfish harvesting closures to protect human health.

Karlodinium blooms were also associated with fish kills in Weeks Bay, Alabama in the summer of 2007 (see Box 2.3 for more about *Karlodinium*).

Violet Goby showing hemorrhaging characteristic of karlotoxin exposure.
Photo: Lucie Novoveska, Dauphin Island Sea Lab

Box 2.5. HABs and HAB Impacts along the Pacific Coast



Domoic acid-producing ***Pseudo-nitzschia*** blooms are a recurrent problem along the entire Pacific coast of the United States. In the Pacific Northwest, research indicates that the seasonal Juan de Fuca Eddy, a nutrient-rich, retentive physical feature off the Washington coast, serves as an incubator for growth of *Pseudo-nitzschia* and other algae (see Sections 3.2.3 and 3.4). Toxic amnesic shellfish poisoning (ASP) events along the Pacific Northwest coast depend on factors that control transport processes from the eddy to the shore[66]. *Pseudo-nitzschia* blooms have significant effects on commercial and recreational fisheries and local communities in Washington and Oregon. For example, the razor clam fishery in Washington is a significant source of revenue for tourism-dependent businesses, such as restaurants and motels, an important source of community identity, and the basis for subsistence of coastal native cultures. Periodic and sometimes prolonged closures of the recreational fishery have diminished the collective identity of surrounding communities and decreased opportunities for family and community recreatio[1] Closures in 2002-03 resulted in an estimated $10-12 million in lost revenue[67].

Pseudo-nitzschia australis cells under light microscopy. This sample was collected off the Los Angeles coast during a highly toxic bloom in 2007.
Photo: Astrid Schnetzer, University of Southern California

In California, blooms of *Pseudo-nitzschia* are recurrent and have caused large numbers of seabird and marine mammal deaths annually since 1998. In fact, it was a sea lion unusual mortality event in 1998 that brought about awareness of the threat of domoic acid to marine mammals in California[68]. Domoic acid exposure may lead to permanent brain damage, reproductive failure, and death in marine animals; commonly observed effects include seizures and head weaving[68]. Domoic acid can also have significant chronic effects, such as epilepsy and behavioral changes, due to repeated exposures at sub-lethal levels[69]. In 2007, domoic acid levels in water samples from southern California were reported as some of the highest ever recorded in natural samples[70].

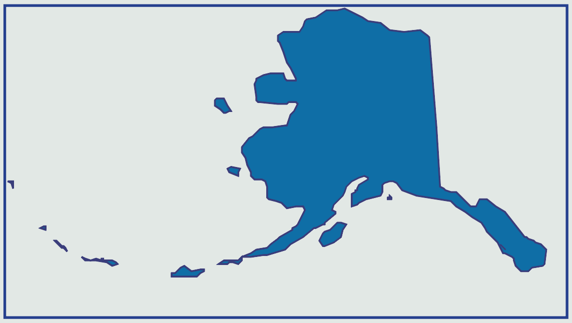
Alexandrium catenella, which produces paralytic shellfish poisoning (PSP) toxins, is prevalent in Washington, Oregon, and California where seasonal harvesting closures are common to protect humans from PSP. For example, an annual quarantine on sport-harvested shellfish is issued for the entire coast of California, usually from May 1 to October 31. Commercial harvesting undergoes stringent sampling to protect consumers from both PSP and ASP.

Blooms of the fish-killing raphidophyte, ***Heterosigma akashiwo***, have been documented in the Pacific Northwest annually since the 1960s[71] with the first major bloom that killed commercial net pen fish in 1989[72]. Wild fish kills are likely underreported because wild fish tend to sink when killed by *Heterosigma*. The mechanism by which *Heterosigma* kills fish is not well understood, but no persistent toxin has been characterized. Blooms of the raphidophyte, ***Chattonella***, also cause fish kills in the region. *Heterosigma* has also formed high biomass, nuisance blooms in California[73].

Macroalgal blooms are a problem in Washington's coastal waters where they harm seagrasses, fish, and invertebrates due to hypoxia and potentially due to the production of bioactive compounds[7,74].

In California, ***Dinophysis*** could pose a potential threat in the future because abundance of *Dinophysis* has been correlated with low levels of diarrhetic shellfish poisoning toxins in mussel samples from Monterey Bay[75].

Box 2.6. HABs and HAB Impacts in Alaska



Alexandrium catenella is also a widespread problem in Alaska. There were 51 reported cases of paralytic shellfish poisoning (PSP) in humans in Alaska from 1995-2000 (http://www.pices.int/publications/scientific_reports/Report23/HAB_US.pdf), and most of these cases occurred on Kodiak Island as a result of subsistence harvesting. More recently, in 2007, there was a case of PSP illness in Alaska associated with consumption of sport-harvested butter clams (http://www.dec.state.ak.us/psa/2007/PSA_for_PSP.pdf). Because of PSP and the high cost involved in monitoring the entire Alaska coastline, bivalves in Alaska are an underutilized resource.

There is a general perception that ***Pseudo-nitzschia*** spp. are causing similar problems in Alaska waters as in Washington, Oregon, and California. There have been incidents of amnesic shellfish poisoning toxins in Alaska[76], but it is difficult to find data to assess the threat, possibly because most shellfishing is already closed in Alaska due to PSP.

Overall, there is little information on impacts of biotoxins from *Alexandrium* and *Pseudo-nitzschia* to Native Alaskan populations who rely on subsistence foods such as seabird eggs and marine mammal tissues.

Box 2.7. HABs and HAB Impacts in Hawaii and the Pacific Territories

Ciguatera Fish Poisoning (CFP) is a problem in Hawaii, Guam, and other Pacific Island territories. From 1996 to 2005, the Hawaii State Department of Health received reports of 250 separate incidents of CFP involving 470 individuals. ***Gambierdiscus toxicus*** is the primary known CFP toxin producer found in Hawaii, but other species of potential concern have also been isolated (see Section 3.2.1.6). The environmental factors leading to CFP outbreaks are not well understood, in large part due to the patchiness in time and space of the outbreaks. Prevention of exposure to CFP is also challenging because of this patchiness.

Macroalgal blooms have been a recurring problem for the past two decades in Maui. Macroalgae overgrowth adversely affects corals and accumulates in odorous masses on some Maui beaches. These blooms are estimated to cause over $20 million a year in lost tourism revenues and decreased property values[77,78]. Evidence suggests that these blooms may be linked to anthropogenic nutrient inputs (see Section 3.2.6).

Blooms of the marine cyanobacteria, ***Lyngbya majuscula***, have also been a problem in Hawaii and Guam. *L. majuscula* was first implicated as the cause of acute contact dermatitis in Hawaii in 1959[79]. In Guam, the marine cyanobacterial blooms have been linked to fish kills[80].

Chapter 3

Federal Research on Marine HABs in the United States

Major advances in understanding the causes and impacts of marine HABs have occurred in recent years, due in large part to Federal investments in marine HAB research. Research has been conducted as part of national research programs focused on HAB research and at the individual project level as a part of other research programs (Table 3.1). It is also important to recognize that state and local agencies have a major role in monitoring blooms and alerting the public to health threats posed by HABs. Some states either have active research programs or participate in Federally-funded extramural research programs (see Appendix I for state activities).

Information on the state of research for this chapter was gathered via: 1) a request for information from Federal agencies involved in various aspects of HAB research and response, 2) a careful review of the *HARRNESS* report[2], and 3) public information on the web. An overview of Federal program and agency focus areas for marine HAB research is given in Section 3.1. Programs focused solely on HABs are discussed in Section 3.1.1, and agencies conducting HAB research as part of other programs are discussed in Section 3.1.2. A more detailed program analysis is also given in Section 3.1 for the ECOHAB and Monitoring and Event Response for HABs (MERHAB) Programs, the two national extramural funding programs for HAB research authorized by HABHRCA in 1998 and 2004. Major research efforts and accomplishments are discussed by research topic in Section 3.2, with contributing agencies emphasized with blue font. Highlights of major advances and their management implications are provided in Boxes 3.1-3.6.

3.1. Program and Agency Research Focus Areas

3.1.1. Research Programs Focused on Marine HABs

Interagency ECOHAB Program

The ECOHAB Program, authorized by HABHRCA 1998 and 2004, is a multi-agency program comprising the National Oceanic and

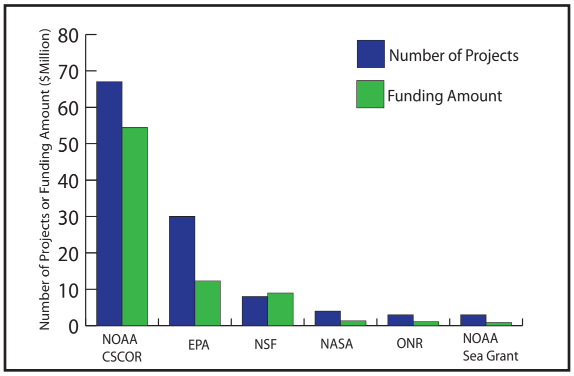


Figure 3.1. Marine HAB ECOHAB projects (blue) and the funding amounts (green) supported by the different agency partners in ECOHAB. Projects shown include the total supported (111 projects, $78 million) from fiscal years 1997 to 2008.

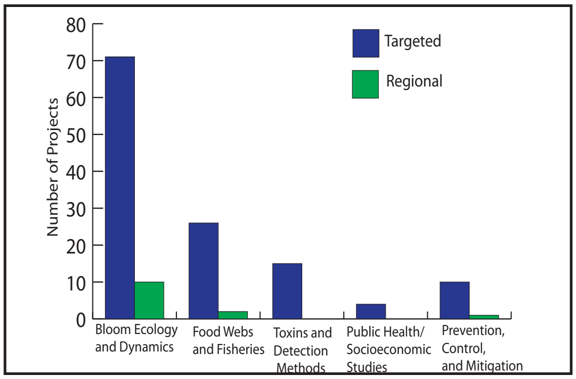


Figure 3.2. Marine HAB ECOHAB targeted (blue) and regional (green) projects categorized by the revised *HARRNESS*[2] research categories. Projects shown include the total supported from fiscal years 1997 to 2008. Projects can be counted in more than one research category.

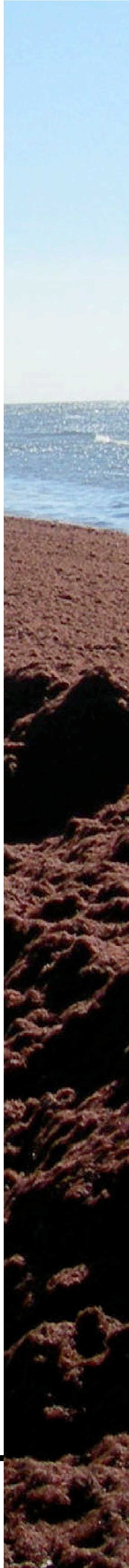


Table 3.1 Federal agencies involved in marine HAB research and response.

Federal Programs Focused on HAB Research			
Agency	**Program or Office**	**Extramural**	**Intramural**
National Oceanic and Atmospheric Administration (NOAA) U.S. Environmental Protection Agency (EPA) National Science Foundation (NSF) National Aeronautics and Space Administration (NASA) Office of Naval Research (ONR)	Ecology and Oceanography of Harmful Algal Blooms (ECOHAB)		
NOAA	National Centers for Coastal Ocean Science (NCCOS) Monitoring and Event Response for Harmful Algal Blooms (MERHAB)		
NOAA	NCCOS Harmful Algal Bloom Event Response Program		
NOAA	NCCOS Marine Biotoxins Program		
NOAA	Northwest Fisheries Science Center (NWFSC) Harmful Algal Bloom Program		

Federal Agencies Conducting HAB Research as Part of Other Programs			
Agency	**Program or Office**	**Extramural**	**Intramural**
Centers for Disease Control and Prevention (CDC)	National Center for Environmental Health (NCEH)		
EPA	Office of Research and Development (ORD)		
	Gulf of Mexico Program		
Food and Drug Administration (FDA)	Center for Food Safety and Applied Nutrition		
Marine Mammal Commission (MMC)	--		
NASA	Applied Sciences Program		
National Institutes of Health (NIH)/ National Institute of Environmental Health Sciences (NIEHS) NSF	Centers for Oceans and Human Health (COHH)		
NIH	National Institute of General Medical Sciences (NIGMS)		
	NIEHS		
NOAA	Oceans and Human Health Initiative		
NOAA	Various National Ocean Service Programs		
NOAA	Various National Marine Fisheries Service (NMFS) Programs		
NOAA	Various Office of Oceanic and Atmospheric Research (OAR) Programs		
NSF	Biological Oceanography Program (lead) Chemical Oceanography Program Physical Oceanography Program Ocean Technology and Interdisciplinary Coordination Program		
U.S. Army Medical Research Institute of Infectious Diseases (USAMRIID)	--		
U.S. Department of Agriculture (USDA)	Agricultural Research Service		
U.S. Geological Survey (USGS)	Various programs contribute to marine HAB research		
U.S. Fish and Wildlife Service (USFWS)	Various programs contribute to marine HAB research		

Table 3.2. Regional ECOHAB projects on marine HABs and the grant and research partners involved.

Calendar Year	Regional ECOHAB Project	Agency Funding Partners	Research Partners
1996	Brown tide research initiative	NOAA CSCOR NY Sea Grant NSF	**Academic or Private Institutions**: Bigelow Laboratory of Ocean Sciences (BLOS), Woods Hole Oceanographic Institution (WHOI), University of Rhode Island (URI), State University of New York (SUNY) Stony Brook University, University of Delaware (UDel), University of Maryland (UMD), Old Dominion University (ODU) **Federal Government**: Brookhaven National Laboratory, NOAA
1997	ECOHAB Gulf of Maine: Ecology and oceanography of toxic *Alexandrium* blooms in the Gulf of Maine	NOAA CSCOR NSF	**Academic or Private Institutions**: WHOI, BLOS, University of New Hampshire, University of Maine (UMaine) **Federal Government**: NOAA, USGS
1997	ECOHAB Florida: Ecology and oceanography of harmful algal blooms (Gulf of Mexico)* *This project was focused on *Karenia*	NOAA CSCOR EPA	**Academic or Private Institutions:** University of South Florida (USF), Mote Marine Laboratory, University of Southern Mississippi, North Carolina State University (NCSU), Rutgers University **Federal Government**: EPA, USDA, NOAA
1998	Molecular approaches to *Pfiesteria*-complex dinoflagellates in Chesapeake Bay	NOAA CSCOR	**Academic or Private Institutions**: University of Maryland Biotechnology Institute
1998	Impacts of *Pfiesteria piscicida* on shellfish and the role of shellfish as possible toxin vectors	NOAA CSCOR	**Academic or Private Institutions**: NCSU, University of Connecticut **Federal Government**: NOAA
1998	Toward a mechanistic understanding of outbreaks of *Pfiesteria* and related dinoflagellates	NOAA CSCOR	Academic or Private Institutions: NCSU, UDel, UMD
1999	Causes and prevention of Long Island brown tides	NOAA CSCOR	Academic or Private Institutions: University of Southern California, SUNY Stony Brook, BLOS, UMD **Federal Government**: NY Sea Grant
2002	Ecology and oceanography of toxic *Pseudo-nitzschia* in the Pacific Northwest coastal ocean	NOAA CSCOR NSF	**Academic or Private Institutions**: University of Washington, University of Western Ontario, San Francisco State University, UMaine Federal Government: NOAA **Canadian Government**: Fisheries and Oceans Canada
2002	Nuisance macroalgal blooms in coastal Maui: assessment and integration of physical factors and biological processes	NOAA CSCOR	**Academic or Private Institutions**: University of Hawaii **Federal Government**: USGS
2006	*Karenia* nutrient dynamics in the eastern Gulf of Mexico	NOAA CSCOR	**Academic or Private Institutions**: Virginia Institute of Marine Science, Mote Marine Laboratory, U. Miami, ODU, UMD, USF **State or Local Government**: Florida Fish and Wildlife Research Institute
2006	GOMTOX: Dynamics of *Alexandrium fundyense* distributions in the Gulf of Maine: An observational and modeling study of nearshore and offshore shellfish toxicity, vertical toxin flux, and bloom dynamics in a complex shelf sea	NOAA CSCOR	**Academic or Private Institutions:** WHOI, University of Massachusetts, UMaine, NCSU, North Atlantic Clam Association **State or Local Government**: Maine Department of Marine Resources, Massachusetts Division of Marine Fisheries **Federal Government**: FDA, NOAA **Canadian Government**: Fisheries and Oceans Canada, Canadian National Research Council

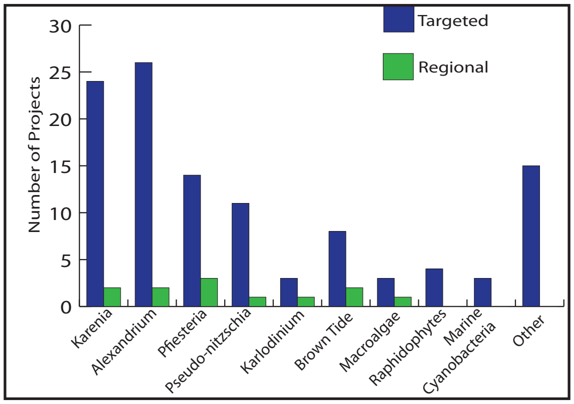


Figure 3.3. Marine HAB ECOHAB projects, targeted in blue and regional in green, by HAB organism. Projects shown include the total supported from fiscal years 1997 to 2008. Projects can be counted in more than one HAB group.

Atmospheric Administration (NOAA) Center for Sponsored Coastal Ocean Research (CSCOR - lead), NOAA Office of Protected Resources, NOAA Sea Grant, U.S. Environmental Protection Agency (EPA), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and the U.S. Department of Defense's Office of Naval Research (ONR). Through extramural, competitive, peer-reviewed research, ECOHAB funds research to better understand the causes and dynamics of HABs; produce new detection methods for HABs and their toxins; develop predictions of HAB growth, transport, and toxicity; and understand and predict impacts on ecosystems and humans. Research results are used to guide management of coastal resources so that HAB impacts can be prevented or reduced.

The ECOHAB program as a whole has supported 111 projects since it began in 1996. NOAA has provided the largest amount of funding for ECOHAB and supported the largest number of projects, followed by EPA and NSF (Figure 3.1). The majority of ECOHAB projects have advanced knowledge in the category of 'bloom ecology and dynamics' (Figure 3.2) and have led to improved management in the process. *Karenia* and *Alexandrium*, HAB taxa that are recurrent problems on the Gulf Coast and in New England/on the West Coast, respectively, have been the most studied (Figure 3.3).

Eleven projects have been regional studies (Table 3.2), which are longer-term studies usually focused on a particular HAB problem to improve understanding of multiple aspects of bloom dynamics in a particular region, ultimately leading to better monitoring and prediction. Accomplishments of the smaller, "targeted" projects have included development of new detection methodologies now being used in state monitoring programs, increased understanding of causes including the role of human activities in stimulating HABs, discovery of potential control methods, and improved understanding of trophic transfer of toxins through the food web.

NOAA MERHAB Program

Through extramural, competitive, peer-reviewed research, the MERHAB program in NOAA/National Centers for Coastal Ocean Science (NCCOS)/CSCOR aims to help build sustainable regional partnerships that provide managers with information in time for critical decisions needed to mitigate HAB impacts. The MERHAB Program supports initiatives that build on basic research gained from programs like ECOHAB and advance HAB-related technologies, such as improvements in monitoring capabilities. The MERHAB Program has funded 25 projects on marine HABs since it began in 2000, with a total funding of $22 million from fiscal years 2001-2008. All of these projects have been directly applicable to improving HAB prevention, control, and mitigation, and some

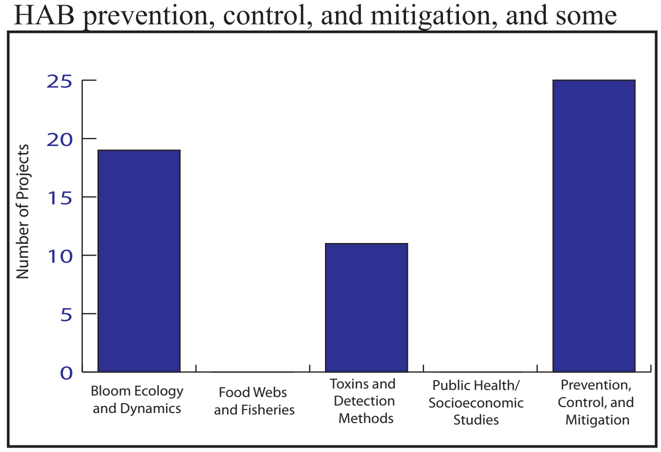


Figure 3.4. Marine HAB MERHAB projects categorized by the revised *HARRNESS* research categories[2]. Projects shown include those supported beginning fiscal year 2001 through fiscal year 2008.

Table 3.3. NOAA MERHAB regional projects for marine HABs.

Calendar Year	Regional MERHAB Project	Research Partners
2001	Olympic region harmful algal bloom (ORHAB) project	**Academic or Private Institutions**: University of Washington, Battelle, Pacific Shellfish Institute **State or Local Government**: Washington Department of Fish and Wildlife, Washington Department of Health **Federal Government**: NOAA **Tribal**: Quinalt Indian Nation
2001	Intensive monitoring for *Pfiesteria* and *Pfiesteria*-like organisms in the St. John's River	**State or Local Government**: Florida Fish and Wildlife Research Institute (FWRI) **Federal Government:** NOAA
2001	Intensive monitoring for *Pfiesteria* and HAB-related events in Maryland	**Academic or Private Institutions**: University of Maryland (UMD) **State or Local Government**: Maryland Department of Natural Resources (MD DNR)
2001	Fish health, habitat quality, and *Pfiesteria* surveillance in support of Maryland's response to toxic outbreaks of *Pfiesteria* and similar dinoflagellates	**State or Local Government**: MD DNR
2002	Eastern Gulf of Mexico sentinel program	**Academic or Private Institutions**: University of South Florida, Mote Marine Laboratory **State or Local Government**: Florida FWRI
2003	California program for regional enhanced monitoring of phyco-toxins (Cal-PreEmpt)	**Academic or Private Institutions**: University of California Santa Cruz (UCSC) **State or Local Government**: California Department of Health Services (CA DHS)
2003	Development and implementation of an operational harmful algal bloom prediction system for Chesapeake Bay	**Academic or Private Institutions:** University of Evansville, UMD, Chesapeake Research Consortium **State or Local Government**: MD DNR **Federal Government**: NOAA
2005	RAPDALERT: Rapid analysis of *Pseudo-Nitzchia* and domoic acid, Locating events in near real time	**Academic or Private Institutions**: University of Southern California, University of California Los Angeles, UCSC, UMD, Old Dominion University, Southern California Water Research Project **State or Local Government:** CA DHS, Los Angeles Regional Water Quality Control Board, MD DNR, Delaware Department of Natural Resources and Environmental Control **Federal Government**: NOAA (MD Sea Grant)
2007	Integrated HAB monitoring and event response for coastal Oregon	**Academic or Private Institutions:** Oregon State University, University of Oregon **State or Local Government**: Oregon Department of Fish and Wildlife **Federal Government**: NOAA

have also made advances in the topics of 'bloom ecology and dynamics' and 'toxins and detection methods' (Figure 3.4). Nine projects on marine HABs have been regional studies (Table 3.3), which are longer-term studies aimed at enhancing state monitoring and response capabilities. These have included projects in Washington State, Oregon, the Chesapeake Bay, the Eastern Gulf of Mexico, and along the central and southern California coast. Additional, targeted projects are testing or refining promising new technologies for routine monitoring use by coastal managers. Because MERHAB projects are primarily focused on improving mitigation, project accomplishments are also discussed in detail in the report, *Harmful Algal Bloom Management and Response: Assessment and Plan* (Box 1.3).

NOAA Event Response Program

The NOAA Event Response Program administered by NCCOS/CSCOR provides immediate assistance, either as funding or expertise, for managing events and for advancing the understanding of HABs as they occur. The program focuses on rapid response whereas MERHAB focuses on building partnerships and capabilities for improved long-term response. The Event Response Program may provide a modest amount of funding to assist states or independent researchers to collect data, conduct training, and enhance or expand monitoring in coastal and estuarine waters, upper reaches of estuaries, and the Great Lakes. Since both the ECOHAB and MERHAB extramural funding programs are administered by the same office, anyone who requests financial assistance through the Event Response Program is also directed to others that might collaborate or assist in response efforts. Some examples of the types of activities funded over the past four years include: 1) investigation of linkages between animal mortalities and HAB events; 2) taxonomic training; 3) investigation of potential emerging HAB problems; 4) intensified sampling to protect human health; and 5) coordination of sampling and information flow. http://www.cop.noaa.gov/stressors/extremeevents/hab/current/fact-ev_resp.html

NOAA Marine Biotoxins Program

The NOAA Marine Biotoxins Program is an intramural research program administered by NCCOS at its Center for Coastal Environmental Health and Biomolecular Research (CCEHBR) and the Hollings Marine Laboratory. The program targets its research and services at issues related to algal toxins and the organisms responsible for their production. Biotoxin research has focused on transfer of toxins through food webs, impacts of toxins, biomonitoring of toxins, and remote detection of toxins. Other HAB research has focused on taxonomy and distribution of HAB species, developing molecular tools to identify factors regulating HAB growth and toxicity, and potential avenues for bloom control. The Analytical Response Team, a component of the Marine Biotoxins Program, provides rapid and accurate identification and quantification of marine algal toxins in suspected HABs, marine animal mortality events, and human poisonings. The Phytoplankton Monitoring Network, also a component of this program, is an outreach program to unite volunteers and scientists in monitoring the marine phytoplankton community and HABs. http://www.chbr.noaa.gov/default.aspx?category=mb&pageName=biotoxin

NOAA Harmful Algal Bloom Program

The NOAA Harmful Algal Bloom Program is an intramural research program coordinated by NOAA's National Marine Fisheries Service (NMFS)/Northwest Fisheries Science Center (NWFSC) to gain a better understanding of the production, presence, and persistence of algal toxins in marine foodwebs and fisheries. This research program has focused on HABs and marine biotoxins in the Eastern Pacific, an area that stretches geographically from the Arctic Circle to south of the equator. The research has also focused on factors controlling algal growth, methods for the detection of marine biotoxins, toxicology, and analysis of past and current HAB events. In order to meet the challenge of monitoring thousands of miles of coastline, the NWFSC HAB Program has developed working partnerships with coastal tribes, universities, the shellfish industry, state agencies, and private companies, as well as other NOAA centers, and the OHH programs (see Section 3.1.2). http://www.nwfsc.noaa.gov/hab

3.1.2. Marine HAB Research as part of Other Federal Research Programs

OHH Programs

The NSF-National Institute of Environmental Health Sciences (NIEHS) Centers for Oceans and Human Health (COHH) represent a joint

Federal agency initiative with the overarching vision to promote state-of-the-art, interdisciplinary research that unites the oceanographic and medical communities, allows for cross-fertilization of ideas and technologies, and provides a more comprehensive insight of the potential risks and benefits to human health generated by the oceans. The four NSF-NIEHS Centers are located at the Woods Hole Oceanographic Institution, the University of Miami, the University of Washington, and the University of Hawaii. These competitively awarded Centers collaborate with a number of non-affiliated academic institutions and have formed working partnerships with several Federal agencies and state and local heath departments, grassroots groups, and others. Also, each of the NSF-NIEHS Centers has collaborated with international academic institutions. Research projects conducted by these Centers are often carried out in collaboration with other agency/institutional partners, and there is considerable joint planning with NOAA's Oceans and Human Health Initiative (OHHI) Centers. The COHH coordinate with the interagency ECOHAB Program and NOAA's MERHAB Program through joint participation in the IWG-4H. A substantial amount of HAB-focused research is conducted within the NSF-NIEHS Centers. All four centers have one or more research projects focused on various aspects of the ecology and oceanography of HABs. NSF has provided approximately $9 million and NIEHS approximately $7.5 million for marine HAB research through the COHH since 2004. http://www.whoi.edu/science/cohh/index.htm

NOAA's OHHI is founded on interdisciplinary partnerships among marine and biomedical scientists, public health decisionmakers and natural resource managers, and works within NOAA and across agencies and academia. NOAA's OHHI includes three competitively awarded internal Centers of Excellence for Oceans and Human Health located at NWFSC in Seattle, Washington, the Great Lakes Environmental Research Laboratory (GLERL) in Ann Arbor, Michigan, and the Hollings Marine Laboratory in Charleston, South Carolina. Each includes non-Federal partner institutions as integral elements of the Center. In addition, NOAA OHHI supports a robust external grant program, with some active grants on HAB-related issues, as well as distinguished scholars and traineeships in oceans and human health.

NOAA OHHI has ongoing HAB-related research in all three OHH Centers and in five of 26 external grants. Research conducted at GLERL focuses on freshwater instead of marine HABs and is covered in the *Scientific Assessment of Freshwater Harmful Algal Blooms*[8] (Box 1.1). NOAA OHHI research is focused on developing tools and technologies to understand, detect, track, and extract marine biotoxins that pose harmful health effects either through consumption of contaminated seafood or via inhalation of toxins during bloom events. For fiscal years 2003-2006, approximately $2.7 million was allocated within the external grant program towards marine and freshwater HAB activities and $3 million for center research activities. NOAA OHHI interacts closely with the NSF-NIEHS COHH, ECOHAB, MERHAB, and other agencies conducting OHH-related research. http://www.eol.ucar.edu/projects/ohhi/

Centers for Disease Control and Prevention

The Centers for Disease Control and Prevention (CDC), in general, supports research that aims to protect the health and safety of Americans and applies research and findings to improve people's daily lives and responds to health emergencies. In response to the *Pfiesteria* outbreak in 1997, CDC's National Center for Environmental Health (NCEH) established surveillance programs to capture reports of *Pfiesteria*-related human health effects, initiated University-based studies in three states to define health effects, supported six state-wide monitoring programs, funded research on the natural history and environmental precursors of *Pfiesteria* blooms and, over the past seven years, established a comprehensive public health program to assess human health effects of all HABs. A majority of the current public health surveillance efforts grew from CDC's initial response to the *Pfiesteria*-related outbreak in the late 1990s in North Carolina and Maryland. NCEH developed the Harmful Algal Bloom-related

Illness Surveillance System (HABISS) to collect data on HAB events and their effects on human and animal health. NCEH is also supporting numerous state activities to monitor and assess public health impacts of HABs. CDC has given funding to states through the *Pfiesteria*-related Illness Surveillance and Prevention Program and, more recently, through the Cooperative Agreement to Enhance Surveillance of Risk Factors and Health Effects Related to Harmful Algal Blooms. CDC has provided approximately $26 million in extramural funds since 2000 to support HAB research.

EPA

The U.S. EPA is an independent Federal agency with a mission to protect human health and the natural environment. EPA works with state and local agencies, as well as volunteer and other citizens groups, to monitor air and water quality and reduce human exposure to contaminants in the air, land, and water, including marine waters. EPA has funded a significant amount of extramural research as an interagency partner in ECOHAB (see Section 3.1.1). In addition, other extramural regional grants have been awarded to conduct research on surveillance, detection, mitigation, restoration, and public education regarding HABs. EPA has also funded projects related to HABs through its National Estuary Program. Some of these partnerships with local, state, and other Federal organizations list HABs as a priority management issue and have funded research on topics ranging from the relative importance of natural versus anthropogenic nutrient sources to predictive models of phytoplankton abundance and toxin levels in mussels. The EPA has also performed research on marine HABs in some of its laboratories.

Food and Drug Administration

The U.S. Food and Drug Administration (FDA) conducts HAB-related research in support of the agency's regulatory mission of protecting public health by assuring the safety, efficacy, and security of the Nation's food supply. FDA's knowledge and understanding of seafood hazards, risk assessments, and risk management related to HAB toxins are guided by scientific research provided primarily by the agency's Office of Regulatory Science and Office of Food Safety/Division of Seafood Science and Technology. FDA's objectives related to HABs include: 1) identify and characterize existing, emerging and potential health hazards in seafood, 2) determine exposure thresholds and consumer health effects, and recommend guidance levels for health hazards in seafood, 3) develop, optimize, and validate surveillance/monitoring methods for detection of health hazards in seafood, 4) promote surveillance/monitoring method standardization and train Federal and state public health personnel in their applications and use, 5) evaluate strategies and technologies for mitigation of health hazards in seafood, and 6) respond to regional, national, and international seafood disease outbreaks and emergency/threat situations. In conjunction with Federal, state, academic, and public partners, the FDA is responsible for providing the scientific basis for agency policy, regulation, and compliance programs which promote and protect the public's health by ensuring that the Nation's food supply is safe, wholesome, sanitary, and secure. This not only means being prepared to deal with seafood toxin hazards in U.S. waters, but also potential biotoxin threats in seafood imported to the United States from other countries.

Marine Mammal Commission

The Marine Mammal Commission (MMC) was established under the Marine Mammal Protection Act to provide independent oversight of marine mammal conservation policies and programs being carried out by Federal agencies. The MMC is charged with developing, reviewing, and making recommendations on domestic and international actions and policies of all Federal agencies with respect to marine mammal protection and conservation and with carrying out a research program. With respect to HABs, the MMC focuses primarily on the impacts of HABs on marine mammals and works with other Federal agencies to promote prevention, control, and mitigation of HABs. The MMC carries out a small research program and, has occasionally funded research projects relevant to marine HABs. However, the MMC, with its small research budget, has not established a research program focusing solely on HAB issues. Since 2000, the MMC has funded HAB projects focusing on Florida red tide events and their impact on manatees, including improvement and analysis of the manatee mortality database and the development of liver fatty acid markers to identify manatees killed by red tide toxins.

NOAA

Labs and Centers. In addition to CCEHBR-HML (Section 3.1.3), NWFSC (Section 3.1.4), and the OHHI Centers of Excellence (Section 3.2), other NOAA centers and labs with projects focused on HABs include NCCOS's Center for Coastal Fisheries and Habitat Research (CCFHR) and Center for Coastal Monitoring and Assessment (CCMA), NMFS's Northeast Fisheries Science Center (NEFSC), and the Office of Oceanic and Atmospheric Research (OAR)/Atlantic Oceanographic and Meteorological Laboratory (AOML). CCFHR research has focused on bloom ecology, methods of toxin detection, and food web interactions. CCMA, in collaboration with state agencies, NOAA's Coastal Services Center (CSC), CO-OPS, and the National Environmental Satellite, Data, and Information Service (NESDIS), develops forecasting products for HABs. NEFSC is involved in HAB research primarily focused on the effects of HABs on fishery and aquaculture resource species, especially bivalve molluscs. Additionally, the NMFS Marine Mammal Health and Stranding Response Program provides marine mammal response and health assessments, including response to HAB events. Other NOAA programs that conduct research relevant to marine HABs as part of their larger mission include the National Marine Sanctuaries and the National Estuarine Research Reserve System (NERRS).

Extramural funding. In addition to ECOHAB (Sectoin 3.1.1), MERHAB (Section 3.1.2), and OHHI (Section 3.2), NOAA funds HAB-related research through the OAR National Sea Grant College Program, the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET), and the NMFS Marine Mammal Health and Stranding Response Program. There is a Sea Grant program in every coastal state, and Sea Grant has funded an average of $700,000 per year in HAB-related research and outreach projects through both the national and individual state programs. CICEET is a partnership between NOAA and the University of New Hampshire and it focuses on developing and applying new environmental technologies and techniques, including those for HAB detection. CICEET has provided approximately $1.5 million for HAB research since 2000. The projects funded through CICEET are cooperative efforts that involve researchers in NOAA labs, managers of NERRS sites, academia, and industry. The NMFS Marine Mammal Health and Stranding Response Program supports research related to marine mammal UMEs and for marine animal health assessments through the John H. Prescott Grant Program, the Marine Mammal Unusual Mortality Event Fund, and a program for research on animal health assessments. Grants have included support for biotoxin research, emergency response, and other HAB-related research relevant to detection or animal impacts.

NSF

Programs that fund research on HABs at NSF are largely within the Directorate of Geosciences, Division of Oceanography, although the Directorate of Biological Sciences, Division of Environmental Biology, and the Office of Polar Programs supported some work as well. The Biological Oceanography Program is the lead program for this activity, but support may also be provided by the Chemical Oceanography Program, Physical Oceanography Program, and Ocean Technology and Interdisciplinary Coordination Program. In addition, ship support for HAB-related research may be provided through the University-National Oceanographic Laboratory System. NSF-funded HAB research focuses on the basic science questions underlying the ecology and oceanography of HABs. Since 1994, NSF has supported a diverse portfolio of HAB studies submitted as unsolicited proposals to the Biological Oceanography Program, and several proposals have been supported with NSF participation in the Interagency ECOHAB Program (see Section 3.1.1). NSF has also supported international cooperative projects as part of a focused European

Commission-NSF Initiative on HABs. Finally, the Ocean Technology Program has funded equipment development specifically targeted at HAB applications. NSF has provided approximately $11.3 million to support HAB research since 1994 through these programs, which is in addition to funding provided by NSF through ECOHAB (Section 3.1.1, Table 3.1) and COHH (see above). Total funding through all these programs has been approximately $29 million since 1994.

National Institutes of Health

In addition to the COHH, the National Institutes of Health's (NIH) NIEHS is involved in HAB-related work through projects at several universities as well as a collaborative research program between Florida International University and the University of Miami in the Advance Cooperation in Environmental Health Research Program. These NIEHS-supported projects account for approximately $4 million annually and include research on *Alexandrium* genomics, studies of toxin effects on humans, and research on toxin synthesis and therapeutics. NIH's National Institute of General Medical Sciences (NIGMS) also supports HAB-related research as part of its larger mission.

NASA

NASA is an interagency partner in ECOHAB (see Section 3.1.1) and also supports, through its Applied Sciences Program, a cooperative agreement between the Naval Research Laboratory and Applied Coherent Technologies, Inc. to apply NASA earth science observations in support of Gulf of Mexico coastal management activities, including HABs. Research has focused on optical physiology of HAB organisms and understanding remote sensing variables such as backscatter and absorption. In addition to funding through ECOHAB (Table 3.1), NASA has provided approximately $3 million for marine HAB research through the Applied Sciences Program since 2000.

United States Geological Survey

The U.S. Geological Survey (USGS) provides scientific information on the characteristics and quality of the Nation's earth and living resources. A number of USGS programs focus on ocean-related issues. These include activities such as: (1) characterizing riverine and groundwater contributions of flow, sediment, and chemical constituents to coastal systems; (2) quantifying status and trends of critical biological resources and species at risk, (3) providing information on changes in the coastal land surface, connections between people and those changes, and the potential consequences of those changes; (4) documenting declines in coral reef, coastal, wetland, and marine habitats and coastal ecosystems; (5) investigating impacts of contaminants, invasive species, pollution, human use and development, climate change, and other human and natural stressors on marine ecosystems; and (6) providing forecasts of water quality conditions in major estuaries.

Examples of USGS research that is directly relevant to marine HABs are: monitoring delivery of streamflow, sediment, nutrients, and pesticides from major rivers to coastal estuaries and bays; investigating contributions of groundwater and the associated nutrients to nearshore environments, including potential implications for HABs; collaborating with other agencies to investigate mortality events potentially associated with marine HABs—particularly those that involve threatened or endangered species; development and application of methods to measure marine algal toxins in coastal ecosystems; development of methods for forecasting HABs in coastal ecosystems; and long-term studies to characterize estuarine conditions and dynamics including factors affecting HABs in selected major estuaries in the United States.

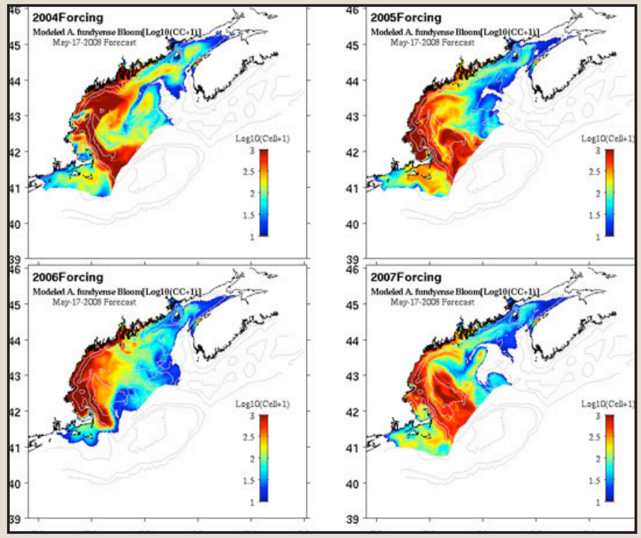
Other Agencies

Other agencies, such as the U.S. Army Medical Research Institute of Infectious Diseases (USAMRIID), U.S. Department of Agriculture (USDA), and U.S. Fish and Wildlife Service (USFWS), conduct some marine HAB-related research as part of their larger missions.

Box 3.1 Highlights of Major Advances in the Northeastern United States

Alexandrium spp. (New England Red Tide)

- A coupled biological-physical model was developed that provides early warnings. The model has also been used to evaluate causes, and the knowledge gained has explained patterns and variations in toxicity and how regional populations of *Alexandrium* persist year after year.
- Weekly predictions of *Alexandrium fundyense* blooms in coastal Gulf of Maine were issued in demonstration mode in 2005, 2006, 2007, and 2008. These predictions helped shellfish mangers to focus sampling and design more precise and selective closures, minimizing economic impacts on local communities while safeguarding human health.
- Successful multi-agency event response assisted states with monitoring and early warnings during large *Alexandrium* blooms in 2005 and 2006.
- A list server was established to improve communications among state, Federal, and academic researchers in New England.
- New maps of *Alexandrium* resting cysts, which are the seeds for future blooms, improved predictions.
- Saxitoxin resistance has been shown in some commercial bivalves due to a genetic mutation. Understanding shellfish toxin resistance, which allows more rapid toxin accumulation, will improve prediction and management of shellfish toxicity.
- An economic assessment of the 2005 *Alexandrium* bloom estimated direct impacts to commercial shellfishers and growers to be as high as $18 million in Massachusetts and at least $2.4 million in Maine.



Forecasts of *Alexandrium fundyense* abundance (red represents higher abundance) in May 2008 under four different weather scenarios, taken from weather and ocean conditions of 2004, 2005, 2006, and 2007 (clockwise starting with upper left panel). All four scenarios were initiated from a map of resting cysts surveyed in late 2007.
Graphic by Dennis McGillicuddy, Woods Hole Oceanographic Institution, and Ruoying He, North Carolina State University

Aureococcus anophagefferens (Brown Tide)

- The geographic range and impacts of brown tide along the East Coast of the United States is better understood. Impacts include reduction in seagrass habitat and negative impacts on some commercially or ecologically important shellfish. This knowledge aids assessment of management needs and development of management strategies.
- Organic nutrient availability and reduced mortality from grazing were both shown to be important for brown tide bloom development in various locations on the East Coast. These findings are not the typical ‘eutrophication scenario’. The knowledge highlights the importance of nutrient ‘quality’ and affects management strategies for prevention.
- First genome sequence of a HAB species was completed for *Aureococcus anophagefferens* and will allow better understanding of factors causing blooms.

3.2. Research and Accomplishments

3.2.1. Bloom Ecology and Dynamics

The topic ‘bloom ecology and dynamics’ refers to research aimed at understanding the biological, physical, and chemical factors that control HAB initiation, maintenance, transport, and decline. Much research has focused on this topic because it is the fundamental basis for advancing prevention, control, and mitigation of HABs and HAB impacts. Important steps to improve understanding of bloom ecology and dynamics include developing appropriate methods of cell detection and determining growth conditions through lab and field studies for a particular HAB species in the natural environment. This information will ultimately evolve to yield models of population growth and mortality and, potentially, predictive models of bloom development, maintenance, dissipation, and impact. Predictive models, along with cell and toxin detection methods, are the ultimate tools for exploring impacts of blooms and developing mitigation strategies to reduce HAB impacts.

3.2.1.1. Organism Life Cycle, Physiology, and Molecular Biology

Life cycle studies have been conducted to investigate the role of resting stages in bloom initiation. These resting stages, or cysts, are formed by some algae at the end of a bloom and settle to the seafloor where they can survive for years. When environmental conditions are favorable, the cysts can emerge to seed a new bloom. The ECOHAB:Gulf of Maine project (Table 3.2) improved understanding of *Alexandrium* cyst distributions in the Gulf of Maine[82,83,84]. This knowledge is important because the location of cyst beds and abundance of cysts within the beds play a critical role in bloom development. This research confirmed that cyst germination was controlled by an internal clock[84] and provided measurements of germination rates as a function of light and temperature[82]. These findings have been critical for improving predictions of blooms in the Gulf of Maine region.

Laboratory and field studies have been used to explore optimal growth conditions for various species (ECOHAB; NOAA CCEHBR, CCFHR, Sea Grant; NSF), as well as what factors influence toxin production (also see Section 3.2.2, ECOHAB; NOAA Sea Grant, CCEHBR; NSF). These governing factors have been shown to be complex and to vary both among and within species. Research on *Pfiesteria* species, for example, has shown a range of nutrient uptake capabilities and toxicity among strains and culture conditions[44] (ECOHAB; also see Section 3.2.1.2).

Researching HAB species at the genetic level has led to development of molecular probes for detecting target organisms (see Section 3.2.1.6), a better understanding of population genetics, and an improved ability to understand the complex ecology and toxicity of HAB organisms. For example, ‘microarrays’ have been developed for profiling gene expression changes related to cell division and toxin synthesis in *Karenia brevis* in response to different environmental conditions[85] (NOAA CCEHBR; NSF-NIEHS COHH). These types of technologies will help uncover the primary environmental factors that control growth and toxin production for a particular species or strain. Additionally, research investigating the genes involved in saxitoxin biosynthesis by *Alexandrium* has led to considerable insight into dinoflagellate genes and their regulation[86] (NSF). This research served as a springboard for research on genetic heterogeneity of *Alexandrium* bloom populations[87] (NSF-NIEHS COHH; NIH NIEHS), which will feed into refining existing biological/physical models described in Section 3.2.1.5.

3.2.1.2. Nutrient Dynamics

Eutrophication has been suggested as an important link to the occurrence of many HABs, so research into HAB causes has largely focused on how nutrient dynamics influence success of specific HAB organisms. For example, relationships have been shown between nutrient enrichment and *Pfiesteria* spp. occurrence[44] (ECOHAB) as well as macroalgal blooms[88] (ECOHAB; NOAA Sea Grant). Furthermore, research has shown variability in nutrient controls among regions as

Box 3.2. Highlights of Major Advances along the Mid- and South-Atlantic Coasts

Pfiesteria spp. and *Karlodinium*

Karlodinium cell under light microscopy.
Photo: Lucie Novoveska, Dauphin Island Sea Lab

- There is a better understanding of *Pfiesteria* distributions. *Pfiesteria* is common in low abundances in estuaries along the East and Gulf Coasts and is most abundant in nutrient-enriched environments.
- A free radical forming metal complex has been isolated from *Pfiesteria* cultures that may be a novel and ephemeral toxin.
- Development of molecular probes for detecting cells led to better identification, improved understanding of occurrence of *Pfiesteria* and other HABs, and identification of *Karlodinium* as an important fish-killing species in the region.
- Economic assessment of the 'halo' economic effect showed that the 1997 *Pfiesteria* event resulted in an estimated $43 million (1997 dollars) in lost seafood sales due to consumer concerns of seafood safety.
- New continuous, real-time tools were developed to measure environmental parameters at high temporal and spatial resolutions. These tools are part of the Maryland "Eyes on the Bay" program (http://mddnr.chesapeakebay.net/eyesonthebay/index.cfm).
- Epidemiological cohort studies exploring human health effects of *Pfiesteria* exposure indicated that occupational (i.e., repeated, low-level) exposure to estuarine waters in which *Pfiesteria* is present was not a significant risk factor for illness.

Pyrodinium bahamense

- Successful multi-agency event response to saxitoxin puffer fish poisonings in Florida in 2002 identified the putative causative agent as saxitoxin-producing *Pyrodinium bahamense* and tracked illnesses. As a result, a recreational fishery closure was instituted in the affected area and was extended indefinitely for all species of puffer fish, as was routine testing of saxitoxin in shellfish, to protect human health.

Sampling during collaborative response to saxitoxin puffer fish poisonings in Florida.
Photo: FDA

Aureococcus anophagefferens (Brown Tide)

- Brown tide in Delaware, Maryland, and Virginia waters was documented (also see Box 3.1).

Toxic Raphidophytes

- An emerging HAB problem was identified through documentation of toxic raphidophyte blooms in Delaware's Inland Bays.

Multiple Species

- An ecological forecast for water quality conditions and HAB occurrence has been developed for the Chesapeake Bay (http://www.chesapeakebay.net/bayforecast.htm).

well as among species. For example, *Pseudo-nitzschia* occurrence in Louisiana coastal waters was associated with coastal eutrophication[61,62] (NSF; NOAA Sea Grant), but in the Pacific Northwest, *Pseudo-nitzschia* blooms are linked to nutrients provided by a natural offshore source, the nutrient-rich Juan de Fuca Eddy[89] (ECOHAB; NOAA NWFSC, OHHI). In southern California, an area where less information on *Pseudo-nitzschia* blooms is available[69], a current project is exploring the potential connection between urban river discharge, associated inorganic nutrient and trace metal loadings, and *Pseudo-nitzschia* blooms (ECOHAB). In addition, recent research in a number of areas, including Maui (http://pubs.usgs.gov/sir/2006/5283/), Florida[90], Washington[91], and the Chesapeake Bay (http://md.water.usgs.gov/publications/fs-150-99/html/index.htm), have highlighted the importance of the flow of nutrients from ground water to coastal ecosystems and, in some cases, groundwater nutrients have been linked to HABs[e.g., 90] (USGS; NASA; ECOHAB).

Research on the role of nutrients has also improved understanding of the importance of various modes of nutrition in the development of some HABs (ECOHAB; NSF; NOAA). Discoveries that some HAB species, such as *Aureococcus anophagefferens*[92] (ECOHAB; NOAA Sea Grant) and *Pfiesteria*[93] (ECOHAB; NSF), grow well and potentially outcompete other beneficial phytoplankton by using organic nutrients when inorganic sources are low have highlighted the importance of nutrient quality for some HABs. Some species, such as *Pfiesteria*[94,95] and *Karlodinium*[96] (NSF), have also been shown to feed on other cells to gain nutrition, and a recent technological development using digital holographic microscopy has allowed better understanding of this behavior[97] (NSF). Furthermore, unexpected nitrogen sources for growth have been hypothesized in some cases, such as nitrogen fixed by cyanobacteria fueling blooms of *Karenia brevis*[98] (ECOHAB; NSF). A current regional ECOHAB project is focusing on unraveling the critical elements of *K. brevis* nutrient dynamics (Table 3.2).

3.2.1.3. Physical Processes and Bloom Dynamics

Investigating the role of physical processes in bloom dynamics, and integrating that knowledge with biological information into predictive models (see Section 3.2.1.5), has been another important focus. Important physical processes that govern bloom dynamics include small-scale turbulence, water column stratification and mixing, and horizontal transport processes.

The ECOHAB Gulf of Maine project (Table 3.2) contributed significantly to our understanding of the Gulf of Maine's physical oceanography and the extent to which regional *Alexandrium* populations are connected hydrographically. For example, direct linkages were made between Bay of Fundy populations and blooms in the Eastern Maine Coastal Current (EMCC). Links were also made between EMCC populations and toxicity in the Western Gulf, and results suggest that variability in transport of offshore populations and this east-west connectivity may be the primary drivers of interannual variability in toxicity[99,100]. The Gulf of Maine Coastal Plume[101] was also identified as an important feature by which cells can travel inshore into the Western Maine Coastal Current region.

The ECOHAB Florida project (Table 3.2) revealed that, in waters along the West Florida Shelf, the bottom water layer serves as a primary conduit for transport of cells from offshore to inshore. These findings highlight that three-dimensional data on *Karenia* distributions and transport is necessary for monitoring and bloom prediction purposes.

Researchers with NOAA NWFSC and the Pacific Northwest COHH (NSF-NIEHS) are making progress, in collaboration with ECOHAB (Table 3.2) and NOAA MERHAB, toward a better understanding of the oceanographic processes that result in toxic outbreaks of *Pseudo-nitzschia* spp. and the impacts of these outbreaks on humans. Development of larger *Pseudo-nitzschia* blooms within the Juan de Fuca Eddy likely depend on sustained periods of downwelling that strengthen the eddy, as was seen in September 2004[102]. In addition to being nutrient-replete, the Juan de

Fuca Eddy is more iron-deficient than surrounding coastal waters, and both factors likely contribute to the eddy acting as an incubator for toxic *Pseudo-nitzschia* blooms[89]. Results also show that the variability of inshore toxicity is likely related to variability in transport pathways from the eddy[66].

In Puget Sound, data over a 13-year period showed that a combination of low streamflow, weak surface winds, and small tidal variability tended to precede toxic blooms of *Alexandrium catenella* (NOAA OHHI, NWFSC). This information will be useful for forecasting toxic events in Puget Sound and evaluating possible influences of climate change on the occurrence of future events.

3.2.1.4. Biological Controls of HAB Dynamics

Investigations of bacterial, viral, parasitic, and grazer interactions with HAB organisms (ECOHAB; NOAA CCEHBR, CCFHR, Sea Grant; NSF) have not only revealed better understanding of the cause and decline of blooms, but have also provided insights into potential avenues for control (also see Section 3.2.5). For example, algicidal bacteria have been identified and isolated that can lyse *Karenia brevis* cells and reduce toxicity as toxins are released[103] (NOAA CCEHBR; ECOHAB). These bacteria may represent an indicator of bloom decline, and the algicidal compounds they produce may also represent a potential option for HAB control. In addition to the nutrient regime (see Section 3.2.1.2), lowered grazing mortality has been shown to be important for the development of brown tides, and viruses may be important as a mortality agent for brown tides as well as a bloom promoter[104] (ECOHAB). NOAA Sea Grant-supported researchers are investigating the potential of ribbed mussels for reducing the incidence of harmful blooms, such as brown tides. Research supported by NSF and ECOHAB has developed probes specific for the parasitic dinoflagellate *Amoebophrya*[105], which will yield information about the interactions between parasite and HAB host in the natural environment. Research on grazer interactions is discussed in further detail in Section 3.2.3.

3.2.1.5. Developing Predictive Models

Models are developed in order to better predict HAB events and forecast HAB impacts so that appropriate management actions can be taken for mitigation and control. They are also useful for looking at past events to determine the most important factors driving bloom dynamics. Such models may incorporate information on cell life cycles, physiology, grazer impacts, physical processes, and important environmental parameters. Ultimately, these models can also be used to test the efficacy of proposed management actions that may lead to bloom prevention.

The ECOHAB Gulf of Maine project ultimately led to a coupled bio-physical model that allows simulation of *Alexandrium* bloom dynamics. It has been used to evaluate numerous factors, from cyst dynamics to how factors that control growth vary in space and time[106,107,108]. Circulation (ECOHAB; NOAA Sea Grant, MERHAB) and sediment models (USGS) contributed critical components to this effort. Observations and model simulations together revealed, among other things, that the primary environmental controls of *A. fundyense* growth in offshore waters were light and inorganic nutrients and that two major cyst seedbeds, one in the Bay of Fundy and one offshore of Penobscot and Casco Bays, were critical to bloom dynamics[109]. This knowledge gained from the collective efforts in the Gulf of Maine explained patterns and variations of toxicity and how the regional populations of *Alexandrium* persist year after year. These model projections are being refined by research supported by ECOHAB and NSF-NIEHS COOH.

A model for *Pfiesteria* population dynamics was developed that incorporated measurements of nitrogen uptake, turbulence responses, and grazing impacts to simulate differences in nontoxic versus toxic strains (ECOHAB; NOAA MERHAB). Results suggested that toxic *Pfiesteria* blooms are more likely to occur in environments that are calm, have low grazing, and are rich in organic nutrients, whereas non-toxic blooms are more likely in more turbulent and inorganic nutrient rich environments[110].

Box 3.3. Highlights of Major Advances in the Gulf of Mexico

Karenia spp. (Florida and Texas Red Tide)

Control by clay flocculation has shown effectiveness for controlling blooms under certain conditions.
Photo: J. Culter, Mote Marine Laboratory

- A coupled biological-physical model for *Karenia* bloom dynamics was developed, which has helped clarify important environmental factors controlling blooms and is now used to guide monitoring.
- One of the longest (48 years) datasets for marine ecosystems in general was made available. These data are being used to study bloom dynamics and environmental factors controlling blooms. The data were also the basis of the Harmful Algal Blooms Observing System case study and used to validate satellite imagery used in the HAB Forecasting System.
- Potential methods of control for *Karenia* blooms have been discovered. These include bloom removal by clay flocculation and algicidal bacteria.
- Field testing of bloom control by clay flocculation was conducted. This was the first 'demonstration' of this technology in Florida.
- Various methods were developed for detection of *Karenia*, including the 'Brevebuster', which optically detects *Karenia* in the water and can be deployed on underwater vehicles and moorings to provide higher temporal resolution than monitoring by any other means.
- Two highly sensitive and accurate methods—enzyme-linked immunosorbent assay (ELISA) and liquid chromatography mass spectrometry (LCMS)—for detecting brevetoxin in shellfish were developed and are being considered by the Interstate Shellfish Sanitation Conference for regulatory use. The tests are more sensitive and have higher throughput than the standard mouse bioassay.
- Biomarkers of human exposure to brevetoxins were identified and an LCMS method for confirmation of clinical diagnosis of NSP was developed.
- The mechanism for chemical synthesis of brevetoxin was discovered.
- Human health effects, including respiratory effects, due to acute exposures to brevetoxin have been established.
- Brevenal, a natural inhibitor of brevetoxin, has been isolated. Additional research is leading to its characterization as a potential therapeutic for cystic fibrosis and other respiratory disorders.
- A comprehensive monitoring network was established for Florida.
- 'Microarray' technology was developed that can be used to determine factors influencing *Karenia* growth and toxin production.
- A HAB Forecasting System has been in operational mode for Florida since 2004 and is currently in demonstration mode for the Texas Coast.

- Formal evaluation of HAB outreach and education materials, specifically the Aquatic Toxins Hotline, demonstrated that the materials provided useful HAB-related information. Results are leading to expansion and improvement of HAB outreach, education, and surveillance tools.
- An unusual mortality event of bottlenose dolphins in the Florida panhandle was associated with brevetoxin exposure. Research during this event also identified for the first time the accumulation and persistence of brevetoxin in the muscle and viscera of fish, which can serve as a pathway for toxin transfer to higher trophic levels.
- Several unusual mortality events of manatees were associated with brevetoxin exposure. Research identified accumulation of brevetoxin in epiphytes on seagrasses, which are consumed by manatees providing another mode of toxin transfer.
- A biomarker for brevetoxin exposure in manatees through liver fatty acid analysis has been developed. This research allows easier identification of manatees killed by brevetoxicosis.

Ciguatera

- A recent increase in CFP cases has been associated with grouper and barracuda landed in Florida and Texas and are possibly tied to toxic *Gambierdiscus* associated with hard structure provided by oil platforms and artificial reefs in the northwestern Gulf of Mexico. This research suggests CFP may be expanding to new areas in the Gulf of Mexico.
- An industry advisory on ciguatera emergence in the Flower Garden Banks National Marine Sanctuary in the northern Gulf of Mexico was issued by the FDA.
- A two-tiered screening confirmatory method protocol for ciguatera toxins from the Caribbean and Pacific Coast was developed.

Reef fish can be contaminated with toxins that cause ciguatera fish poisoning.
Photo: FDA

Bio-physical models have also been developed through two other regional ECOHAB projects (Table 3.1). In Florida, a model has been used to elucidate environmental factors controlling blooms and is now used as a component of the NOAA MERHAB-supported comprehensive monitoring network (see Section 3.2.5). In the Pacific Northwest, a model is helping to understand the generation of the Juan de Fuca Eddy and *Pseudo-nitzschia* bloom dynamics, including transport to the coast (ECOHAB; NOAA NWFSC).

3.2.1.6. Understanding Occurrence of HABs through Better Detection

From studies on HAB physiology and molecular biology, many new technologies for detecting HABs are emerging. New molecular-based assays are being developed and, in several regions of the country, are used routinely for HAB detection (ECOHAB; NOAA MERHAB, NOAA; NSF; NSF-NIEHS COHH). NOAA CICEET is working to advance a number of innovative approaches to detect, quantify, and monitor different HAB species and toxins, including a molecular assay for *Karenia brevis* developed by NOAA AOML. DNA fingerprinting techniques have been developed for the rapid identification of *Pseudo-nitzschia* spp. as well as associated bacteria, which, when combined, provide the ability to link species distributions with toxicity and environmental conditions (NSF-NIEHS COHH).

These improved tools for cell detection are leading to a better understanding of species distributions as well as identification of new species of potential concern. For example, species-specific probes developed through *Pfiesteria* research (EPA; NOAA) showed that *Pfiesteria* is common and widespread, but generally in low abundance in the water column[111]. This research also revealed that another phytoplankton species, now called *Karlodinium veneficum*, was toxic to fish, had previously been misidentified, and may have caused some fish kills previously attributed to other species[46]. Research in Hawaii has identified two entirely new species of *Gambierdiscus*, as well as a species of *Osteropsis*, as potentially associated with CFP in Hawaiian waters (NSF-NIEHS COHH; NOAA CCEHBR). Furthermore, NOAA CCFHR is working to isolate and molecularly characterize dinoflagellates responsible for CFP and is conducting a systematic survey for these organisms in Florida waters. The COHH (NSF-NIEHS) at the University of Miami has also identified and is isolating a number of potentially harmful algal species[4].

3.2.1.7. Long-term Data Sets for Understanding Causes and Distributions

In addition to field and laboratory studies, long-term time series of phytoplankton and environmental data in U.S. estuaries and coastal waters shed light on historical bloom patterns—which is important knowledge for understanding bloom dynamics and anthropogenic or natural drivers of change. For example, three decades of observation in San Francisco Bay revealed how climate-influenced changes in the Pacific Ocean modified the conversion efficiency of land-based nutrients into algal biomass, illustrating a strong linkage with the coastal ocean that influences the potential for HABs in the estuary[112] (USGS, http://toxics.usgs.gov/highlights/phytoplankton_blooms/). Additionally, long-term data sets from California have been used to identify shifts in algal species composition[113] (NSF) and exceptional algal bloom events[114] (USGS). NOAA NWFSC also participates in the HAB section of the North Pacific Marine Science Organization (PICES) (see Chapter 4) which aims to develop and implement annual bloom reporting procedures so data can be incorporated into the Harmful Algal Event Database (http://ioc.unesco.org/hab/HAEDAT.htm). This database will be important for assessing HAB impacts and improving predictive capabilities.

3.2.2. Toxins and their Effects

One of the first steps in research on toxins and their effects is to chemically characterize and elucidate the structure of the toxin. Once characterized, routine methods for detection can be developed, and the mechanisms for toxin biosynthesis as well as the impacts on humans and animals can more easily be researched.

Box 3.4. Highlights of Major Advances along the Pacific Coast

Pseudo-nitzschia spp.

- The Olympic Region HAB Monitoring Network (ORHAB) focused on early warning of domoic acid in razor clams, including Federal, state, academic, tribal partners, is now operational and funded by Washington State.
- A rapid, low-cost test for domoic acid was developed with the Quileute Nation's natural resources agency and is currently being commercialized for use in environmental sampling.
- Research confirmed that the Juan de Fuca Eddy is an important regional source of toxic *Pseudo-nitzschia* blooms. Weakened or broken eddy circulation allows the toxic phytoplankton to escape the eddy where they can be transported to coastal areas of the Pacific Northwest. This knowledge will be valuable for improving predictions of toxic events in coastal areas of the Pacific Northwest.
- Multiple studies have postulated a link between domoic acid production and low copper and iron concentrations in the environment. Genes have also been identified that may be used as markers for determining the growth status or toxicity of cells in the field. These findings will improve understanding of toxin occurrence.
- Successful test deployment of the Environmental Sample Processor to detect *Pseudo-nitzschia* and domoic acid in California represented the first automated, *in situ* detection of both algal cell abundance and toxin presence in coastal waters.
- A five-year epidemiological cohort study with Native populations in the Pacific Northwest has been undertaken to determine human health effects of low-level exposure to domoic acid through razor clam consumption. This research will help identify at-risk populations.
- In California, research showed domoic acid penetrated many components of the food web, including both benthic and pelagic species. The toxin was shown to quickly enter the food chain and be transferred up to higher trophic levels, including humpback whales.
- Research established that domoic acid exposure in sea lions causes not only acute mortality but also brain damage and reproductive failure. Chronic effects due to repeated, sub-lethal exposures have also been documented.

California sea lion in rehabilitation undergoing MRI scanning to detect extent of brain injury due to domoic acid toxicosis
Photo: MMC

Alexandrium catenella

- Resting cysts for *Alexandrium catenella* were mapped for Puget Sound, Washington, which is important for predicting bloom hot spots.
- A sensitive, high-throughput, real-time method has been developed for assessing the abundance of *Alexandrium catenella* in Puget Sound, Washington.
- The zebrafish model was developed and can be used as a model to test toxin exposure effects in vertebrates; the model illustrated sub-lethal effects in larval fish due to saxitoxin exposure.

General

- A list server for Puget Sound researchers and fish mariculturists was established to improve information exchange and response to HABs.
- Long-term datasets illustrated linkage between changes in climate and algal bloom occurrence (e.g., http://toxics.usgs.gov/highlights/phytoplankton_blooms/)

3.2.2.1 Toxin Characterization and Detection

Research on toxin characterization and synthesis is important not only to advance research on the mechanisms of toxicity, the factors controlling toxin biosynthesis, and the toxin impacts on human and ecosystem health, but also because it leads to improved availability of toxins for research. NIH NIGMS is supporting numerous projects that aim to unravel the mechanisms for chemical synthesis of algal toxins, including saxitoxin, brevetoxins, maitotoxin, gonyautoxins, and ciguatera toxins, as well as other algal toxins that may have public health impacts. As a result of these efforts, a breakthrough in the mechanism for the chemical synthesis of brevetoxin, which may approximate the biosynthetic mechanism and be applicable to other 'ladder' toxins, was recently published[115]. NIH NIEHS-supported researchers have achieved total synthesis of an azaspiracid toxin and partial characterization of biological effects. Other studies to explore the mechanism for domoic acid biosynthesis in *Pseudo-nitzschia* spp. (NOAA Sea Grant) and the environmental factors controlling biosynthesis (NOAA; NSF) suggest a link between domoic acid production and low copper and iron concentrations in the environment[116]. From this research, genes have been identified that may be used as markers for determining the growth status or toxicity of cells in the field[117]. Additionally, NOAA Sea Grant has supported work to characterize *Heterosigma* fish-killing toxins and determine the cellular mechanism that regulates toxin biosynthesis. NOAA CCEHBR (supported by ECOHAB) identified an ephemeral free radical-forming metal complex produced by *Pfiesteria*[45], which may partly explain the observed variable nature of toxicity associated with *Pfiesteria*. NIH NIGMS is also supporting work to characterize new neurotoxins derived from marine algae, which may have potential ecosystem or health impacts.

A range of analytical methods for detection—from very accurate and expensive laboratory analytical techniques to quick and easy screening methods for the field—is necessary for successful management of toxic outbreaks. Developing modern methods to improve detection of algal toxins in a variety of matrices has been a research focus for many agencies (ECOHAB; FDA; NOAA MERHAB, CCEHBR, CCFHR, CICEET, OHHI, NWFSC, and Sea Grant; NSF; NIH NIEHS and NIGMS; USAMRIID). Several newly developed tests for PSP (NOAA CCEHBR) and NSP (FDA; NOAA MERHAB) that are more sensitive and efficient than the traditional mouse bioassay are being considered for regulatory approval. Other quick and easy tests are being developed for environmental sampling. Such simple test kits are desirable as screening methods to reduce the number of samples taken for laboratory analysis. For example, a new, low cost enzyme-linked immunosorbent assay (ELISA) method for detecting domoic acid in razor clams was developed in collaboration with the Quileute tribe in the Pacific Northwest[118], and a dip stick version of this test for use in the field is in development (NOAA MERHAB, CCFHR, NWFSC). A NOAA MERHAB project in California is comparing newly developed test kits for domoic acid and saxitoxins to evaluate their efficacy. Researchers at the FDA have developed a two-tiered ciguatoxin analytical procedure that does a much more efficient job of identifying ciguatoxic fish than any previously used methodology. The two-tiered procedure will be assessed for Caribbean and Pacific ciguatera in a proposed collaborative study with the University of Texas Marine Science Institute and the Pacific Research Center for Marine Biomedicine (NSF-NIEHS COHH). It is expected that this new approach will find broad application in CFP studies globally.

Toxin detection methods are typically validated for extracts from the causative algae and/or the affected seafood. There are presently no officially validated methods for detecting marine toxins in clinical matrices. This capability is required to confirm intoxication during outbreaks and to investigate specific case studies. Furthermore, relevant information on human toxicokinetics and treatment windows are lacking due predominantly to the absence of these validated methods for clinical matrices. There is an ongoing collaboration between USAMRIID and FDA to improve detection capabilities for PSP toxins by extending the use of the Lawrence High Performance Liquid

Chromatography (HPLC) method (validated for seafood extracts) to clinical samples. This enhanced detection capability was tested during an actual PSP outbreak in 2007 (see Box 2.1) and researchers found that PSP toxins in human urine and serum could be detected and monitored with minimal modifications to the method. Results are encouraging that this method could be employed during future PSP outbreaks and lead to an improved knowledge base about human health effects.

3.2.2.2. Toxin Effects on Humans and Ecosystems (also see 3.2.3 and 3.4.4)

Assessing the impact of HAB toxins on individual species, including humans, and across ecosystems has been slower than research in some other areas, but has become more of a priority in recent years. Most assessments of human impacts have been through animal studies, but there have also been case studies during events (see Section 3.4.4 for public health studies). NOAA NWFSC research established the zebrafish as an appropriate model for evaluating toxin impacts on vertebrates in general. Initial studies with saxitoxin showed important sublethal effects on marine fish populations[119,120] (ECOHAB; NOAA NWFSC). The zebrafish model is now being used to test potential human impacts from long-term, low-level exposures to various toxins and to characterize embryonic effects, such as behavioral deficits or reproductive failure (NOAA NWFSC, CCEHBR; NSF-NIEHS COHH). Other research (NSF-NIEHS COHH) using animal models is evaluating the effects of domoic acid exposure on brain developmental processes and responses, including proliferation, differentiation, oxidative stress, cell toxicity, and cell death, in both prenatal and postnatal phases. NOAA CCEHBR has shown that early life exposure to domoic acid results in behavior and memory impairment in rats[121]. It has also been confirmed that inhalation of brevetoxins causes airway responses in humans at environmentally relevant concentrations[122], and the biological basis for these responses is being investigated (NIH NIEHS; CDC).

Box 3.5. Highlights of Major Advances in Hawaii and the Pacific Territories

- Potentially new CFP-causing species have been discovered and isolated.
- A tiered protocol to assess ciguatoxicity in fish tissues has been developed; research is currently working toward derivation of advisory levels for ciguatoxins in Caribbean and Pacific waters.

Research with California sea lions has shown reproductive failure associated with domoic acid exposure[123] (NOAA NMFS, OHHI, and CCEHBR). Furthermore, findings suggest chronic effects, such as epilepsy and behavioral changes, can occur in sea lions from sublethal, repeated exposures to domoic acid[69] (NOAA NMFS, OHHI, CCEHBR). Research with California sea lions has been significant not only for assessing environmental effects, but also as an important source of information to protect human health.

There has also been considerable effort to increase wildlife illness surveillance, which is not only important for wildlife assessments, but also for human health threat identification. For example, recent association of domoic acid exposure with whale mortalities on the East Coast expanded the known geographic range of this threat. Furthermore, as a result of increased surveillance during HAB events, NOAA's Marine Mammal Health and Stranding Response Program is establishing that more and more mammal stranding events are linked to biotoxins[25]. The development of biomarkers for identifying effects due to toxin exposure, such as fatty acid biomarkers for brevetoxin in manatees (MMC), is an important goal that will help assessments of wildlife impacts. In addition, the MMC has dedicated funds to improving and analyzing the manatee mortality database. USGS, at its National Wildlife Health Center in Madison, Wisconsin, has worked collaboratively with universities and Federal laboratories to document impacts of biotoxins on marine and aquatic birds, mammals, and reptiles. This Center receives carcasses and tissue samples from the entire United States including Alaska, Hawaii, and U.S. territories. USGS also maintains a database of the findings.

Research to explore therapeutics for reducing impacts of toxins on human and animals has led to some promising discoveries. For example, brevenal, a compound antagonistic to effects of brevetoxin, may represent a possible treatment for people exposed to brevetoxin[122] (NIH NIEHS). Brevenal is being further characterized as a potential therapeutic for cystic fibrosis and other respiratory disorders (NIH NIEHS), which highlights the ancillary benefits of HAB research. Additionally, NIH NIGMS is supporting research on mechanisms of toxicity, including one study investigating how potential antagonists may protect against toxicity of brevetoxins and could be used for therapeutics.

3.2.3. Food webs and fisheries

Analysis of food web function and fisheries dynamics in relation to HABs has recently been an active area of research. This research has focused on the interaction of HABs and food web structure, toxin transfer through the foodweb, and toxin accumulation and depuration (elimination) in food web components.

3.2.3.1. Food Web Alterations

Alterations in food web structure play a disruptive role in ecosystem balance, and such alterations, which can include grazer decline, can be both a cause and an effect of HABs. For example, research supported through ECOHAB and NOAA Sea Grant showed that reduced grazing is an important factor in brown tide bloom development (reviewed by Gobler et al.[38]) and that prolonged brown tides can also affect recruitment of filter-feeding bivalves[124], thereby reducing grazing pressure. Further, research in Florida Bay (NOAA Sea Grant) attributed the decline in filter-feeding sponges as a key factor in the proliferation of nuisance algae, which indirectly resulted in the significant loss of critical seagrass habitat through light limitation[125].

Racks of Pacific oysters grown in Drakes Estero, one of California's largest oyster-producing areas and an area intensively monitoring for *Alexandrium* and the PSP toxins. *Photo: Gregg Langlois, California Department of Health Services*

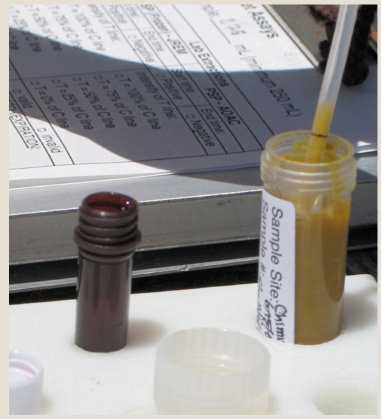
Grazing studies with zooplankton and *Karenia brevis* suggest that brevetoxins can cause behavioral changes in some copepods, but that accumulation and behavioral effects vary among species of copepods[126,127] (ECOHAB; NOAA CCFHR; NSF). Further, some copepods may be able to acquire a level of resistance to toxin exposure. In lab studies, copepods that had been historically exposed to *Alexandrium* blooms were less severely affected by exposure to toxic *Alexandrium* than copepods that had little or no exposure to blooms[128] (ECOHAB). HABs may have other physiological traits, aside from toxin production, that make them a less desirable or nutritious food source. Research has shown that brown tides adversely impact recruitment of hard clams by prolonging the time spent in the more vulnerable larval stage[129] (ECOHAB; NOAA Sea Grant). Other research found that brine shrimp and scallops were unable to metabolize unusual sterols from some harmful dinoflagellates[130] (ECOHAB; NOAA NEFSC). These results suggest that HAB sterols may have detrimental consequences for commercial fisheries and for the zooplankton grazers that might otherwise control a bloom.

3.2.3.2. Toxin Transfer, Accumulation, and Depuration in Food Webs

Understanding how certain HAB toxins are transferred through the food web is very important for explaining or predicting impacts from a bloom. In the Gulf of Maine, saxitoxin has been documented in both North Atlantic Right Whales and the zooplankton community,

Box 3.6. Highlights of Major Advances Applicable in Multiple Regions of the United States

Preparing a shellfish sample extract for a the Jellett rapid test for PSP toxins (Jellett Rapid testing Systems, Ltd.) *Photo: Gregg Langlois, California Department of Health Services*



- A receptor binding assay for PSP toxins has been developed and is being considered by the ISSC for regulatory use. The test is more sensitive and has higher throughput than the standard mouse bioassay so would give managers more lead time.
- The Jellett Rapid Test for PSP toxins was approved by the ISSC as a Type IV screening method with restrictions (http://www.cfsan.fda.gov/~ear/nss3-42j.html). This rapid test can be used in lieu of the mouse bioassay to maintain an area in open status, implement a precautionary closure of an area in open status, and determine when to perform a mouse bioassay in a previously closed area.
- Citizen monitoring networks have been created. A number of states have established citizen monitoring programs for HAB species. FDA and NOAA have supported establishment of these programs and training for volunteers. These programs can reduce the cost of monitoring and managing our coastal resources.
- NOAA CCEHBR's Analytical Response Team was established. It is national in scope and maintains a database of all samples and analyses conducted since 1998 (see Section 3.1.1).
- NOAA CSCOR Event Response Program was established. This program supports researchers and managers faced with responding to unusual or unexpected HABs (see Section 3.1.1).
- CDC's HABISS was established to coordinate with states to mitigate HAB exposure and employ illness prevention strategies to more effectively to protect public health.
- NOAA's National Marine Mammal Health and Stranding Response Program monitors the shoreline for stranded marine mammals and responds quickly to gather data necessary to identify the cause of strandings.
- Outreach and communication has been improved through development of the following (also see Section 4.1):
  - State web sites (see Appendix I)
  - National Office for Harmful Algal Blooms
  - National HAB Committee
  - U.S. HAB Symposia Series

indicating that zooplankton may serve as an entry point for saxitoxin into the pelagic food web and potentially lead to exposure of fish and marine mammals[131,132] (ECOHAB; NOAA CCEHBR). NOAA CCEHBR has also identified that domoic acid can co-occur with saxitoxin in North Atlantic Right Whales. In Florida, investigation of an UME of bottlenose dolphins in the Panhandle region led to the first-time identification of the accumulation and persistence of brevetoxin in the muscle and viscera of fish, which can serve as a vector to higher trophic levels[27] (NOAA NMFS). Similarly, the accumulation of brevetoxin in some copepods[126] and in layers on seagrass leaves[27] have illustrated additional pathways for brevetoxin entry into the food web (NOAA CCFHR; ECOHAB). Research in California (ECOHAB) revealed that during toxic bloom events, domoic acid quickly entered the food chain and was then transferred to large predators, including blue and humpback whales[133]. NOAA NWFSC is exploring potential impacts

A sign indicates shellfish beds are closed to harvesting due to PSP toxins.
Photo: Judy Kleindinst, WHOI

of domoic acid on salmon and killer whales (via consumption of salmon) on the West Coast.

It is also important to know which components of the food web accumulate toxins and how long it takes for toxins to be eliminated. NOAA OHHI research is identifying pathways by which brevetoxin accumulates in fish, which will help identify which species may present a human health risk and what parts of the fish should be avoided. Experiments with shellfish in Puget Sound and along the Washington coast indicate that razor clams consume *Pseudo-nitzschia* (and associated domoic acid) at a much slower rate than oysters and mussels, but retain some of the highest levels of toxin (NSF-NIEHS COHH). This research will explore properties of the toxin receptors in razor clams, which may help design methods for purging the toxin from the clams. These data can also be incorporated into predictive models. For example, the high feeding rate of mussels and oysters found in Puget Sound, combined with the ability of mussels to quickly purge toxin from their tissues, may explain the decreased frequency of beach closures for *Pseudo-nitzschia* in Puget Sound. A current food web study (EPA) is developing a model of domoic acid elimination in razor clams and crabs, which will be useful for risk managers who need to predict how long it takes for shellfish to eliminate domoic acid and become safe for human consumption. Furthermore, shellfish may biotransform toxins by initially producing a suite of compounds of variable toxicity. Studies are underway (ECOHAB and FDA) to identify and determine the toxicity of these degradation products and develop the best analytical methods for assessing shellfish toxicity for protecting human health. Intraspecies variations in toxin accumulation are also important as other work has shown commercial bivalves from areas exposed to *Alexandrium* blooms can be more resistant to saxitoxin due to a genetic mutation and can, thus, accumulate toxin more rapidly[134] (ECOHAB; NOAA NWFSC). NOAA NWFSC is working to develop genetic markers that distinguish this PSP toxin susceptibility. Understanding shellfish toxin resistance will improve prediction and managing of shellfish toxicity.

3.2.4. Public Health and Socioeconomic Studies (also see Section 3.4.2)

3.2.4.1. Public Health Research

Research on public health impacts of HAB toxins has been slower to advance. In the late 1990s to early 2000s, formal risk assessment or cohort-based epidemiological studies related to HABs were limited, for the most part, to *Pfiesteria*-related studies supported by CDC in the Mid-Atlantic states[135,136,137]. Those initial *Pfiesteria* incidents in North Carolina and Maryland highlighted the presence of public health issues associated with human exposure to HABs.

More recently, an epidemiological cohort study and risk analysis began in the Pacific Northwest with Native American infants, children, and adults who may be exposed to domoic acid through razor clam consumption (NIH NIEHS). This research is making headway for identifying populations most at-risk for exposure and effects from toxic HABs. Additionally, CDC is now supporting numerous state activities to monitor and assess public health impacts of HABs. NIH NIEHS, NSF-NIEHS COHH, and CDC are working with the state of Florida and to assess inland air transport of aerosolized brevetoxins, chronic effects from aerosolized brevetoxin exposure, and the biological basis for respiratory effects. Research demonstrated, for example, that during active *Karenia brevis* blooms, there was an increased rate of respiratory emergency department admissions (for upper airways disease, asthma, pneumonia, and bronchitis), particularly for coastal residents, compared to the rate for a similar unexposed period[138] (CDC; NIH NIEHS).

HABISS was also created by CDC in collaboration with its state partners to help track blooms and their public health impacts. The information collected through this system will be useful for developing predictive criteria.

The geographic areas impacted by major HAB illness syndromes are well-known, but recent work has identified public health issues emerging in new areas. For example, a collaborative public health investigation into the cause of human illness associated with puffer fish in Florida identified the causative agent was saxitoxin produced by the dinoflagellate *Pyrodinium bahamense* [23] (CDC; FDA; ECOHAB). CDC's partnership with the American Association of Poison Control Centers and the use of the Toxic Exposure Surveillance System was integral to identifying additional illnesses during the puffer fish poisoning incident.

Furthermore, some illnesses are likely underreported and better tools for diagnosis are needed. For example, CFP, although the most common illness associated with algal toxins, is difficult to diagnose and, therefore, typically is not reported. CDC is currently supporting research to develop a biomarker to verify CFP exposure, which will facilitate research and surveillance of CFP occurrence and impacts. NOAA CCEHBR is also developing 'biomonitoring' methods for monitoring domoic acid, brevetoxin, and ciguatoxin exposure in living animals to provide early diagnosis. Accomplishments include the development of blood collection cards that can be used for monitoring ciguatoxin and brevetoxins in blood. Improved communication between public heath and wildlife managers is benefiting monitoring programs that aim to protect public health. One example has been the use of sentinel organisms, such as sea lions and brown pelicans in California, for early warning of potential public health threats.

3.2.4.2. Socioeconomic Research

In the last decade, several thorough, yet conservative, assessments of the economic impacts of HABs in the United States have been conducted[22,31,139] (NOAA Sea Grant; ECOHAB; NSF). Additionally, assessments of individual events have been supported by Federal and state agencies and illustrate well the large economic impact that just one event can have on local communities. These assessments include direct impacts to the commercial shellfishing industry in Maine and Massachusetts due to the 2005 *Alexandrium* bloom[33] (approximately $20 million in 2005 dollars), the effect of red tide on the Florida Gulf Coast tourist industry each year[58] ($18-29 million in 2005 dollars), and the *Pfiesteria* halo effect on seafood sales in Maryland[32] ($60 million in 2005 dollars, NOAA Sea Grant). Cost/benefit studies of HAB management strategies and assessments of sociocultural impacts are new areas that are just starting to be addressed[1].

NOAA Sea Grant conducted significant outreach efforts to accurately inform the public during the *Pfiesteria* events in the 1990s. Products included a scientifically accurate documentary on HABs with emphasis on *Pfiesteria*, an education resource guide, and a survey to better understand public perceptions and concerns with a goal of

Recreational clam harvesting.
Photo: Washington Department of Fish and Wildlife

more effective education. Most coastal states combating HAB problems now have a significant outreach component, resulting in more effective management.

NSF-NIEHS COHH supported the first formal evaluation of use and satisfaction of HAB outreach and education materials, specifically the Florida Poison Information Center-Miami's Aquatic Toxins Hotline. The research found that the hotline was successful at quickly providing useful information on HABs to a large majority of the callers; results are expected to lead to expansion and improvement of this tool[140].

A mussel cage used in the Washington Department of Health's Sentinel Mussel Biotoxin Monitoring Program.
Photo: Liz Cox-Bolin and Frank Cox

3.2.5. Prevention, Control, and Mitigation Studies

Most of the advances discussed in the previous sections have led to improved HAB management, but this section highlights examples of research directly applicable to HAB prevention, control, and mitigation. These advances are covered in more detail in the *Harmful Algal Bloom Management and Response: Assessment and Plan* (Box 1.3).

3.2.5.1. Prevention

HAB prevention requires a thorough understanding of HAB physiology, ecology, and oceanography (see Section 3.2.1). Although the underlying causes of most HABs are not well understood, it is generally accepted that some HAB events are intensified by high nutrients or by changes in nutrient regime[13]. Therefore, some agencies have looked directly at potential benefits of nutrient management. Other agencies have focused on water quality monitoring, which has given important long-term information on nutrients and other water quality changes. This knowledge is a critical basis for developing methods of prevention. Examples include:

- In Puerto Rico, USDA is collaborating with NOAA to investigate impacts of upstream nutrient conservation on downstream water quality. NOAA Sea Grant is also investigating potential impacts of upstream land use changes in South Carolina.
- EPA is supporting a new project to assist management decisions in the Gulf of Maine by identifying causal relationships between river basin inputs, coastal condition, and HAB-induced shellfish toxicity using a probabilistic model.
- EPA and USGS have supported nutrient monitoring and development of nutrient models which have utility in management of nutrient loadings to estuaries and coastal waters of the United States (e.g., http://water.usgs.gov/nawqa/sparrow/index.html).

3.2.5.2. Control

Bloom control has been an active area of research and a number of potential control agents have been identified:

- The use of naturally occurring HAB-specific pathogens, such as bacteria, viruses, and parasites, is being investigated, but this research is still in its early stages (ECOHAB; NOAA CCEHBR; NSF-NIEHS COHH, see Section 3.2.1.4).
- Physical cell removal by clay flocculation is a form of mechanical control that has been tested in a series of projects and has shown promise (ECOHAB). Further evaluation in the context of risk management and cost/benefit analysis is the next step for consideration.

3.2.5.3. Mitigation

Mitigation, or minimizing impacts of HABs, is currently the most feasible, and thus operational, management strategy for HABs. Mitigation strategies include monitoring for cells and toxins (also see Sections 3.2.1.6 and 3.2.2.1), short-term predictions/early warnings, and event response. Operational examples of these mitigation strategies are provided below. Cell and toxin detection methods are discussed in Sections 3.2.1.6 and 3.2.2.1. Outreach and education are also important components of successful mitigation, and those advances are discussed in Section 3.2.4.2.

Improving Monitoring Capabilities

Monitoring is essential for mitigation of HAB impacts, and the responsibility for most coastal monitoring resides at the state level (except in Federal waters where FDA has jurisdiction). Federal programs have assisted states by supporting development and transfer to operations of regional HAB monitoring systems:

- Outcomes of the ORHAB regional project (Table 3.3), supported by NOAA MERHAB and conducted in collaboration with NWFSC and other partners (http://www.orhab.org/partners.html), include a monitoring network in Washington focused on early warning of domoic acid in razor clams.
- A regional project investigating *Pfiesteria* and other HAB events in Chesapeake Bay (NOAA MERHAB) produced new continuous, real-time tools to measure environmental parameters in critical shallow water areas at unprecedented temporal and spatial resolutions. These tools are part of the Maryland "Eyes on the Bay" program (www.eyesonthebay.net) and are vital to the state strategy of building community and institution partnerships to sustain monitoring programs and improve predictive capabilities. In addition, *in situ* nutrient monitoring technologies developed with support from NOAA MERHAB are now being adopted by the States of Maryland and Florida.
- In the Gulf of Mexico, a networked system of autonomous sampling platforms incorporating physical, chemical, and biological sensor packages is being developed and assessed (NOAA MERHAB). This project facilitates model and forecast initializations and statewide, adaptive field sampling. For example, the data is used for near real-time 'ground-truthing' of the NOAA HAB forecasting system (NOAA CCMA, CSC, NESDIS, CO-OPS).
- The first field test of an automated, *in situ* method for domoic acid detection onboard the Environmental Sample Processor was successful (NOAA CCEHBR), showing promise for integration in ocean observing systems (toxin detection is also discussed in Section 3.4.2).
- A number of states have established citizen monitoring programs for HAB species. FDA and NOAA have supported establishment of these programs and training for volunteers. NOAA Sea Grant also leads the citizen monitoring program in Delaware (http://www.ocean.udel.edu/mas/DIBCMP/about.html) and in the Great Bay Estuary in New Hampshire (http://www.gbcw.unh.edu/). Citizen monitoring programs can reduce the cost of monitoring and managing our coastal resources.

Short-term Predictions

Short-term predictions allow early warnings of bloom occurrence and transport. This knowledge allows managers to have advanced preparation, focus sampling in critical areas, and warn the public of potential impacts.

- In Florida, the HAB forecasting system (http://tidesandcurrents.noaa.gov/hab/), which incorporates field data, satellite imagery, and surface transport information, has been operational since 2004 and is issued twice weekly to warn managers and the public of potential HAB impacts (NOAA CCMA, CSC, NESDIS, CO-OPS).
- Data from model simulations in the coastal Gulf of Maine have been used successfully since the historic *Alexandrium* bloom of 2005 to provide early warnings of potential toxicity, allowing managers to focus sampling in critical areas to safeguard human health while minimizing impacts on fishers (ECOHAB).
- The ORHAB partnership described above has allowed early warnings of domoic acid in razor clams in Washington. Estimates indicate that selective beach openings made possible by the ORHAB partnership have saved at least $3 million per year for Washington's coastal fisheries (NOAA MERHAB, NWFSC).
- The Chesapeake Bay Program, in partnership with multiple Federal agencies (EPA; NOAA;

USGS) produces an ecological forecast for HAB occurrence in the Chesapeake Bay (http://www.chesapeakebay.net/bayforecast.htm).

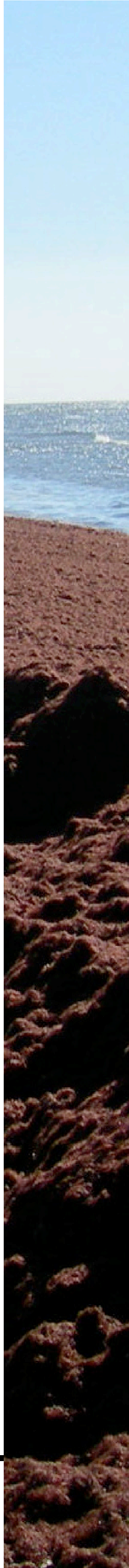
Rapid Response to HAB Events

HAB events can occur unexpectedly and sometimes involve species and toxins that are new to a geographic area. Within the past 10 years, some Federal agencies have developed programs to provide immediate funding and/or scientific expertise for responding to such HAB events. The *Harmful Algal Bloom Management and Response: Assessment and Plan* presents a strategy for improving this type of response. Below are recent examples of collaboration for successful event response:

- Timely and effective responses to the *Alexandrium* bloom in 2005 by states with assistance from FDA and NOAA resulted in protection of humans from PSP illnesses despite remarkably high toxicity in the unmarketed product (see Box 26 in the *Prediction and Response Report*[5]).
- Collaborative efforts from the State of Florida, American Association of Poison Control Centers, CDC, FDA, and NOAA identified saxitoxin as the causative agent of human illness associated with puffer fish consumption and allowed tracking of additional illnesses in 2002.

Chapter 4

Coordination and Communication for Marine HAB Research and Response



Coordination and communication in response to the growing problem of marine HABs in the United States has improved greatly since the first marine HAB assessment, the National Assessment of Harmful Algal Blooms in U.S. Waters[6], was completed for Congress in response to the original HABHRCA legislation. This chapter provides a descriptive overview of the opportunities for information exchange and coordination both at the national and international levels.

These enhanced opportunities will lead to improvements in 1) interagency, intramural and extramural research program planning, 2) intramural and extramural program planning integration, 3) Federal, state, local, private, academic, and international research program implementation, and 4) dissemination of research results. These improvements will also speed and enhance the development of infrastructure, tools, information, and guidance needed by state, local, and tribal governments to develop options and strategies for reducing the risks posed by HABs and HAB toxins in U.S. marine waters. Improved communication and coordination will help prevent duplication of effort.

4.1. National Coordination and Communication

4.1.1. Synergy of HAB Programs Will Continue to Advance HAB Research

Many agencies and programs conduct research on marine HABs (Table 3.1) with the ultimate goal to protect public health, economies, communities, ecosystems, and fisheries. Together these programs constitute an integrated HAB research program. The relationship of all of these programs was laid out in the *HAB Management and Response: Assessment and Plan*[3] (Box 1.3). *HARRNESS*[2], a plan developed by the HAB research and management community to guide research from 2005 to 2015, identified the major research needs. The four HABHRCA reports (Box 1.1), including this report, lay out how the Federal government is responding to the HAB problem and recommend approaches for improving future HAB research and response. A number of other reports address specific areas of HAB research and response[1,141,142]. Several themes are recurring in all of these reports:

- Basic research provides new understanding of the causes and impacts of HABs and new technologies for improved monitoring and prediction. These provide the basis for developing new strategies and technologies for HAB prevention, control, and mitigation.
- Programs that focus on HABs in the environment and programs that focus on human and community impacts need to be well coordinated in order to derive the most benefit from the research.
- Programs dedicated to moving new information, predictive models, and potential prevention and control methods to operational use by managers at the Federal, state, and local levels will greatly advance HAB response.
- A combination of extramural and intramural, competitive and noncompetitive research, and operations can best meet the multiple goals required to improve HAB response.

No single approach, program, or agency can fulfill all of these needs, but a well coordinated suite of programs can do so.

4.1.2 Federal Coordination

The 2004 reauthorization of *HABHRCA* calls for this report to "identify ways to improve coordination and to prevent unnecessary duplication of effort among Federal agencies and departments with respect to research on harmful algal blooms." *HABHRCA* 2004 also calls for three other reports about different aspects of HAB research and response (Box 1.1), all of which are required by the legislation to address Federal coordination.

Federal coordination for HAB research and response, including marine HABs, should be provided by the IWG-4H. As described in Chapter 1, the IWG-4H was formed by the JSOST to fulfill the requirement of the *HABHRCA* 2004 to reestablish the Interagency Task Force on HABs and Hypoxia (Box 1.2). Section E.2 of the Charter of the IWG-4H specifies that it will "(e)nsure interagency communication, coordination and cooperation."

4.1.3. Coordination of Federal Agencies with the HAB Research and Management Community

U.S. National Office for Harmful Algal Blooms. The U.S. National Office for Harmful Algal Blooms, established with funding from NOAA CSCOR and administered at Woods Hole Oceanographic Institution, provides critical infrastructure, including communication, coordination, and technical support capabilities that enhance the Nation's ability to respond to and manage the growing threat posed by HABs. It aids coordination by organizing HAB meetings, symposia, and workshops and facilitates training and student participation in HAB activities. Communications are facilitated by maintaining the "Harmful Algae Page" web site (http://www.whoi.edu/redtide/), hosting list servers for national and regional HAB issues, archiving HAB reports and providing a central location for announcements of funding opportunities and meetings. The National Office maintains databases of U.S. HAB events that are coordinated at the international level, provides technical information through its web site, and assists with the preparation of national and international HAB reports. The activities of the National Office also facilitate some functions of the National HAB Committee (NHC).

The National HAB Committee. The *HARRNESS* report (HARRNESS 2005) called for the formation of a NHC to facilitate coordination and communication of activities for the U.S. HAB community at a national level (http://www.whoi.edu/page.do?pid=13935). The NHC is a body elected by and representing the HAB research and state and local management communities. Representatives from some Federal agencies serve as non-voting ex-officio members and, as described in the *Scientific Assessment of Freshwater Harmful Algal Blooms* report[8], provide a linkage between the IWG-4H and NHC (Box 5.1) so that common coordination activities can be undertaken. An Interprogram Coordination Subcommittee of the NHC will develop a framework and strategy for communication and coordination, with multiple national and international programs which are relevant to HAB issues.

Ocean Observing Systems. The U.S. Integrated Ocean Observing System (IOOS) (http://www.ocean.us/) is a coordinated national network of observations and data transmission, data management, and communications intended to routinely and continuously acquire and disseminate quality-controlled data and information on current and future states of the oceans and Great Lakes from the global scale of ocean basins to local scales of coastal ecosystems. The IOOS is part of the U.S. Integrated Earth Observing System (IEOS), the U.S. contribution to the Global Ocean Observing System (GOOS, http://www.ioc-goos.org/), and a contribution to the Global Earth Observation System of Systems (GEOSS). These broad, coordinated observing systems have the potential to greatly enhance HAB forecasting capabilities and to coordinate data flow within regions, but their utility in these respects will depend upon the appropriate location and integration of HAB-specific sensors and data in regions where HABs are common occurrences (see 'Regional Coordination' section below).

Regional Coordination. Regional coordination is also important because HAB problems are often similar within regions. The Gulf of Mexico Alliance is a regional alliance of the five Gulf of Mexico states that shares and coordinates science, expertise, and financial resources to protect the Gulf of Mexico ecosystem. They have a number of HAB-related goals related to the improvement of HAB detection and forecasting in the region. Similar efforts are occurring in other regions, such as the West Coast Governor's Alliance. In addition, the *HAB Management and Response: Assessment and Plan*, another report required by HABHRCA 2004 (Box 1.1), recommends regional coordination of HAB research infrastructure and event response.

Further, Regional Coastal Ocean Observing Systems, components of IOOS, are meant to provide the local-scale data and information to address issues that are important to the stakeholders in a particular region, which in some cases includes HABs. The Gulf of Maine Ocean Observing System, which has provided oceanographic data for use in conjunction with other data in order to monitor and predict *Alexandrium* bloom movement in the Gulf of Maine, offers a preliminary example of their application for enhancing HAB prediction.

Interstate Shellfish Sanitation Conference. The Interstate Shellfish Sanitation Conference (ISSC), formed in 1982, fosters and promotes shellfish sanitation through the cooperation of state and Federal control agencies, the shellfish industry, and the academic community. The ISSC: 1) adopts uniform procedures, incorporated into an Interstate Shellfish Sanitation Program, and implemented by all shellfish control agencies; 2) gives state shellfish programs current and comprehensive sanitation guidelines to regulate the harvesting, processing, and shipping of shellfish; 3) provides a forum for shellfish control agencies, the shellfish industry, and academic community to resolve major issues concerning shellfish sanitation; and 4) informs all interested parties of recent developments in shellfish sanitation and other major issues of concern through the use of news media, publications, regional and national meetings, internet, and by working closely with academic institutions and trade associations. The ISSC promotes cooperation and trust among shellfish control agencies, the shellfish industry, and consumers of shellfish, and insures the safety of shellfish products consumed in the United States. The ISSC Biotoxin Committee provides guidance and recommendations concerning biotoxin issues, including addressing methods of analysis for regulation of biotoxins in shellfish. A biennial meeting is held to address emerging issues, which is widely attended by state and Federal regulators. More information about ISSC can be found at http://www.issc.org/.

The Working Group on Unusual Marine Mammal Mortality Events. The working group on unusual marine mammal mortality events was created under the Marine Mammal Protection Act as an advisory board to the Secretary of Commerce and Secretary of the Interior and is another component of the NOAA NMFS Marine Mammal Health and Stranding Response Program. The Working Group is made up of 12 members that rotate every three years, two international observers from Canada and Mexico, and representatives from Federal agencies, including NOAA NMFS, USFWS, and MMC. The primary role of the Working Group is to determine when a UME is occurring and then to direct responses to such events. Response to UMEs is coordinated by the NMFS regional offices and the regional stranding networks, as well as other Federal, state, and local agencies. Increased marine animal strandings can be the first sign of a HAB event, so UMEs can serve to identify HABs in areas not actively monitored. Investigation of such events has also led to a greater understanding of HAB impacts on marine mammal populations.

The National Water Quality Monitoring Council. The National Water Quality Monitoring Council was created in 1997 and has taken the lead to design the National Water Quality Monitoring Network. It has 35 members and has a balanced representation of Federal, tribal, interstate, state, local and municipal governments, watershed and environmental groups, the volunteer monitoring community, universities, and the private sector, including the regulated community. The Council is co-chaired by the USGS and EPA, and its other Federal members include NOAA, Tennessee Valley Authority, U.S. Army Corps of Engineers, USDA, and the remaining U.S. Department of the Interior agencies. The purpose of the Council is to provide a national forum for coordination of consistent and scientifically defensible methods and strategies to improve water quality monitoring, assessment, and reporting. The Council promotes partnerships to foster collaboration, advance the science, and improve management within all elements of the water quality monitoring community. More information on the National Water Quality Monitoring Council is available at: http://acwi.gov/monitoring/.

National Workshops and Meetings. Currently in the United States, communication between HAB researchers and Federal, state, and local managers is facilitated by the U.S. HAB Symposia Series, a biennial national meeting that is organized by the U.S. National Office for Harmful Algal Blooms and sponsored by NOAA. The latest research findings and their application to resource and public health management are the main topics of these meetings (http://www.whoi.edu/sbl/liteSite.do?litesiteid=13352). The Gordon Research Conference on Mycotoxins and Phycotoxins provides a forum for the presentation and discussion of leading edge research on the biology, chemistry, risk assessment, and toxicology of fungal, algal, and cyanobacterial toxins that are known food or water contaminants. The conference has a history of support from numerous Federal agencies, including the USDA, FDA, NIEHS, and NOAA (http://www.grc.org/conferences.aspx?id=0000175). The first Gordon Research Conference for Oceans and Human Health (http://www.grc.org/programs.aspx?year=2008&program=oceans) from June 29-July 4, 2008, included a substantial component on HABs and human health.

4.2. International Coordination and Communication

4.2.1. U.S. Participation in International Organizations

HABs are a global phenomenon and many countries have a long history of research and management responses. Representatives from the United States participate in a variety of international organizations that address HAB issues. Through these activities, the United States benefits from the experience with similar problems in other countries, preventing duplication of effort.

The Intergovernmental Oceanographic Commission (IOC) HAB Programme focuses on HAB management and research in order to understand HAB causes, predict their occurrences, and mitigate their impacts (http://ioc.unesco.org/hab/intro.htm). It also supports infrastructure such as training courses, web-based learning modules, the *Harmful Algae News* newsletter, and databases of global HAB events. It is also one of several sponsors of the Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB) Program.

GEOHAB is an international program aimed at fostering and promoting co-operative research directed toward improving the prediction of HAB events (http://www.obs-vlfr.fr/LOV/OMT/GEOHAB/). Through open science meetings, it has developed plans for comparative research on HABs in upwelling systems, eutrophic coastal and estuarine systems, fjords and coastal embayments, and stratified systems focused on HAB biodiversity and biogeography, nutrients and eutrophication, adaptive strategies comparative ecosystems, and observation, modeling, and prediction.

The International Society for the Study of Harmful Algae (ISSHA) was founded in 1997 (http://www.issha.org/). It co-sponsors meetings at the national, regional, and international levels and promotes and fosters research and training programs on harmful algae.

The Association of Analytical Communities (AOAC) International's Marine and Freshwater Toxins Task Force (http://www.aoac.org/marine_toxins/task_force.htm#Overview) is an international group of experts on marine and freshwater toxins and stakeholders who have a strong and practical interest in the development and validation of methods for detection of these toxins. In response to the global need for improved testing methods for these toxins, the Task Force validates and provides training in new methods. Regional meetings, online forums, and journals of the AOAC provide an opportunity for the exchange of information about new methods.

U.S. representatives participate in regional groups in the North Pacific and North Atlantic—PICES HAB Section and the International Council for the Exploration of the Sea Working Group on Harmful Algal Bloom Dynamics. Both groups are working with the IOC to create a global "Harmful Algal Event Database" and also hold meetings to address current HAB issues and share regional experience in HAB management.

4.2.2. International Scientific Meetings

International meetings attended by HAB researchers and managers, such as the International Conference on Harmful Algae organized by ISSHA, also provide a forum to exchange recent research results that may lead to new management approaches. The United States (NOAA and NSF) as well as other countries and international organizations, have provided support for this meeting. The International Union of Pure and Applied Chemistry International Symposia on Mycotoxins and Phycotoxins have a broader focus on research in toxin analysis, human health effects, risk assessments, and control and treatment strategies. U.S. participation in and support of these meetings benefit both the United States and the international community.

References

1. Bauer M. (ed.) 2006. Harmful Algal Research and Response: A Human Dimensions Strategy. National Office for Marine Biotoxins and Harmful Algal Blooms, Woods Hole Oceanographic Institution, Woods Hole, MA., 58 pp http://coastalscience.noaa.gov/stressors/extremeevents/hab/HDstrategy.pdf

2. HARRNESS. 2005. Harmful Algal Research and Response: a National Environmental Science Strategy 2005-2015. Ramsdell JS, Anderson DM, and Glibert PM. (eds.) Ecological Society of America, Washington, D.C., 96pp. http://www.whoi.edu/fileserver.do?id=24149&pt=10&p=19132

3. Jewett EB, Lopez CB, Dortch Q, Etheridge SM, Backer LC. 2008. Harmful Algal Bloom Management and Response: Assessment and Plan. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

4. Sandifer, P., Sotka, C., Garrison, D., and Fay, V. 2007. Interagency Oceans and Human Health Research Implementation Plan: A Prescription for the Future. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Washington, D.C.

5. Jewett EB, Lopez CB, Dortch Q, Etheridge SM. 2007. National Assessment of Efforts to Predict and Respond to Harmful Algal Blooms in U.S. Waters. Interim Report. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

6. CENR. 2000. National Assessment of Harmful Algal Blooms in U.S. Waters. National Science and Technology Council Committee on Environment and Natural Resources, Washington, D.C., 38 pp.

7. Van Alstyne KL, Wolfe GV, Freidenburg TL, Neill A, Hicken C. 2001. Activated defense systems in marine microalgae: evidence for an ecological role for DMSP cleavage. Marine Ecology Progress Series 213: 53-65.

8. Lopez CB, Jewett EB, Dortch Q, Walton BT, Hudnell HK. 2008. Scientific Assessment of Freshwater Harmful Algal Blooms. Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health of the Joint Subcommittee on Ocean Science and Technology. Washington, DC.

9. Anderson DM. 1989. Toxic algal blooms and red tides: A global perspective, pp. 11-16. In: Okaichi T, Anderson DM, and Nemoto T (eds.) Red Tides: Biology, Environmental Science and Toxicology. Elsevier, New York.

10. Smayda TJ. 1990. Novel and nuisance phytoplankton blooms in the sea: evidence for a global epidemic, pp. 29-40. In: Graneli E, Sundstrom B, Edler L, Anderson DM. (eds.), Toxic Marine Phytoplankton. Elsevier.

11. Hallegraeff GM. 1993. A review of harmful algal blooms and their apparent global increase. Phycologia 32: 79-99.

12. Hallegraeff GM. 2003. Harmful algal blooms: a global overview. In: Hallegraeff, G.M., Anderson, D.M., and Cembella, A.D. (eds). Manual on Harmful Marine Microalgae. UNESCO, Paris, 793 pp.

13. GEOHAB. 2006. Global Ecology and Oceanography of Harmful Algal Blooms, Harmful Algal Blooms in Eutrophic Systems. P.Glibert (ed.). IOC and SCOR, Paris and Baltimore, 72 pp.

14. Heisler J, Glibert P, Burkholder J, Anderson D, Cochlan W, Dennison W, Gobler C, Dortch Q, Heil C, Humphries E, Lewitus A, Magnien R, Marshall H, Stockwell D, Suddleson M. 2008. Eutrophication and harmful algal blooms: A scientific consensus. Harmful Algae. In press.

15. Jackson JB, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury R, Cooke R, Erlandson J, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ, Warner R. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293: 629 - 638.

16. Hallegraeff GM, Bolch C J. (1992) Transport of dinoflagellate cysts in ships' ballast water: implications for plankton biogeography and aquaculture. Journal of Plankton Research 14, 1067–1084

17. Vanderploeg HA, Liebig JR, Carmichael WW, Agy MA, Johegen TH, Fahnenstiel GL, Nalepa TF. 2001. Zebra mussel (Dreissena polymorpha) selective filtration promoted toxic Microcystis blooms in Saginaw Bay (Lake Huron) and Lake Erie. Can. J. Fish. Aquat. Sci. 58: 1208-1221.

18. Ferreira JG, Wolff WJ, Simas TC, Bricker SB. 2005. Does biodiversity of estuarine phytoplankton depend on hydrology. Ecological Modeling 187: 513-523.

19. Edwards M, Johns DG, Leterme SC, Svendsen E, Richardson AJ. 2006. Regional climate change and harmful algal blooms in the northeast Atlantic. Limnol. Oceanogr. 52(2): 820-829.

20. Dale B, Edwards M, Reid PC. 2006. Climate change and harmful algal blooms. In Granéli E, Turner JT (eds.), Ecology of Harmful Algae. Ecological Studies. 189: 367-378.

21. Glibert PM, Anderson DM, Gentien P, Graneli E, Sellner KG. 2005. The global complex phenomena of harmful algal blooms. Oceanography 18(2): 136-147.

22. Hoagland P, Scatasta S. 2006. The economic effects of harmful algal blooms. In Graneli E and Turner J (eds.), Ecology of

Harmful Algae. Ecology Studies Series. Dordrecht, The Netherlands: Springer-Verlag, Chap. 29.

23. Landsberg JH, Hall S, Johannessen JN, White KD, Conrad SM, Abbott JP, Flewelling LJ, Richardson RW, Dickey RW, Jester EL, Etheridge SM, Deeds JR, Van Dolah FM, Leighfield TA, Zou Y, Beaudry CG, Benner RA, Rogers PL, Scott PS, Kawabata K, Wolny JL, Steidinger KA. 2006. Saxitoxin puffer fish poisoning in the United States, with the first report of Pyrodinium bahamense as the putative toxin source. Environ Health Perspect. Oct;114(10):1502-7.

24. Landsberg JH. 2002. The effects of harmful algal blooms on aquatic organisms. Reviews in Fisheries Science 10: 113-390.

25. Gulland FMD, Hall AJ. 2007. Is marine mammal health deteriorating? Trends in the global reporting of marine mammal disease. EcoHealth; 4:135-150.

26. Lefebvre KA, Powell CL, Busman M, Doucette GJ, Moeller PD, Silver JB, Miller PE, Hughes MP, Singaram S, Silver MW, Tjeerdema RS. 1999. Detection of domoic acid in northern anchovies and California sea lions associated with an unusual mortality event. Natural Toxins. 7(3):85-92.

27. Flewelling LJ, Naar JP, Abbott J, Baden D, Barros N, Bossart GD, Bottein MD, Hammond DG, Haubold EM, Heil CA, Henry MS, Jacocks HM, Leighfield TA, Pierce RH, Pitchford TD, Rommel SA, Scott PS, Steidinger KA, Truby EW, Van Dolah FM, Landsberg JH. 2005. Unexpected vectors of brevetoxins during marine mammal mortalities. Nature 435:755-756.

28. Lund JK, Barnett HJ, Hatfield CL, Gauglitz EJ, Wekell JC, Rasco B. 1997. Domoic acid uptake and depuration in Dungeness crab (Cancer magister Dana 1852). J. Shellfish Res. 16: 225-231.

29. Onuf CP. 1996. Seagrass response to long term light reduction by brown tide in upper Laguna Madre, Texas: Distribution and biomass patterns. Marine Ecology Progress Series 138:219-231.

30. Valiela I, McClelland J, Hauxwell J, Behr PJ, Hersh D, Foreman K. 1997. Macroalgal blooms in shallow estuaries: Controls and ecophysiological and ecosystem consequences. Limnology and Oceanography 42:1105-1118.

31. Hoagland P, Anderson DM, Kaoru Y, White AW. 2002. The economic effects of harmful algal blooms in the United States: estimates, assessment issues, and information needs. Estuaries 25(4b): 677-695.

32. Lipton DW. 1999. Pfiesteria's economic impact on seafood industry sales and recreational fishing. In: Gardner BL, Koch L (eds.), Economics of Policy options for Nutrient Management and Pfiesteria. Proceedings of the Conference, Nov. 16, 1998, Laurel, MD.

33. Jin D, Thunberg E, Hoagland P. 2008. Economic impact of the 2005 red tide event on commercial shellfish fisheries in New England. Ocean and Coastal Management. 51(5): 420-429.

34. Doucette, G.J., Cembella, A.D., Martin, J.L., Michaud, J., Cole, T.V.N., Rolland, R.M. 2006. Paralytic shellfish poisoning (PSP) toxins in North Atlantic right whales Eubalaena glacialis and their zooplankton prey in the Bay of Fundy, Canada. Marine Ecology Progress Series 306: 303-313.

35. Anderson D, McGillicuddy D, Townsend D, Turner J. 2005. Preface, Deep Sea Research Part II: Topical Studies in Oceanography, The Ecology and Oceanography of Toxic Alexandrium fundyense Blooms in the Gulf of Maine, 52(19-21): 2365-2368

36. Kahn J, Rockel M. 1988. Measuring the Economic Effects of Brown Tides. Journal of Shellfish Research. 7(4): 677-682.

37. Lomas MW, Gobler CJ. 2004. Aureococcus anophagefferens research: 20 years and counting. Harmful Algae 3: 273-277.

38. Gobler CJ, Londsdale DJ, Boyer GL. 2005. A review of the causes, effects, and potential management of harmful brown tide blooms caused by Aureococcus anophagefferens (Hargraves et Sieburth). Estuaries 28(5): 726-749.

39. Maranda L, Keller MD, Hurst JW, Bean LL, Mcgowan JD, Hargraves P. 2000. Spatio-temporal distribution of Prorocentrum lima in coastal waters of the Gulf of Maine: a two-year survey. Journal of Shellfish Research 19(3):1003-1006.

40. Maranda L, Shimizu Y. 1987. Diarrhetic shellfish poisoning in Narragansett Bay. Estuaries 10(4): 298-302.

41. Trice RM, Glibert PM, Lea C, Van Heukelem L. 2004. HPLC pigment records provide evidence of past blooms of Aureococcus anophagefferens in the Coastal Bays of Maryland and Virginia, USA. Harmful Algae 3: 295-304.

42. Wazniak CE, Glibert PM. 2004. Potential impacts of brown tide, Aureococcus anophagefferens, on juvenile hard clams, Mercenaria mercenaria, in the Coastal Bays of Maryland, USA. Harmful Algae 5: 321-329.

43. Burkholder JM, Noga EJ, Hobbs CW, Glasgow HB, Smith SA. 1992. New "phantom" dinoflagellate is the causative agent of major estuarine fish kills. Nature 358:407-410.

44. Glibert PM, Burkholder JM. 2006. Ecology of Pfiesteria. Harmful Algae Special Issue 5(4): 339-480.

45. Moeller PDR, Beauchesne KR, Huncik KM, Davis WC, Christopher SJ, Riggs-Gelasco P, Gelasco AK. 2007. Metal Complexes and Free Radical Toxins Produced by Pfiesteria piscicida. Environ. Sci. Technol., 41 (4), 1166 -1172.

46. Place AR, Saito K, Deeds JR, Robledo JAF, Vasta GR. 2007. Pfiesteria spp toxins: unresolved questions and an alternative hypothesis. In Botana L (ed.), Seafood and Freshwater Toxins, Pharmacology, Physiology, and Detection. Taylor and Francis, 2nd Edition. CRC.

47. Chesapeake Quarterly. 2007. Was there another fish killer? Volume 6, Issue 1. http://www.mdsg.umd.edu/cq/v06n1/index.html#TOC

48. Bordelais AJ, Tomas, CR, Naar J, Kubanek J, Baden DG. 2002. New fish-killing alga in coastal Delaware produces neurotoxins. Environmental Health Perspectives 110(5)465-470.

49. Keppler CJ, Hoguet J, Smith K, Ringwood AH, Lewitus AJ. 2005. Sublethal effects of the toxic alga Heterosigma akashiwo on the southeastern oyster (Crassostrea virginica), Harmful Algae 4: 275–285.

50. Glibert PG, Sellner KG (eds.) 2005. Ecology and physiology of Prorocentrum minimum. Harmful Algae Special Issue 4(3): 447-650.

51. Lapointe BE, Barile PJ, Littler MM, Littler DS, Bedford BJ, Gasque C. 2005. Macroalgal blooms on southeast Florida coral reefs: I. Nutrient stoichiometry of theinvasive green alga Codium isthmocladum in the wider Caribbean indicates nutrient enrichment. Harmful Algae, 4:1092-1105.

52. Murphy EB, Steidinger KA, Roberts BS, William J, Jolley JW. 1975. An explanation for the Florida east coast Gymnodinium breve red tide of November 1972. Limnol. Oceanogr. 20:481-486.

53. Steidinger, K.A., Vargo, G.A., Tester, P.A., Tomas, C.R., 1998. Bloom dynamics and physiology of Gymnodinium breve with emphasis on the Gulf of Mexico. In: Anderson DM, Cambella AD, Hallegraeff GM. (eds.), Physiological Ecology of Harmful Algal Blooms. Springer, New York, pp. 135–153.

54. Thessen AE, Bowers BA, Stoecker DK, Oldach DW. 2006. Pseudo-nitzschia spp. and domoic acid in Maryland and Virginia waters. 12th International Conference on Harmful Algae, Copenhagen, Denmark, September 4-8, 2006.

55. Magaña HA, Contreras C., Villareal TA. 2003. A historical assessment of Karenia brevis in the western Gulf of Mexico, Harmful Algae 2:163–171.

56. Maier Brown AF, Dortch Q, Van Dolah FM, Leighfield TA, Morrison W, Thessen AE, Steidinger KA, Richardson B, Moncreif CA, Pennock JR. 2006. Effect of salinity on the distribution and growth, and toxicity of Karenia spp. Harmful Algae, 5, 199-212.

57. Haywood AJ, Steidinger KA, Truby EW, Bergquist PR, Bergquist PL, Adamson J, MacKenzie L. 2004. Comparative morphology and molecular phylogenetic analysis of three new species of the genus Karenia (Dinophyceae) from New Zealand. J. Phycol. 40: 165-179.

58. Steidinger KA, Landsberg JH, Tomas CR, Burns JW. 1999. Harmful algal blooms in Florida, Unpublished technical report submitted to the Florida Harmful Algal Bloom Task Force, Florida Marine Research Institute, 63pp.

59. Evans G, Jones L. 2001. Economic Impact of the 2000 Red Tide on Galveston County, Texas A Case Study. Final Report. TPWD No. 666226. Texas Parks and Wildlife.

60. Villareal TA, Hanson S, Qualia S, Jester ELE, Granade HR, Dickey RW. 2007. Petroleum production platforms as sites for the expansion of ciquatera in the northwestern Gulf of Mexico. Harmful Algae 6: 253-259.

61. Dortch Q, Robichaux R, Pool S, Milsted D, Mire G, Rabalais NN, Soniat TM, Fryxell GA, Turner RE, Parsons ML. 1997. Abundance and vertical flux of Pseudo-nitzschia in the northern Gulf of Mexico. Marine Ecology Progress Series 146:249-264.

62. Parsons ML, Dortch Q, Turner RE. 2002. Sedimentological Evidence of an Increase in Pseudo-nitzschia (Bacillariophyceae) Abundance in Response to Coastal Eutrophication. Limnology and Oceanography 47(2): 551-558.

63. Lapointe BE, Bedford BJ. 2007. Drift rhodophyte blooms emerge in Lee County, Florida, USA: Evidence of escalating coastal eutrophication. Harmful Algae 6: 421-437.

64. Moikeha SN, Chu GW. 1971. Dermatitis producing alga Lyngbya majuscula Gomont in Hawaii. II. Biological properties of the toxic factor. J. Phycol. 7: 8.

65. Osborne NJT, Web PM, Shaw GR. 2001. The toxins of Lyngbya majuscule and their human and ecological health effects. Environmental International. 27:381-392.

66. Hickey BM, MacFadyen A, Trainer VL, Lessard EJ, Cochlan WP, Trick CG, Wells ML. 2007. Regional oceanography leading to toxic Pseudo-nitzschia events on beaches in the northern California Current. Fourth Symposium on Harmful Algae in the U.S. 28Oct -1Nov 2007. Woods Hole, Massachusetts.

67. Ayres D, Reed H. 2004. Managing important recreational and commercial shellfish fisheries around harmful algal blooms. In: Droscher TW and Fraser DA (eds.). Proceedings of the 2003 Georgia Basin/Puget Sound Research Conference. Session 4F. http://www.psat.wa.gov/Publications/03_proceedings/start.htm [February 2004]

68. Gulland F. 2000. Domoic acid toxicity in California sea lions (Zalophus californianus) stranded along the central California coast, May-October 1998. Report to the National Marine Fisheries Service Working Group on Unusual Marine Mammal Mortality Events. U.S. Department of Commerce, NOAA Technical Memo. NMFS-OPR-17, 45p.

69. Goldstein T, Mazet JA, Zabka TS, Langlois G, Colegrove KM, Silver M, Bargu S, Van Dolah F, Leighfield T, Conrad PA, Barakos J, Williams DC, Dennison S, Haulena M, Gulland FM. 2008. Novel symptomatology and changing epidemiology of domoic acid toxicosis in California sea lions (Zalophus californianus): an increasing risk to marine mammal health. Proc. Biol. Sci. 275: 267-76.

70. Schnetzer A, Miller PE, Schaffner RA, Stauffer BA, Jones BH, Weisberg SB, DiGiacomo PM, Berelson WM, Caron DA. 2007. Blooms of Pseudo-nitzschia and domoic acid in the San Pedro Channel and Los Angeles harbor areas of the Southern California Bight, 2003-2004. Harmful Algae 6: 372-387.

71. Horner RA, Garrison DL, Plumley FG. 1997. Harmful algal blooms and red tide problems on the US West Coast. Limnol. Oceanagr. 42(5): 1076-1088.

72. Rensel J. 1995. Harmful algal and finfish resources in Puget Sound. In Puget Sound Research 95 Proceedings. Puget Sound Water Quality Authority, Olympia, Wash. pp. 422–429.

73. O'Halloran C, Silver MW, Holman TR, Scholin CA. 2006. Heterosigma akashiwo in central California waters, Harmful Algae 5: 124–132.

74. Nelson TA, Lee D, Smith BC. 2003. Toxic extracts from ulvoid macroalgae: Are "green tides" harmful algal blooms?, J. Phycol. 39: 874–879.

75. Sutherland C, Silver M. 2007. Dinophysis species and diarrhetic shellfish toxins in Monterey Bay, CA. Fourth Symposium on Harmful Algae in the U.S. 28Oct -1Nov 2007. Woods Hole, Massachusetts.

76. RaLonde R. (ed). 2001. Harmful algal blooms on the North American West Coast. University of Alaska Sea Grant. AK-SG-0105.

77. Cesar H, van Beukering P, Pintz S, Dierking J. 2002. Economic Value of the Coral Reefs of Hawaii, Final Report, December 23, 2002.

78. NOAA. 2006. NOAA Economic Statistics Report. http://www.economics.noaa.gov/library/documents/economic_statistics_and_methodology/NOAAEconomicStatistics-May2006.pdf

79. Arnold H. 1959. Seaweed dermatitis apparently caused by a marine alga. Clinical Observations. In: Proceedings of the 34th Annual Meeting of the Hawaiian Academy of Sciences.

80. Nagle DJ, Paul VJ. 1999. Production of secondary metabolites by filamentous tropical marine cyanobacteria: Ecological functions of the compounds. J.Phycology 35(6): 1412-1421

81. ICGPSIA (Interorganizational Committee on Guidelines and Principles for Social Impact Assessment). 2003. Principles and guidelines for social impact assessment in the USA. Impact Assessment and Project Appraisal 21(3): 231-250

82. Anderson DM, Stock CA, Keafer BA, Bronzino Nelson A, Thompson B, McGillicuddy DJ, Keller M, Matrai PA, Martin J. 2005. Alexandrium fundyense cyst dynamics in the Gulf of Maine. Alexandrium fundyense cyst dynamics in the Gulf of Maine. Deep-Sea Research II. 52: 2522-2542

83. Kirn SL, Townsend DW, Pettigrew NR. 2005. Suspended Alexandrium spp. hypnozygote cysts in the Gulf of Maine. Deep-Sea Research II. 52: 2543-2559.

84. Matrai P, Thompson B, Keller M. 2005. Circannual excystment of resting cysts of Alexandrium spp. from eastern Gulf of Maine populations. Deep-Sea Research II. 52: 2560-2568.

85. Lidie KB, Ryan JC, Barbier M, Van Dolah FM. 2005. Gene Expression in the Florida Red Tide Dinoflagellate Karenia brevis: Analysis of an Expressed Sequence Tag (EST) Library and Development of a DNA Microarray. Mar Biotechnol. 7(5):481-493.

86. Erdner DL, Anderson DM. 2006. Global transcriptional profiling of the toxic dinoflagellate Alexandrium fundyense using massively parallel signature sequencing. BMC Genomics. 7: 88.

87. Erdner DL, McCauley LAR, Libera K, Anderson DM. 2007. Population genetics of toxic Alexandrium blooms in the Gulf of Maine. Fourth Symposium on Harmful Algae in the U.S. 28Oct -1Nov 2007. Woods Hole, Massachusetts.

88. Martinetto P, Teichberg M, Valiela I. 2006. Coupling of estuarine benthic and pelagic food webs to land-derived nitrogen sources in Waquoit Bay, Massachusetts, USA. Marine Ecology Progress Series 307: 37–48.

89. Trainer VL, Hickey BM, Horner RA. 2002. Biological and physical dynamics of domoic acid production off the Washington Coast. Limnol. Oceanogr. 47(5): 1438-1446.

90. Hu C, Muller-Karger FE, Swarzenski PW. 2006. Hurricanes, submarine groundwater discharge, and Florida's red tides. Geophysical Research Letters. 33, L11601.

91. Swarzenski PW, Simonds FW, Paulson AJ, Kruse S, Reich C. 2007. Geochemical and geophysical examination of submarine groundwater associated nutrient loading estimates into Lynch Cove, Hood Canal, Wa. Environ. Sci.Technol. 41: 7022-7029.

92. Kana TM, Lomas MW, MacIntyre HL, Cornwell JC, Gobler CJ. 2004. Stimulation of a brown tide organism, Aureococcus anophagefferens, by selective nutrient additions to in situ mesocosms. Harmful Algae 3:403-438.

93. Glibert PM, Burkholder JM, Parrow MW, Lewitus AJ, Gustafson D. 2006. Rates of direct uptake of nitrogen and nitrogen nutritional preferences by functional types of Pfiesteria piscicida and Pfiesteria shumwayae. Harmful Algae 5: 380-394.

94. Seaborn DW, Dunstan WM, Marshall HG, Gordon AS, Seaborn AM. 2001. Growth and toxicity studies of the dinoflagellates cryptoperidiniopsis sp., Gyrodinium galatheanum, and Pfiesteria piscicida. In: Hallegraeff GM, Blackburn SI, Bolch CJ, Lewis RJ, Editors, Harmful Algal Blooms, Proceedings of the Ninth International Conference on Harmful Algal Blooms IOC UNESCO, Paris, France (2001), pp. 92–96.

95. Egerton TA, Marshall HG. 2006. Feeding preferences and grazing rates of Pfiesteria piscicida and a cryptoperidiniopsoid preying on fish blood cells and algal prey. Harmful Algae 5(4): 419-426.

96. Adolf JE, Stoecker DK, Harding LW. 2006. The balance of autotrophy and heterotrophy during mixotrophic growth of Karlodinium micrum (Dinophyceae). Journal of Plankton Research 28(8):737-751.

97. Sheng J, Malkiel E, Katz J, Adolf J, Belas R, Place AR. 2007. Digital holographic microscopy reveals prey-induced changes in swimming behavior of predatory dinoflagellates. PNAS 104:17512-17517.

98. Lenes JM, Darrow BP, Cattrall C., Heil CA, Callahan M, Vargo GA, Byrne RH. 2001. Iron fertilization and the Trichodesmium response on the West Florida Shelf. Limnol. Oceanogr. 46(6): 1261-1277.

99. Keafer BA, Churchill JH, Anderson DM. 2005a. Blooms of the toxic dinoflagellate, Alexandrium fundyense in the Casco Bay region of the western Gulf of Maine: Advection from offshore source populations and interactions with the Kennebec River plume. Deep-Sea Research II. 52: 2631-2655.

100. Bean LL, McGowan JD, Hurst JW. 2005. Annual variations of paralytic shellfish poisoning in Maine, USA 1997–2001. Deep-Sea Research II. 52: 2834-2842.

101. Keafer BA, Churchill JH, McGillicuddy DJ, Anderson DM. 2005b. Bloom development and transport of toxic Alexandrium fundyense populations within a coastal plume in the Gulf of Maine. Deep-Sea Research II. 52: 2674-2697.

102. MacFadyen A, Hickey BM, Foreman MGG. 2005. Transport of surface waters from the Juan de Fuca eddy region to the Washington coast. Continental Shelf Research 25: 2008-2021.

103.Doucette GJ, McGovern ER, Babinchak JA. 1999. Algicidal bacteria active against Gymnodinium breve (Dinophyceae). I. Bacterial isolation and characterization of killing activity. J. Phycol. 35:1447-1454.

104.Gobler CJ, Deonarine S, Leigh-Bell J, Downes Gastrich M, Anderson OR, Wilhelm SW. 2004. Ecology of phytoplankton communities dominated by Aureococcus anophagefferens: the role of viruses, nutrients, and microzooplankton grazing. Harmful Algae 6: 471-483.

105.Gunderson JH, Goss SH, Coats W. 2001. FISH probes for the detection of parasitic dinoflagellate Amoebophrya sp. infecting the dinoflagellate Akashiwo sanguinea in Chesapeake Bay. J. Eukaryot. Microbiol. 48(6)670-675.

106. McGillicuddy DJ, Signell RP, Stock CA, Keafer BA, Keller MD, Hetland RD, Anderson DM. 2003. A mechanism for offshore initiation of harmful algal blooms in the coastal Gulf of Maine . Journal of Plankton Research, 25(9), 1131-1138.

107. McGillicuddy DJ, Anderson DM, Lynch DR, Townsend DW. 2005. Mechanisms regulating large-scale seasonal fluctuations in Alexandrium fundyense populations in the Gulf of Maine: Results from a physical–biological model. Deep-Sea Research II. 52: 2698-2714.

108. Stock CA, McGillicuddy DJ, Solow AR, Anderson DM. 2005. Evaluating hypotheses for the initiation and development of Alexandrium fundyense blooms in the western Gulf of Maine using a coupled physical–biological model. Deep-Sea Research II. 52: 2715-2744.

109. Anderson DM, Keafer BA, McGillicuddy DJ, Mickelson MJ, Keay KE, Libby PS, Manning JP, Mayo CA, Whittaker DK, Hicky JM, He R, Lynch DR, Smith KW. 2005. Initial observations of the 2005 Alexandrium fundyense bloom in southern New England: General Patterns and Mechanisms. Deep-Sea Research II. 52: 2856-2876.

110. Hood RR, Zhang X, Glibert PM, Roman MR, Stoecker DK. Modeling the influence of nutrients, turbulence and grazing on Pfiesteria population dynamics. Harmful Algae: 5(4)459-479.

111. Rublee PA, Kempton JW, Schaefer EF, Allen C, Harris J, Oldach DW, Bowers H, Tengs T, Burkholder JM, Glsgow HB. 2001. Use of molecular probes to assess geographic distribution of Pfiesteria species. Environmental Health Perspectives 109(5):765-767.

112.Cloern JE, Jassby AD, Thompson JK, Hieb KA. 2007, A cold phase of the East Pacific triggers new phytoplankton blooms in San Francisco Bay: Proceedings of the National Academy of Sciences USA, v. 104, p.18,561-18,565.

113. Carter M, McGowan J, Buss L, Venrick E, Hilbern M. 2007. Coastal bloom dynamics in sourthern California – Have there been any changes since 1917? Fourth Symposium on Harmful Algae in the U.S. 28Oct -1Nov 2007. Woods Hole, Massachusetts.

114.Cloern JE, Schraga TS, Lopez CB, Knowles N, Labiosa RG, Dugdale R. 2005. Climate anomalies generate an exceptional dinoflagellate bloom in San Francisco Bay. Geophysical Research Letters 32, LI4608.

115. Vilotijevic I, Jamison TF. 2007. Epoxide-Opening Cascades Promoted by Water. Science, 317, 1189-1192.

116. Maldonado MT, Hughes MP, Rue EL, Wells ML. 2002. The effect of Fe and Cu on growth and domoic acid production by Pseudo-nitzschia multiseries and Pseudo-nitzschia australis. Limnology and Oceanography, 47: 515-526.

117. Parker MS, Armbrust EV, Lin EO, Jenkins BD, Iverson VS, Rodrigues H, Kudela R. 2006. Gene Expression Associated With Domoic Acid Production and Silicate Limitation in the Diatom Pseudo-nitzschia australis. Eos Trans. AGU, 87(36), Ocean Sciences Meeting Supplement, Abstract OS24D-06.

118. Litaker RW, Trainer V, Le Eberhart B-T, Wekell J, Spencer S, Moon M, Schumacker J, Northcut K, Krueger K, Wojciechowski M, Wojciechowski M, Bonaventura C, Tester P. 2003. Detecting Domoic Acid. Estuarine Research Federation Conference 2003 14-18 September, 2003 Seattle, Washington.

119. Lefebvre KA, Trainer VL, Scholz NL. (2004) Morphological abnormalities and sensorimotor deficits in larval fish exposed to

dissolved saxitoxin. Aquatic Toxicology 66:159-170.

120. Lefebvre K A, Elder N, Hershberger PK, Trainer VL, Stehr CM, Scholz NL. 2005. Dissolved saxitoxin causes transient inhibition of sensorimotor function in larval Pacific herring (Clupea harengus pallasi). Marine Biology, 147:1393-1402.

121. Levin ED, Pizarro K, Pang WG, Harrison J, Ramsdell JS. 2005. Persisting behavioral consequences of prenatal domoic acid exposure in rats. Neurotoxicol Teratol. Sep-Oct; 27(5):719-25.

122. Abraham WM, Bourdelais AJ, Sabater JR, Ahmed A, Lee TA, Serebriakov I, Baden DG. 2005. Airway Responses to Aerosolized Brevetoxins in an Animal Model of Asthma Am. J. Respir. Crit. Care Med. 171: 26-34.

123.Brodie EC, Gulland FMD, Greig DJ, Hunter M, Jaakola J, St Leger J, Leighfield TZ, Van Dolah FM. 2006. Domoic acid causes reproductive failure in California sea lions (Zalophus californianus). Mar Mamm Sci. 2006;22(3):700–707.

124.Bricelj VM, MacQuarrie SP, Smolowitz R. 2004. Concentration-dependent effects of toxic and non-toxic isolates of the brown tide alga Aureococcus anophagefferens on growth of juvenile bivavles. Marine Ecology Progress Series 282:101-114.

125. Peterson BJ, Chester CM, Jochem FJ, Fourqurean JW. 2006. Potential role of sponge communities in controlling phytoplankton blooms in Florida Bay. Marine Ecology Progress Series. 328: 93-103.

126.Cohen JH, Tester PA, Forward R.B. 2007. Sublethal effects of the toxic dinoflagellate Karenia brevis on marine copepod behavior. Journal of Plankton Research. 29(3): 301-315.

127. Prince EK, Lettieri L, McCurdy KJ, Kubanek J. 2006. Fitness consequences for copepods feeding on a red tide dinoflagellate: deciphering the effects of nutritional value, toxicity, and feeding behavior. Oecologia. 147(3):279-288.

128.Colin SP, Dam HG. 2007. Comparison of the functional and numerical responses of resistant versus non-resistant populations of the copepod Acartia hudsonica fed the toxic dinoflagellate Alexandrium tamarense. Harmful Algae. 6: 875-882.

129.Bricelj VM, MacQuarrie SP. 2007. Effects of brown tide (Aureocuccus anophagefferens) on hard clam Mercenaria mercenaria larvae and implications for benthic recruitment. Marine Ecology Progress Series 331:147-159.

130.Giner JL, Zhao H, Dixon MS, Wikfors GH. 2007. Metabolism of algal sterols by Bay Scallops and Brine Shrimp. Fourth Symposium on Harmful Algae in the U.S. 28Oct -1Nov 2007. Woods Hole, Massachusetts.

131.Doucette GJ, Turner JT, Powell CL, Keafer BA, Anderson DM. 2005. Trophic accumulation of PSP toxins in zooplankton during Alexandrium fundyense blooms in Casco Bay, Gulf of Maine, April–June 1998. I. Toxin levels in A. fundyense and zooplankton size fractions, Deep-Sea Research II. 52: 2764-2783.

132. Turner JT, Doucette GJ, Keafer BA, Anderson DM. 2005. Trophic accumulation of PSP toxins in zooplankton during Alexandrium fundyense blooms in Casco Bay, Gulf of Maine, April–June 1998. Zooplankton abundance and size-fractionated community composition. Deep-Sea Research II. 52: 2784-2800.

133. Lefebvre KA, Bargu S, Kieckhefer T, Silver MW. 2002. From sanddabs to blue whales: the pervasiveness of domoic acid. Toxicon. 40: 971-977

134.Bricelj VM, Connell LB, Konoki K, MacQuarrie SP, Scheuer T, Catterall WA, Trainer VL. 2005. Sodium channel mutation leading to saxitoxin resistance in clams increases risk of PSP. Nature. 434: 763-767.

135. Grattan LM, Oldach D, Morris JG. 2001. Human health risks of exposure to Pfiesteria piscicida. BioScience 51(10): 853-857.

136. Moe CL, Turf E, Oldach D, Bell P, Hutton S, Savitz D, Koltai D, Turf M, Ingsrisawang L, Hart R, Ball JD, Stutts M, McCarter R, Wilson L, Haselow D, Grattan L, Morris JG, Weber DJ. 2001. Cohort studies of health effects among people exposed to estuarine waters: North Carolina, Virginia, and Maryland. Environmental Health Perspectives 109: 781-786.

137. Morris Jr JG, Grattan LM, Wilson LA, Meyer WA, McCarter R, Bowers HA, Richard Hebel J, Matuszak DL, Oldach DW. 2006. Occupational Exposure to Pfiesteria Species in Estuarine Waters Is Not a Risk Factor for Illness. Environmental Health Perspectives 114(7): 1038-1043.

138. Kirkpatrick B, Fleming LE, Backer LC, Bean JA, Tamer R, Kirkpatrick G, Kane T, Wanner A, Dalpra D, Reich A, Baden DG. 2006. Environmental exposures to Florida red tides: effects on emergency room respiratory diagnoses admissions. Harmful Algae. 5(5)526-533.

139. Anderson DM, Hoagland P, Kaoru Y, White AW. 2000. Estimated Annual Economic Impacts from Harmful Algal Blooms (HABs) in the United States. WHOI Tech Rept. No. 2000-11. Woods Hole, MA: Department of Biology and Marine Policy Center, Woods Hole Oceanographic Institution.

140. Fleming LE, Jerez E, Stephan W, Cassedy A, Bean JA, Reich A, Kirkpatrick B, Backer L, Nierenberg K, Watkins S, Hollenbeck J, Weisman R. 2007. Florida aquatic toxins hotline: formal evaluation of HAB outreach and educational activities. Fourth Symposium on Harmful Algae in the U.S. 28Oct -1Nov 2007. Woods Hole, Massachusetts.

141. Hudnell HK. (ed.). 2008. Cyanobacterial Harmful Algal Blooms: State of the Science and Research Needs. Advances in Experimental Medicine & Biology. Vol. 619. Springer. 500 pp.

142. Dortch, Q., Anderson, D., Ayres, D., Glibert, G. (eds). 2008. Harmful Algal Bloom Research, Development, Demonstration and Technology Transfer National Workshop Report. Woods Hole, Massachusetts. http://www.whoi.edu/fileserver.do?id=43464&pt=10&p=19132

Appendix. Marine HAB Research and Response by State, Local, and Tribal Governments

State and local governments and tribal entities are involved in HAB monitoring and mitigation, and some states also have research programs. Tribal and state public health or resource management agencies are responsible for monitoring programs and shellfish harvesting or beach closures. FDA works closely with state shellfish control authorities to ensure the safety of shellfish harvested from state waters. State programs disseminate toxin advisory information to the public through web sites, the media, and written materials. Several citizen HAB monitoring networks have also been established, which assist state efforts to track HABs and contribute to ground-truthing of HAB forecasts. Entities conducting HAB research and response are outlined by region and state below.

Northeast

Connecticut

- Department of Agriculture: monitoring and shellfish closures, http://www.ct.gov/doag/cwp/view.asp?a=1369&q=259172

Maine

- Department of Marine Resources
  - Red tide and shellfish sanitation status information, http://www.maine.gov/dmr/rm/public_health/closures/shellfishhotline.htm
  - Maine Red Tide Information System, http://megisims.state.me.us/dmr_redtide/
  - Maine volunteer phytoplankton monitoring program, http://www.umext.maine.edu/shorestewards/phyto.htm

Massachusetts

- Division of Marine Fisheries: protocols for monitoring, harvesting closures, and other regulatory information, http://www.mass.gov/dfwele/dmf/
- Department of Public Health: permit procedures and food safety

New Hampshire

- Department of Environmental Services Shellfish Program and New Hampshire Fish and Game Department: shellfish monitoring, http://www.des.state.nh.us/wmb/shellfish/index.html

New Jersey

- Department of Environmental Protection, Division of Marine Water Monitoring: water quality procedures and shellfish monitoring, http://www.state.nj.us/dep/bmw/
- Department of Environmental Protection, Division of Science, Research and Technology: Brown Tide information, http://www.state.nj.us/dep/dsr/browntide/bt.htm

New York

- Department of Environmental Conservation: shellfish closure information, http://www.dec.ny.gov/outdoor/345.html
- Brown Tide Research Initiative, http://www.seagrant.sunysb.edu/btri/

Rhode Island

- Bureau of Environmental Protection: shellfish closures, http://www.dem.ri.gov/programs/benviron/water/shellfsh/clos/index.htm

Mid-Atlantic and South-Atlantic

Delaware

- Department of Natural Resources and Environmental Control, in collaboration with the University of Delaware Sea Grant College Program: supports the Inland Bays Citizen Monitoring Program, http://www.ocean.udel.edu/mas/DIBCMP/index.html

Maryland

- Department of Natural Resources: HAB monitoring; website with HAB information, bloom status reports, hotline for reporting potential HAB events, http://www.dnr.state.md.us/Bay/hab/index.html
- Eyes on the Bay: interactive access to Chesapeake monitoring stations with HAB data, http://mddnr.chesapeakebay.net/eyesonthebay/index.cfm
- Department of the Environment: notices of shellfish closures and fish advisories, http://textonly.mde.state.md.us/CitizensInfoCenter/FishandShellfish/home/index.asp
- Department of Health and Mental Hygiene: cooperative agreement with CDC to conduct HAB public health response activities.

North Carolina

- Department of Environment and Natural Resources, Division of Water quality: monitoring data and fish kill maps for area rivers; Division of Marine Fisheries: shellfish closure status
- Department of Health and Human Services: cooperative agreement with CDC to conduct HAB public health response activities.

South Carolina

- Department of Health and Environmental Control: monitoring and shellfish closure status and Cooperative agreement with CDC to conduct HAB public health response activities, http://www.scdhec.gov/environment/water/shellfish.htm
- South Carolina Algal Ecology Lab: HAB research, partnership between Department of Natural Resources and University of South Carolina, http://www.dnr.sc.gov/ael/research/research.html

Virginia

- Department of Environmental Quality: procedures and regulations for water quality monitoring, http://www.deq.virginia.gov/watermonitoring/pfiest.html
- Department of Health: cooperative agreement with CDC to conduct HAB public health response activities

Gulf of Mexico

Florida

- Florida Fish and Wildlife Research Institute: HAB research, current red tide status for the Florida coast, network of volunteers monitoring for *Karenia brevis* (developed with MERHAB funding), http://research.myfwc.com/features/view_article.asp?id=12373
- Department of Agriculture and Consumer Services, Division of Aquaculture: shellfish closure status
- Department of Health: cooperative agreement with CDC to conduct HAB public health response activities, http://www.doh.state.fl.us/environment/community/aquatic/index.html
- Florida's Harmful Algal Bloom Task Force: Advisory body to address specific HAB issues and human health risks

Mississippi

- Department of Marine Resources: shellfish closure status

Texas

- Parks and Wildlife Department: Texas coast red tide status reports, inland golden algae bloom status reports, http://www.tpwd.state.tx.us/landwater/water/environconcerns/hab/
- Department of Health: shellfish closures due to red tide, http://www.dshs.state.tx.us/seafood/RedTide.shtm
- Red Tide Rangers: volunteer HAB monitoring

West Coast

Alaska

- Department of Environmental Conservation, Division of Environmental Health: monitoring for PSP and status of shellfish closures, http://www.dec.state.ak.us/eh/fss/seafood/psphome.htm

California

- Department of Health Services, Division of Drinking Water and Environmental Management: advisories and reports for marine biotoxin monitoring, http://www.cdph.ca.gov/healthinfo/environhealth/water/Pages/Shellfish.aspx
- Department of Fish and Game: Investigations of wildlife mortalities

Oregon

- Department of Human Services: beach monitoring programs and fish advisories, http://www.oregon.gov/DHS/ph/envtox/index.shtml

Washington

- Department of Health: shellfish closure status, monitoring program, and biotoxin bulletins, http://www.doh.wa.gov/ehp/sf/BiotoxinProgram.htm
- Department of Fish and Wildlife: shellfish harvesting regulations, collection of shellfish tissue samples, collection and analysis of phytoplankton samples, http://wdfw.wa.gov/fishing/
- Olympic Region Harmful Algal Bloom Program: monitoring of phytoplankton and toxins in seawater, http://www.orhab.org/

Hawaii

- Department of Health: information on ciguatera fish poisoning, http://hawaii.gov/health/family-child-health/contagious-disease/wnv/comm-disease/factsheet/ciguatera.pdf