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Anton Bruun Memorial Lecture

The ecology and oceanography of harmful algal blooms

multidisciplinary approaches to research and management

by

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Presented

27 June 2005, UNESCO, Paris

ANTON FREDERICK BRUUN

ANTON FREDERICK BRUUN was born on the 14th of December 1901 as the oldest son of a farmer, but a severe attack of polio in his childhood led him to follow an academic, rather than agrarian, career. In 1926 Bruun received a Ph.D. in zoology, having several years earlier already started working for the Danish Fishery Research Institute. This association took him on cruises in the North Atlantic where he learned from such distinguished scientists as Johannes Schmidt, C.G. Johannes Petersen and Thomas Mortensen.

Of even more importance to his later activities was his participation in the *Dana* Expedition's circumnavigation of the world in 1928-1930, during which time he acquired further knowledge of marine animal life of the sea, general oceanography and techniques in oceanic research.

In the following years Bruun devoted most of his time to study the rich *Dana* collections and to the publication of his treatise on the flying fishes of the Atlantic. In 1938 he was named curator at the Zoological Museum of the University of Copenhagen and later also acted as lecturer in oceanology.

From 1945-1946 he was the leader of the *Atlantide* Expedition to the shelf areas of West Africa. This was followed by his eminent leadership of the *Galathea* Expedition in 1950-1952, which concentrated on the benthic fauna below 3,000 m and undertook the first exploration of the deep-sea trenches, revealing a special fauna to which he gave the name "hadal".

The last decade of Bruun's life was devoted to international oceanography. He was actively involved in the establishment of bodies like SCOR, IACOMS, IABO, and the IOC and was elected IOC's first chairman in 1961.

His untimely death a few months later, on 13 December 1961, put an end to many hopes and aspirations.

In 1962, the former US Presidential yacht *Williamsburg* was converted into a research vessel and renamed Anton Bruun in honour of the great scientist. The *Anton Bruun* took part in the International Indian Ocean Expedition (1959–1965) and, in the late 1960's, circumnavigated the globe in one of the last great exploratory expeditions of modern oceanography.

To formally honour Bruun's role in international oceanography, Dr Patricio Bernal, IOC's Executive Secretary, announced the annual award of a 'Anton Bruun Medal' to all Bruun Memorial Lecturers, starting on the occasion of the Twenty-third Assembly in 2005.

The Bruun Memorial Lectures

This series of lectures is dedicated to the memory of the noted Danish oceanographer and first chairman of the Commission, Dr Anton Frederick Bruun. The "Anton Bruun Memorial Lectures" were established in accordance with Resolution 19 of the Sixth Session of the IOC Assembly, in which the Commission proposed that important inter-session developments be summarized by speakers in the fields of solid earth studies, physical and chemical oceanography and meteorology, and marine biology.

Twenty-third Session of the Assembly, 21 - 30 June 2005

The Ecology and Oceanography of Harmful Algal Blooms: Multidisciplinary Approaches to Research and Management by Donald M. Anderson. In: IOC Bruun Memorial Lectures, Paris, UNESCO, 2007. *(Technical Series, 74)*.

Twenty-second Session of the Assembly, 24 June - 2 July 2003

– Gas-Hydrates – A Potential Source of Energy from the Oceans by Harsh K. Gupta. In: IOC Bruun Memorial Lectures, Paris, UNESCO, 2004. *(Technical Series, 65)*.
– Energy from the Sea: The Potential and Realities of Ocean Thermal Energy Conversion (OTEC) by Patrick Takahashi. In: IOC Bruun Memorial Lectures, Paris, UNESCO, 2004. *(Technical Series, 66)*.

Twenty-first Session of the Assembly, 9 - 13 July 2001

Operational Oceanography — a perspective from the private sector by Ralph Rayner. IOC Bruun Memorial Lectures, Paris, UNESCO, 2003. *(Technical Series, 58)*.

Twentieth Session of the Assembly, 29 June - 9 July 1999

Ocean Predictability, by John Woods. In: IOC Bruun Memorial Lectures, Paris, UNESCO, 2000. *(Technical Series, 55)*.

Nineteenth Session of the Assembly, 2 - 18 July 1997

Common Resources, Conflicting Uses: The Economics of Coastal Resources Management, by John A. Dixon. Sixty-five Years of the Continuous Plankton Recorder Survey: 1931-1995, by Philip C. Reid; Sonia D. Batten; Harry G. Hunt.

Eighteenth Session of the Assembly, Paris, 13 - 26 June 1995

Some Results of the Tropical Ocean and Global Atmosphere (TOGA) Experiment Application of El Niño Prediction to Food Production in Peru, by Pablo Lagos; New Applied Knowledge Resulting from the TOGA Programme in all Three Oceans, by James J. O'Brien.

The ecology and oceanography of harmful algal blooms: multidisciplinary approaches to research and management

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Donald M. Anderson is a Senior Scientist in the Biology Department of the Woods Hole Oceanographic Institution. He earned a doctorate from the Department of Civil Engineering at MIT in 1977 and joined the scientific staff at the Woods Hole Oceanographic Institution in 1978. In 1993, he was awarded the Stanley W. Watson Chair for Excellence in Oceanography. In 2004, he was appointed Director of the Coastal Ocean Institute at the Woods Hole Oceanographic Institution. In 2006, Dr. Anderson was presented the Yasumoto Lifetime Achievement Award from the International Society for the Study of Harmful Algae (ISSHA).

Dr. Anderson's research focus is on toxic or harmful algal blooms (HABs), commonly called "red tides". Specifically, he studies the physiology and genetic regulation of toxicity in dinoflagellates, their bloom dynamics and ecology, and the global biogeography of toxic algal species. Ongoing research programs involve the study of large- and small-scale physical and biological mechanisms underlying toxic dinoflagellate blooms, the development of new techniques to identify and quantify these toxic cells and their toxins using molecular "probes", the search for the genes involved in toxin production, development of species-specific indicators of nutrient limitation and cell physiology, and the development of methods to directly control blooms. He served as Project Director for a major ECOHAB field program involving 14 investigators from

9 institutions who conducted a 5-year field investigation of the ecology and oceanography of toxic *Alexandrium* blooms in the Gulf of Maine, as well as for a program involving 9 investigators from 4 institutions investigating strategies to directly control Florida red tides. Anderson is also one of the lead investigators in the newly created Woods Hole Center for Oceans and Human Health, a national research facility funded by the National Science Foundation and the National Institute of Environmental Health Sciences to explore mechanisms that govern relationships between marine processes and human health.

Along with an active field and laboratory research program, Anderson is heavily involved in national and international program development for research and training on red tides, marine biotoxins, and harmful algal blooms (HABs). He serves as Director of the U.S. National Office for Marine Biotoxins and Harmful Algal Blooms, located at the Woods Hole Oceanographic Institution (http://www.whoi.edu/redtide/). Anderson represents the U.S. in many international workshops and committees that deal with these issues, including chairing the IOC Group of Experts which established the IOC's international HAB program, chairing a SCOR working group on The Physiological Ecology of Harmful Algal Blooms, and serving on ICES and PICES HAB working groups. He also serves as an advisor to several foreign countries and international aid organizations on red tides and HABs.

On the occasion of this lecture Dr. Donald Anderson was awarded the IOC Anton Bruun Medal.

Anderson is the author or co-author of over 230 scientific papers and 11 books.

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Photos of Dr Bruun: Courtesy of the archives services of the Zoological Museum, University of Copenhagen.

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The ecology and oceanography of harmful algal blooms: multidisciplinary approaches to research and management

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Opening remarks

Virtually every coastal country in the world is affected by harmful algal blooms (HABs, commonly called "red tides"). This diverse array of phenomena includes blooms of toxic, microscopic algae that lead to illness and death in humans, fish, seabirds, marine mammals, and other oceanic life. There are also non-toxic HABs that cause damage to ecosystems, fisheries resources, and recreational facilities, often due to the sheer biomass of the accumulated algae. The term "HAB" also applies to non-toxic macroalgae (seaweeds), which can cause major ecological impacts such as the displacement of indigenous species, habitat alteration and oxygen depletion in bottom waters. The frequency, spatial extent, and economic impact of HABs have all expanded in recent decades, in parallel with, and sometimes a result of, the world's increasing exploitation on the coastal zone for shelter, food, recreation, and commerce.

The HAB problem is significant and growing worldwide and poses a major threat to public health, ecosystem health, and to fisheries and economic development.

HABs are complex oceanographic phenomena that require multidisciplinary study ranging from molecular and cell biology to large-scale field surveys, numerical modelling, and remote sensing from space. Multi-lateral international programmes and bilateral initiatives are bringing scientists together from different countries and disciplines in a concerted attack on this complex and multi-faceted issue. Our understanding of these phenomena is increasing dramatically, and with this understanding come technologies and management tools that can reduce HAB incidence and impact. More effective HAB management is sure to be one major outcome of the growing investment in the Global Ocean Observing System.

HABs will always be with us, and in the next few decades at least, are likely to continue to expand in geographic extent and frequency. Nevertheless, scientifically based management should permit full exploitation of fisheries, recreational, and commercial resources, despite the recurrent and diverse threat that HABs pose.

Introduction

Figure 1. A "red tide bloom" of *Noctiluca scintillans* in New Zealand.
Photo credit: M. Godfrey

Over the last several decades, countries throughout the world have experienced an escalating and worrisome trend in the incidence of problems termed "harmful algal blooms" (HABs). HAB events are characterized by the proliferation and occasional dominance of particular species of toxic or harmful algae. In some cases, these microscopic cells increase in abundance until their pigments discolor the water – hence the term «red tide» (Fig. 1). There are, however, "blooms" of species which do not have high cell concentrations and which do not discolor the water, but which still cause harm, typically because of the potent toxins produced by those algae. The term "harmful algal bloom" is very broad and covers blooms of many types, but HABs all have one unique feature in common - they cause harm, either due to their production of toxins or to the manner in which the cells' physical structure or accumulated biomass affect co-occurring organisms and alter food-web dynamics.

The frequency, spatial extent, and economic impact of HABs have all expanded in recent decades, in parallel with, and sometimes a result of, the world's increasing exploitation on the coastal zone for shelter, food, recreation, and commerce.

Several decades ago, relatively few countries were affected by HABs, but now most coastal countries are threatened, in many cases over large geographic areas and by more than one harmful or toxic species (Anderson, 1989; Hallegraeff 1993). The causes behind this expansion are debated, with possible explanations ranging from natural mechanisms of species dispersal and enhancement (e.g., climate change) to a host of human-related phenomena such as pollution-related nutrient enrichment, climatic shifts, or transport of algal species via ship ballast water (Anderson, 1989; Smayda, 1989; Hallegraeff, 1993). Whatever the reasons, coastal regions throughout the world are now subject to an unprecedented variety and frequency of HAB events. Many countries are faced with a bewildering array of toxic or harmful species and impacts, as well as disturbing trends of increasing bloom incidence, larger areas affected, more fisheries resources impacted, and higher economic losses.

Impacts

When toxic phytoplankton are filtered from the water as food by shellfish, their toxins accumulate in those shellfish to levels that can be lethal to humans or other consumers. The poisoning syndromes have been given the names paralytic, diarrhetic, neurotoxic, amnesic, and azaspiracid shellfish poisoning (PSP, DSP, NSP, ASP, and AZP respectively). Except for ASP, all are caused by biotoxins synthesized by a class of marine algae called dinoflagellates. The ASP toxin, domoic acid, is produced by diatoms that until recently were thought to be free of toxins. A sixth human illness, ciguatera fish poisoning (CFP) is caused by toxins produced by dinoflagellates that live on surfaces in many coral reef communities Ciguatoxins are transferred through the food chain from herbivorous reef fishes to larger carnivorous, commercially valuable finfish.

Another type of HAB impact occurs when marine fauna are killed by algal species that release toxins and other compounds into the water. Fish and shrimp mortalities from these types of HABs have increased considerably at aquaculture sites in recent years. HABs also cause mortalities of wild fish, seabirds, whales, dolphins, and other marine animals, typically as a result of the transfer of toxins through the food web.

Figure 2. One major HAB impact is the mass mortality of farmed fish, as seen here in Japan. *Photo credit: M. Aramaki*

A poorly defined but potentially significant concern relates to sublethal, chronic impacts from toxic HABs that can affect the structure and function of ecosystems. Adult fish can be killed by the millions in a single outbreak, with long- and short-term ecosystem impacts (Fig. 2). Likewise, larval or juvenile stages of fish or other commercially important species can experience mortalities from algal toxins. Impacts of this type are more difficult to detect than the acute poisonings of humans or higher predators, since exposures and mortalities are subtle and often unnoticed. Impacts might not be apparent until a year class of commercial fish reaches harvesting age but is in low abundance. Chronic toxin exposure may therefore have long-term consequences that are critical with respect to the sustainability or recovery of natural populations at higher trophic levels. Many believe that ecosystem-level effects from toxic algae are more pervasive than we realize, affecting multiple trophic levels, depending on the ecosystem and the toxin involved (Ramsdell et al., 2005).

Non-toxic blooms of algae can cause harm in a variety of ways. One prominent mechanism relates to the high biomass that some blooms achieve. When this biomass decays as the bloom terminates, oxygen is consumed, leading to widespread mortalities of plants and animals in the affected area. These "high biomass" blooms are sometimes linked to excessive pollution inputs, but can also occur in pristine waters.

Large, prolonged blooms of non-toxic algal species can reduce light penetration to the bottom, decreasing densities of submerged aquatic vegetation that can have dramatic impacts on coastal ecosystems, as these grass beds serve as nurseries for the food and the young of commercially important fish and shellfish. Macroalgae (seaweeds) also cause problems. Over the past several decades, blooms of macroalgae have been increasing along many of the world's coastlines. Macroalgal blooms often occur in nutrient-enriched estuaries and nearshore areas that are shallow enough for light to penetrate to the sea floor. These blooms have a broad range of ecological effects, and often last longer than "typical" phytoplankton HABs. Once established, macroalgal blooms can remain in an environment for years unless the nutrient supply decreases. They can be particularly harmful to coral reefs (Fig. 3). Under high nutrient conditions, opportunistic macroalgal species out-compete, overgrow, and replace the coral.

Figure 3. Macroalgal HAB: sponges and corals overgrown by the seaweed *Codium isthmocladum* in southeast Florida. *Photo credit: B. Lapointe*

Figures 4-10 show the global distribution of each of the major HAB shellfish poisoning syndromes, as well as those for ciguatera and fish and animal mortalities linked to HABs. In some cases, the relatively recent discovery of a toxin (e.g., the ASP toxin domoic acid in 1987) is reflected in a global distribution that is quite limited at present but which is expected to expand as more outbreaks are detected. In other cases where the syndrome has been known for many years (e.g., PSP), the distribution is truly global and widespread in scale. International cooperation and coordination are important aspects of modern monitoring and management programmes (Anderson et al., 2001).

Figure 4. Global distribution of PSP toxins.

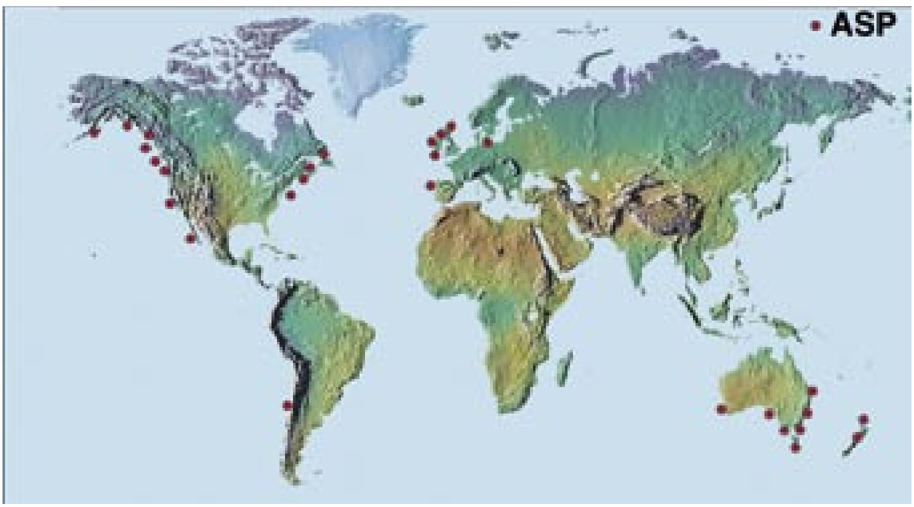

Figure 5. Global distribution of ASP toxins.

Figure 6. Global distribution of DSP toxins.

Figure 7. Global distribution of AZP toxins.

Figure 8. Global distribution of NSP toxins.

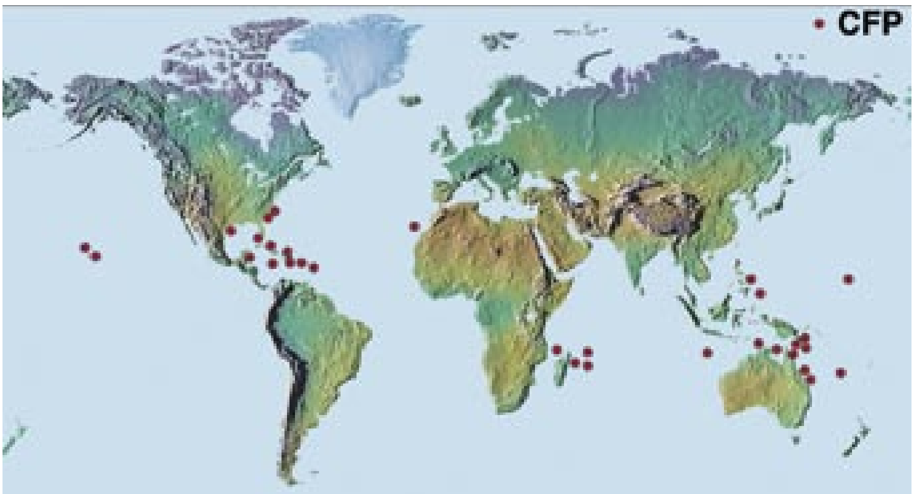

Figure 9. Global distribution of CFP toxins.

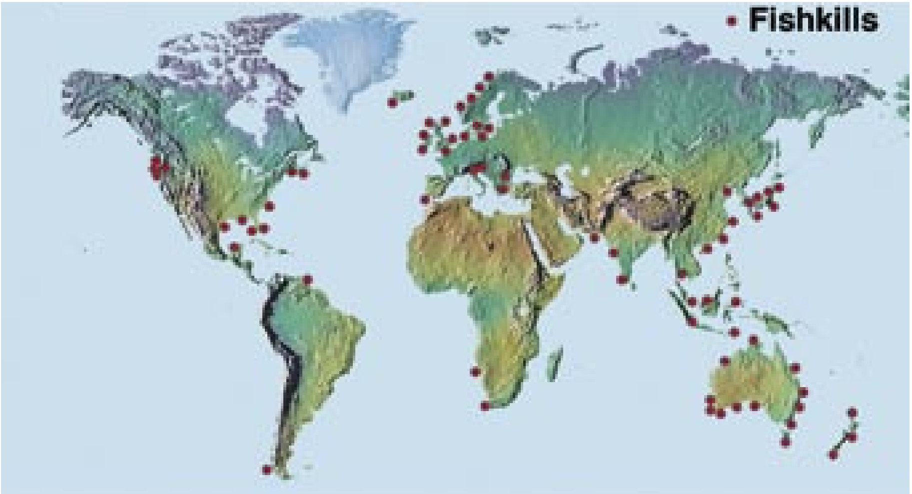

Figure 10. Global distribution of fish and animal mortalities.

Economic and societal impacts

HABs have an array of economic impacts, including the costs of conducting monitoring programmes for shellfish and other affected resources, short- and long-term closure of harvestable shellfish and fish stocks, reductions in seafood sales (including the avoidance of "safe" seafood as a result of over-reaction to health advisories), mortalities of wild and farmed fish, shellfish, and coral reefs, impacts on tourism and tourism-related businesses, and medical treatment of exposed populations. Estimates of actual impacts are few, in part because these economic losses are difficult to quantify. A conservative estimate of the average annual economic impact resulting from HABS in the U.S. is approximately US$75 million over the period 1987 to 2000 (Anderson et al., 2000; Hoagland et al., 2002; 2006.) The impact from individual blooms, however, can exceed this annual average, as occurred for example in 1976 when a massive bloom of the dinoflagellate *Ceratium tripos* led to extensive oxygen depletion in the New York Bight, affecting surf clams, ocean quahogs, scallops, finfish and lobster. Total lost sales in all sectors combined were estimated to be US$1.33 billion in 2000 dollars (Figley et al., 1979).

Losses have been significant in other countries as well. In Japan, for example, fish mortalities due to red tides in the Seto Inland Sea cost fishermen tens of millions of dollars per year, especially during the early 1970s. Even now, after extensive pollution control efforts have decreased bloom incidence (see below), blooms of raphidophytes and dinoflagellates still kill cultured finfish and shellfish (GEOHAB, 2001). In China, a widespread red tide in 1989 along the coast of Hebei Province affected 15,000 hectares of shrimp ponds, resulting in a loss valued at US$ 40 million (Wang and Li, 1998).

Recent trends

The nature of the HAB problem has changed considerably over the last three decades throughout the world. Figure 11 shows the cumulative global increase in the recorded distribution of the causative organisms and the confirmed appearance of PSP toxins in shellfish. Clearly, a dramatic expansion in the areas affected by PSP toxins has occurred in recent years. A similar pattern applies to many of the other HAB types. Few would argue that the number of toxic blooms, the economic losses from them, the types of resources affected, and the number of toxins and toxic species have all increased dramatically in recent years throughout the world (Anderson, 1989; Smayda, 1990; Hallegraeff, 1993). Disagreement only arises with respect to the reasons for this expansion.

The first thought of many is that pollution or other human activities are involved, and this is indeed a factor in some areas. On close inspection, however, many of the «new» or expanded HAB problems have occurred in waters where pollution is not an obvious factor. The organisms responsible for HABs have been on earth for thousands or even millions of years, during which time they had ample opportunities to disperse, assisted by changing climate, movement of tectonic plates, and other global changes. Some new bloom events may thus reflect indigenous populations that are discovered because of better detection methods and more observers. The appearance of ASP toxins along the United States west coast after 1991 is a good example, as it is now known that the diatom species responsible for this problem was present in those waters many years before the initial outbreak. The discovery in 1991 was a direct result of communication with Canadian scientists who had identified the same toxin four years earlier and developed appropriate chemical detection methods (Work et al., 1993).

Several other "spreading events" are most easily attributed to natural dispersal via currents, rather than human activities. The first NSP event ever to occur in North Carolina (USA) (Tester et al., 1991) was shown to be a Florida bloom transported over 1500 km by the Gulf Stream - a totally natural phenomenon with no linkage to human activities. Likewise, a massive 1972 red tide was responsible for introducing dormant cysts of the PSP-producing species *Alexandrium tamarense* to southern New England waters, where it has persisted to this day (Anderson and Wall, 1978).

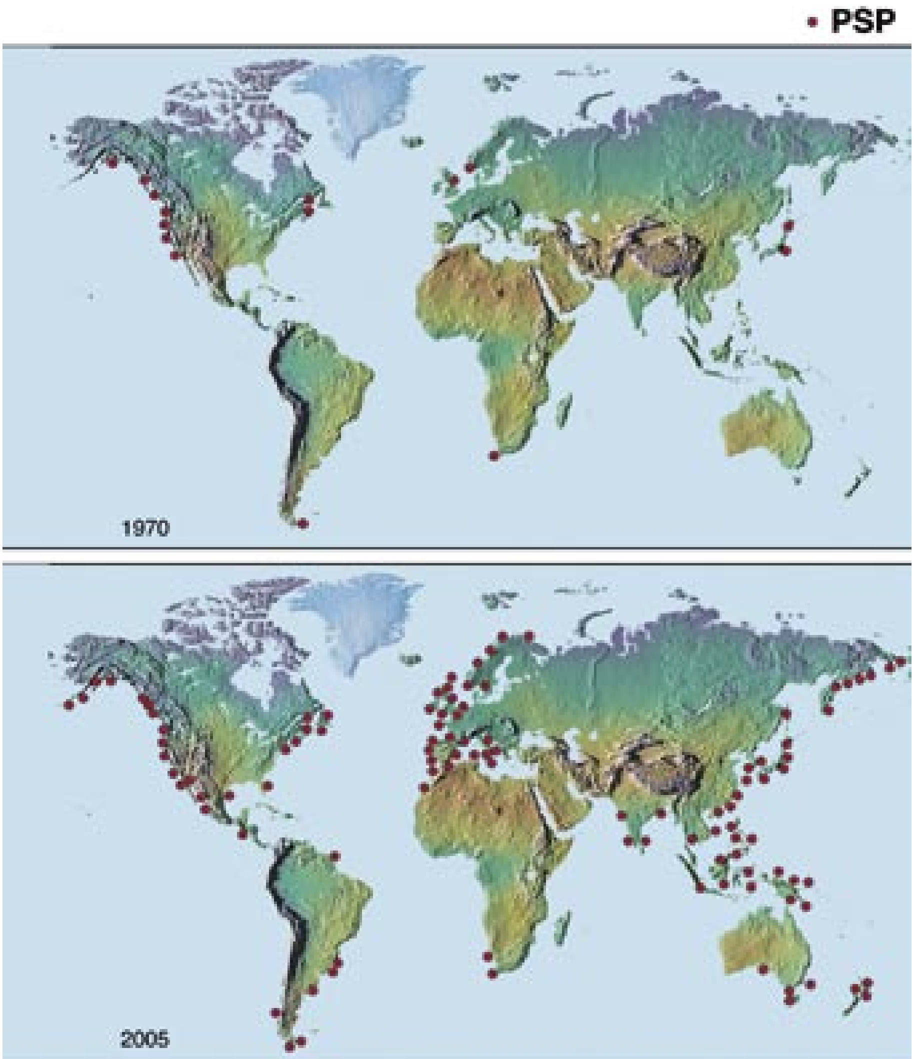

Figure 11. The global expansion in the distribution of PSP toxins – 1970 versus 2005.

It is also clear that human activities have contributed to the global HAB expansion by transporting toxic species in ship ballast water (Hallegraeff and Bolch, 1992). In the past, evidence for such accidental introductions relied on inspection of historical plankton records or analysis of sediment cores for the resting stages of certain HAB species (e.g., McMinnn et al., 1997), but the advent of molecular techniques and extensive sequence databases for HAB species (e.g., Lilly et al., 2002) now allows researchers to provide forensic documentation of introduction events. In Thau Lagoon (Mediterranean, France), for example, PSP toxicity was first detected in 1998. Chemical and genetic techniques were used to demonstrate that the closest relatives of the lagoon populations of the dinoflagellate *Alexandrium catenella* were from Asian waters. There was no homology with strains of this organism from western European waters, including the Mediterranean. It is thus highly probable that *A. catenella* was introduced into the lagoon via the ballast water discharge.

The nature of the HAB problem has changed considerably over the last three decades throughout the world.

Another factor underlying the global expansion in HABs is the dramatic increase in aquaculture activities in many countries. This leads to increased monitoring of product quality and safety, revealing indigenous toxic algae that were probably always there (Anderson, 1989). In addition, the construction of aquaculture facilities will place fish or shellfish resources in areas where toxic algal species occur but were previously unknown, leading to mortality events or toxicity outbreaks that would not have been noticed had the aquaculture facility not been placed there.

Of considerable concern, particularly for coastal resource managers, is the potential relationship between the apparent increase in HABs and the accelerated eutrophication of coastal waters due to human activities. Some HAB outbreaks occur in pristine waters with no influence from pollution or other anthropogenic effects. Linkages between HABs and eutrophication have been noted, however, within the past several decades (e.g., Smayda, 1989; Anderson et al., 2002). Coastal waters are receiving massive and increasing quantities of industrial, agricultural and sewage effluents through a variety of pathways. In many urbanized coastal regions, these anthropogenic inputs have altered the size and composition of the nutrient pool which may, in turn, create a more favorable nutrient environment for certain HAB species. Just as the application of fertilizer to lawns can enhance grass growth, marine algae can grow in response to these types of nutrients, which are often present in domestic and industrial pollution. Such point-sources are relatively easy (though expensive) to identify and control; non-point sources of nutrients, such as agricultural runoff, animal feedlot operations, and automobile exhaust are significant problems in coastal waters, but are much more difficult to regulate.

The steady expansion in the use of fertilizers for agricultural production represents a significant and worrisome source of plant nutrients to coastal waters.

Shallow and restricted coastal waters that are poorly flushed appear to be most susceptible to nutrient-related algal problems. Nutrient enrichment of such systems often leads to excessive production of organic matter (a process known as eutrophication), and increased frequencies and magnitudes of micro- and macroscopic algal blooms (i.e., phytoplankton and seaweeds), including HABs. There is no doubt that this is true in certain areas of the world where pollution has increased dramatically (Fig. 12). It is perhaps real, but less evident in areas where coastal pollution is more gradual and unobtrusive.

Figure 12. In some areas, HABs are on the increase due to stimulation by the plant nutrients found in pollution. *Photo credit: M. Dickman*

A frequently cited dataset from an area where pollution has been a significant factor in HAB incidence is from the Inland Sea of Japan, where visible red tides increased steadily from 44 per year in 1965 to over 300 a decade later, matching the pattern of increased nutrient loading from pollution (Okaichi, 1997). Effluent controls were instituted in the mid-1970s, resulting in a 70% reduction in the number of blooms that has persisted to this day. A related data set for the Black Sea documents a dramatic increase in red tides up to the mid 1990s, when the blooms began to decline (Bodeanu and Ruta, 1998). That reduction has been linked to reductions in non-point source inputs – in this case fertilizer usage in upstream watersheds by former Soviet Union countries no longer able to afford large, state-subsidized fertilizer applications (Anderson et al., 2002). These examples are particularly appealing, as they document decreases in HABs that coincide with major nutrient reductions. Increases in HABs that occur in parallel with nutrient increases are suggestive of a linkage, but less conclusive.

It is now clear that the global expansion of HAB phenomena is in part a reflection of our ability to better define the boundaries of the problem - the nature and extent of toxic or harmful species and their impacts. Those boundaries are, however, also expanding due to natural dispersal via storms or currents, as well as to enhanced growth as a result of pollution or other anthropogenic influences. The fact that part of the expansion is simply because of increased scientific awareness and detection capabilities should not temper our concern. The global problem of HABs is serious and large - much larger than we thought.

Management issues

This diversity in blooms and their impacts presents a significant challenge to those responsible for the management of coastal resources threatened by HABs. The strategies needed to protect fisheries, minimize economic and ecosystem losses, and protect public health vary considerably among locations and among HAB types. A recent review (Anderson et al., 2001) highlights the many different strategies adopted by countries and commercial enterprises worldwide to monitor and manage HABs in coastal waters. Here the objective is to provide a brief summary of some of these strategies, emphasizing the distinctions between management actions that fall into the categories of *mitigation, prevention*, and *control*, as defined by Boesch et al. (1997) .

Mitigation. Many of the management actions taken to respond to HABs can be termed mitigation – i.e., dealing with an existing or ongoing bloom, and taking whatever steps are necessary or possible to reduce negative impacts. Obvious examples are the routine monitoring programmes for toxins in shellfish, as currently conducted in more than 50 countries (Fig. 13). The detection of dangerous levels of HAB toxins in shellfish will lead to harvesting restrictions to keep contaminated product off the market. Another common mitigation strategy is the towing of fish net pens away from the sites of intense HABs.

Figure 13. Shellfish monitoring programmes protect consumers by detecting HAB toxins and restricting commercial and recreational harvesting.

Yet another strategy to mitigate the impact of HAB toxins in shellfish is to process those shellfish in such a way as to reduce toxicity to an acceptable level, such as through the removal of scallop viscera and the marketing of only the adductor muscle, which generally contains no HAB toxins. In general, however, HAB toxins are not decreased significantly with canning or other traditional shellfish processing methods.

These are but a few examples of many different mitigation strategies. In effect, we use these strategies to live with HABs and to manage around them. The question often arises, however, as to whether we can be more pro-active. Can we do something about these blooms *before* they happen or can we do something to destroy or suppress them *while* they are occurring? These questions highlight the "prevention" and "control" aspects of HAB management.

Prevention. Prevention refers to actions taken to keep HABs from happening or from directly impacting a particular resource. Several problems are immediately apparent in this regard. For one, we don't have all of the knowledge we need about why HABs form in many areas, so it is obviously difficult to regulate or control those factors. This argues for substantial and sustained research on all aspects of HABs, including their ecology, physiology and oceanography. All too often managers and agency officials view these topics as fundamental or basic science issues that have little direct practical utility, but in reality, such knowledge is essential for the design and implementation of effective prevention and control strategies.

Another problem that arises with the concept of HAB prevention is that even if we know that certain environmental factors are influencing the population dynamics of a specific HAB organism, there are limitations on what we can feasibly do to modify or control those factors. We might know that a particular HAB is strongly influenced by the outflow of a river system – that it is associated with a buoyant coastal current, for example - but are unlikely to be able to justify the alteration of that river flow solely on the basis of HAB prevention. As discussed below, it is nevertheless important to factor the possible impacts on HABs into large-scale policy decisions on such topics as pollution reductions or alterations in freshwater flows in response to agricultural and drinking water demands.

In many countries there is a continuing upward trend in fertilizer usage, and it is not surprising that there is also a parallel increase in red tides or HABs observed in the receiving waters.

The rapid increase in the input of plant nutrients, particularly nitrogen compounds, into coastal waters throughout the world reflects the growing disposal of sewage from expanding populations, increased use of chemical fertilizers in agriculture, and increased fossil fuel combustion. The legislative or policy changes implemented in the Seto Inland Sea and other locations demonstrate that control of sewage or waste discharges has the potential to prevent certain types of HABs. Many countries are implementing sewage reduction strategies, and this trend should be encouraged. Nevertheless, non-point sources of nutrients to coastal waters are proving much more difficult to control, given the increased population pressures and the need to feed a growing world population.

Some countries are making good strides towards more efficient fertilizer application methods or are instituting other controls that help to capture the nitrogen and phosphorus before they enter rivers and streams. However, there are also trends towards the production of more beef and other meat products that are inefficient in nitrogen assimilation, resulting in extremely high nitrogen loss per kilogram of food produced, compared to production of vegetables and grains (Fig. 14). There are obviously many benefits that derive from our ability to produce inexpensive fertilizers. One wonders, however, how long it will take for policy makers throughout the world to recognize the negative aspects of our increasing reliance on nitrogen to produce the crops needed to feed the growing world population. In effect, we are feeding the world, but in doing so, are over-enriching and poisoning the coastal ocean. For countries that are turning to the coastal ocean for aquaculture and wild fisheries, their policies on land are working directly against those intended to extract more food resources from the sea.

Another topic under the Prevention category of HAB management involves modification of freshwater flows. Human activities can profoundly affect the amount of fresh water that reaches the coast, and this can enhance HABs. In addition to the obvious role fresh water plays in diluting pollution loads as they enter marine systems, it also affects the stratification of coastal waters, which is an important determinant of phytoplankton community composition. Buoyant coastal currents can be critical in the development and transport of certain types of HABs (e.g., Anderson et al., 2005), and as a generalization, stratified waters are often thought to favour the growth of dinoflagellates and other motile groups that can access the nutrients typically found just below the nutrient-deplete surface layer.

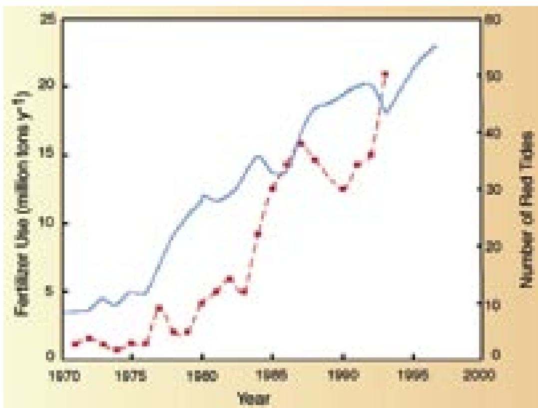

Figure 14. Parallel trends in fertilizer use and the number of red tides reported for Chinese coastal waters (data redrawn from Smil, 2001 and Zhang, 1994).

An example of how changes in freshwater flow may be affecting the patterns of HAB incidence is in the Bohai Sea of China. Due to droughts and water diversions for drinking water and agriculture, several of the rivers that used to flow freely into the Bohai are now dry for many days every year. This is one of several regions in China where the number of HABs has increased dramatically in recent years. It is of note that China has plans to divert the flow of several rivers that presently discharge in

One wonders how long it will take for policy makers to recognize the negative aspects of our increasing reliance on nitrogen to produce the crops needed to feed the growing world population. In effect, we are feeding the world, but in doing so, are over-enriching and poisoning the coastal ocean.

the south to deliver water to the Bohai region. These types of large-scale fresh water diversion projects could have a major affect on HAB events – both positively and negatively. One hopes that comprehensive plankton and water quality monitoring programmes will be sustained in that region so that the effects of these public works projects can be documented and lessons learned.

Control. Bloom control is the most challenging and controversial aspect of HAB management. The concept refers to actions taken to suppress or destroy HABs – to directly intervene in the bloom process. This is one area where HAB science is rudimentary and slow moving (Anderson, 1997).

Figure 15. Clay dispersal as a bloom suppression strategy during a fish-killing HAB outbreak in waters south of Korea. *Photo credit: H. Kim*

There are five general categories or strategies that can be used to combat or suppress an invasive or harmful species. These include: mechanical, biological, chemical, genetic and environmental control. Several of these have been applied to HAB species. For example, one form of mechanical control is the removal of HAB cells from the water by dispersing clay over the water surface. The clay particles aggregate with each other and with HAB cells, removing those cells through sedimentation. In countries such as Republic of Korea, where a fish-farming industry worth hundreds of millions of dollars is threatened by HABs, this control strategy makes sense, economically and socially, and so the work has progressed (Fig. 15; Na et al., 1996). In other areas, the cost/benefit rationale is not as clear, and considerable effort will be required to bring research to direct application. For example, research on clay mitigation has proceeded quite far in countries such as the US (Sengco, 2001; 2005; Sengco and Anderson, 2004) but a significant barrier exists with respect to the ability to obtain permits, environmental clearances, and funds to employ this strategy on more than an experimental scale.

There are a variety of organisms that could theoretically be used to control HABs, but biological control has many logistical problems and is far from the application stage. Biocontrol is used extensively in agriculture, such as in the release of sterile males or the use of pheromones to control insect pests (Hokkanen and Lynch,

Bloom control is one area where HAB science is rudimentary and slow moving.

1995), but there is still considerable opposition to the concept of releasing one organism to control another in the ocean. Despite frequently cited examples where such an approach has had negative long-term consequences on land (such as with the introduction of the mongoose to oceanic islands or the giant toad to Australia (Greathead, 1995), there are many cases where the approach has been both effective and environmentally benign (Hokkanen and Lynch, 1995; National Research Council, 1996). The concept deserves some consideration in marine systems.

Chemical control relies on toxic chemical release, including the potential development of species-specific chemical control agents. Chemical control was attempted in 1957 against the Florida red tide organism using copper sulfate delivered with crop dusting airplanes (Rounsefell and Evans, 1958). Chemical control has not been actively pursued by the HAB community, presumably because of the general feeling that it will be difficult and perhaps impossible to find an environmentally acceptable chemical that would target a particular HAB species but not cause widespread mortality of other organisms.

Another strategy for control of introduced or exotic species is genetic control – the genetic engineering of species that are purposely introduced to alter the environmental tolerances, reproduction or other processes in the undesirable species. The issues surrounding this type of control strategy are similar in many ways to those associated with biological control – concerns about the possible negative impacts of introducing a non-indigenous organism to an area. There are numerous examples where genetic approaches have been used successfully in terrestrial agriculture, such as the engineering of plant crops so that they are capable of producing their own insecticides. Similar genetic manipulations might be used on marine pests such as HABs. It might be possible, for example, to engineer a HAB species so that it no longer produced toxin. Likewise, one can envision genetic manipulations that might make a particular bacterial strain more pathogenic towards HAB cells. However, society's concerns loom large for these types of strategies, and one can expect that it will be exceedingly difficult to obtain approval for such approaches in the near future. Nevertheless, we should not rule out these strategies on the basis of hypothetical impacts, but rather should pursue the research and testing needed to obtain the data on which to base such decisions. Indeed, as the HAB problem continues to worsen in certain areas of the world, the pressure for, and the acceptance of bloom control or suppression strategies is likely to increase.

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The last of the five control strategies is environmental manipulation – physical or chemical modifications of the environment so that either the target species is affected and/or a natural or introduced bio-controlled species is enhanced. For HABs, this might involve the large-scale manipulation of nutrient levels in coastal waters through pollution control policies, as described above under the Prevention category. On shorter time scales, environmental manipulation becomes more difficult to envision but might include efforts to alter water circulation or residence time, such as through dredging or opening of channels. Another approach might be aeration or other methods to disrupt stratification, again leading to changes in the phytoplankton community composition.

Emerging technologies

The HAB problem has been a significant area of research focus throughout the world, and as a result, many new technologies are emerging that can help considerably with the management challenges that face us.

Of paramount importance in this regard are methods to detect and quantify toxins, and here progress has been rapid. Sophisticated analytical techniques combining chromatographic and mass spectrometry techniques (e.g., LC-MS) have been developed for all major HAB toxins, and are now taking the place of many older methods, including the widely used, but socially undesirable mouse bioassays. At the other extreme, simple test kits have been developed that are analogous to home pregnancy kits (Fig. 16). These allow inexpensive, rapid testing for toxins, and show great promise for use in screening samples, avoiding costly analysis for the many samples that are negative in monitoring programmes. These kits also show promise to allow remote areas (such as offshore shellfish beds) to be harvested, as fishermen are more likely to harvest in an area if they can know with reasonable certainty that the product they bring to shore will not contain toxins above regulatory limits.

Scientifically based management of fisheries and other resources threatened by HABs is a reality in many countries, and this capability will rapidly expand to those nations that presently do not recognize their HAB problems, or who are struggling to deal with them.

Figure 16. Jellett MIST test strip for rapid and simple PSP toxin detection.

Another important management need is for bloom detection and tracking. Here again, there has been progress on both ends of the spatial spectrum. At the largest scale, satellite remote sensing is now used operationally to detect HABs in the Gulf of Mexico, and with simple transport models, forecasts are now issued of impending landfall or exposure (Stumpf et al., 2003). That capability is not easily transferred to other HABs, as the blooms being detected are very dense and mono-specific, and thus have a chlorophyll signature that reveals their presence. For other HABs, remote sensing applications rely on detecting the water masses in which the cells reside – using sea surface temperature for example (Luerssen et al., 2005).

At the smallest scale, "molecular probes" have been developed for many HAB species that allow them to be detected and counted more easily and faster than has been possible with traditional microscopy. These probes are often either antibodies or short segments of DNA that are specific for the HAB species of interest. They are then used in a variety of formats, some of which are amenable to remote, automated operation, and thus can be deployed in moored instruments that can become the sentinels for HABs. There is a clear need for technologies of this type in the emerging global ocean observing system.

As a growing world population increases its use of the coastal zone and demands more fisheries and recreational resources, there is a clear need to understand HAB phenomena and to develop scientifically sound management and mitigation policies.

Observations and measurements like those given above are important, but they need to be augmented with numerical models, which are also under rapid development. The most advanced of these are coupled physical-biological models that resolve a region's circulation, and include biological components that simulate a HAB species' bloom dynamics, and in the near future, the uptake of toxin as those organisms are consumed by shellfish (McGillicuddy et al., 2003; 2005). These models are used predominantly in hindcast mode at present (i.e., in simulating past observations), but are advancing rapidly towards operational use for short-term forecasts similar to those used for the weather. These models will require observations of oceanographic parameters and HAB abundance and distribution that can be assimilated into the models to improve forecasts, exactly as is done with weather forecasts. Again, this is a role that ocean observing systems can and should play.

International HAB initiatives and related programmes

Research and management of HABs is a responsibility of individual nations, but the global nature of the problem has led to the formulation of many international programmes, both bi- and multi-lateral. An example of the former is the EU–US Scientific Initiative on Harmful Algal Blooms. For decades, HABs have been studied in relative isolation on both sides of the Atlantic. National and regional programmes such as ECOHAB in the US and EUROHAB in Europe have funded research on HABs, but these efforts did not include significant international collaboration until the European Union and the U.S. National Science Foundation pooled resources for a joint programme.

Examples of multi-lateral cooperative programmes are many, the most significant being GEOHAB, an initiative sponsored by UNESCO's Intergovernmental Oceanographic Commission (IOC) and SCOR (the Scientific Committee on Oceanic Research). GEOHAB (Global Ecology and Oceanography of Harmful Algal Blooms (Fig. 17) is an international, multidisciplinary programme designed to foster cooperative research on HABs in ecosystem types sharing common features (GEOHAB 2001; 2003). GEOHAB is not a funding programme – it coordinates and builds on related national, regional, and international efforts in HAB research. Through such efforts, the emergence of a global synthesis of scientific results is facilitated.

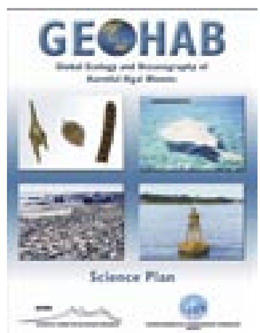

Figure 17. GEOHAB Science Plan. *See www.geohab.info*

A significant factor in the globalization of HAB research, management, and education has been the IOC Harmful Algal Bloom Programme (www.ioc.unesco.org/hab). The overall goal of this programme is "*to foster the effective management of, and scientific research on, HABs in order to understand their causes, predict their occurrences, and mitigate their effects*." In addition to sponsoring, hosting, and coordinating scientific workshops and conferences of various types throughout the world, the IOC programme offers numerous training courses on toxin detection, taxonomy, and other skills that scientists and managers worldwide need in order to effectively manage HABs. Another important aspect of the IOC education and outreach programme are its publication of conference proceedings and workshop reports, and the newsletter *Harmful Algae News* that is distributed to more than 2000 subscribers throughout the world.

Summary

The problems and impacts of HABs are diverse, as are the causes and underlying mechanisms controlling the blooms. Pollution and other human activities in the coastal zone have increased the abundance of algae, including harmful and toxic forms. We cannot blame all new outbreaks and new problems on these actions, however, as HABs in many locations are natural phenomena that occurred long before humans exerted their influence on the ocean. As a growing world population increases its use of the coastal zone and demands more fisheries and recreational resources, there is a clear need to understand HAB phenomena and to develop scientifically sound management and mitigation policies. Research advances are significant and promising in this regard, spurred on by international cooperation and coordination. Scientifically based management of fisheries and other resources threatened by HABs is a reality in many countries, and this capability will rapidly expand to those nations that presently do not recognize their HAB problems, or who are struggling to deal with them. The IOC HAB programme has been a critical component of this global effort, and therefore needs international support and endorsement.

Looking ahead, with continued direction of national and international resources on the HAB problem, the environmental and socioeconomic scale of the HAB problem will be discernibly different from today. HABs will still occur, but the adverse impacts of poisonous seafood, wildlife mortality events, aquaculture kills and ecosystem disruption will be effectively managed and economic and environmental impacts minimized. HABs will always be with us, but we can live with them, and manage around them.

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