

# Harmful algal blooms (red tides): Management and mitigation in the Republic of Korea

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## Introduction

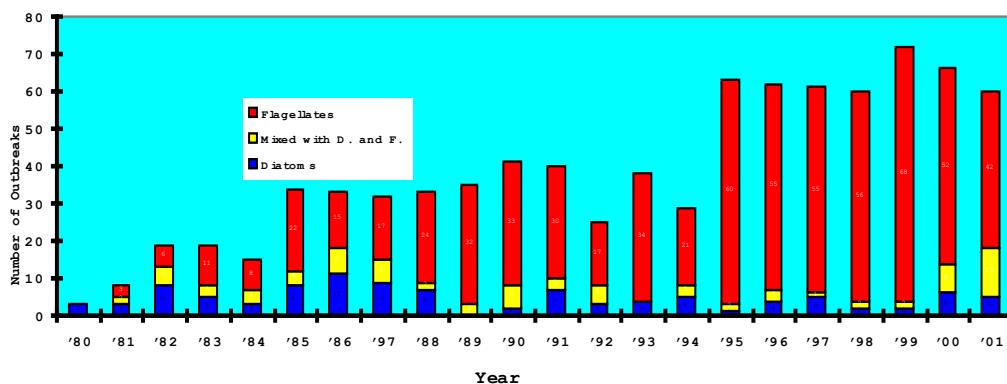
Most of the enclosed and semi-enclosed coastal waters of Korea are in a eutrophic state due to the increase of terrestrial and water-born pollutants. The effects of this coastal pollution and eutrophication have manifested themselves in three ways, namely as harmful dinoflagellate blooms; seasonal anoxia; and shellfish intoxication. Of these, harmful algal blooms have recently become widespread and persistent, and the accompanying mass fish mortalities are the most serious obstacles and risks for the sustainable development of coastal fisheries industries.

Although there are historical records of red tides since the 6th century, the first scientific report on HABs in Korea was published in 1967 (Park and Kim 1967). After then many scientific reports have been published (Cho 1978, 1979, 1981, 1986; Lee *et al.* 1980, 1981, 1982, 1983; Yoo 1982; Han *et al.* 1992; Kim *et al.* 1990, 1993a, 1993b; Park 1980, 1982; Park *et al.* 1988; Lee *et al.* 1992). Since 1981, HABs have mainly occurred on the southern coast in Chinhae Bay and its vicinity. They became more widespread and persistent in 1990s.

As the blooms develop into a harmful phase, such as fish killing, there is an urgent need to monitor the outbreaks and to take appropriate measures for the mitigation of the fisheries damages, especially for aquaculture. HABs will undoubtedly re-occur in the years to come due to abundant benthic cyst populations and eutrophic coastal water. However, it is very hard to accurately forecast the outbreaks of HABs and there are no effective countermeasures to mitigate the fisheries damages. We need to assess the present work on HABs in Korea and establish an efficient scientific agenda for research and mitigation strategies to allow sustainable coastal productivity.

## Overview of the spatio-temporal variations of HABs in southern Korean coastal waters

In Figure 14, the number of red tide outbreaks since 1981 is shown. One event is a bloom occurring in an area, caused by one or several species. It is counted as new when the dominant species changes into other species, even if occurring at the same place. Based on the annual total number of red tide outbreaks recorded in the HABs monitoring program, there were 8 events in 1981, including 3 harmful dinoflagellate blooms,



**Fig. 14** The outbreak number of red tides in Korean costal waters since 1981. Abbreviations are D for Diatoms and F for Flagellates.

as shown in Figure 14. HABs increased in number to 21 in 1982, the first year of a *Cochlodinium polykrikoides* bloom, reaching 65 in 1995, the biggest and persistent year of *C. polykrikoides* in the last two and half decades. In 1998, it increased to 122 outbreaks. The number of *C. polykrikoides* blooms was 3 in 1982, and increased to 28 events in 1995. The duration of blooms is generally less than one week but since 1984, they have continued sometimes for more than two weeks in enclosed or

semi-enclosed bays. These HABs were relatively restricted in geographical distribution in the 1970s. Until the early 1980s, the dinoflagellate blooms occurred mostly in some enclosed or semi-enclosed bays, such as Chinhae and Kosong Bays in the South Sea. But in recent years, they became widespread, extending to Kangnung in the East Sea, to Inchon and Mokpo bordering the Yellow Sea, and Yoja and Kosong Bays in the western part of the South Sea (Fig. 15).



**Fig. 15** Spatial distribution of the red tide outbreaks in Korean coastal waters since 1981.

Now the dinoflagellate blooms affect most of the coastal areas, in many cases over large geographic areas and caused by more than one harmful or toxic algal species (Kim *et al.* 1994).

The prevailing phytoplankton groups responsible for the blooms are Dinophyceae and Bacillariophyceae as listed in Table 8. Diatoms were the most common bloom species until the first half of the 1970s. Since then, dinoflagellates

such as *Prorocentrum micans*, *P. minimum*, *Heterosigma akashiwo*, *Gymnodinium mikimotoi*, *G. sanguineum* and *Cochlodinium polykrikoides* were found to be the major bloom formers. They exclusively form monospecific blooms of high density in the summer season. Some cyst-forming dinoflagellate species make blooms repeatedly at the same place and same time of the year (Kim *et al.* 1990).

**Table 8** List of microalgae responsible for algal blooms in Korean coastal waters.

Division	Class	Order	Red Tide Organisms
Cyanophyta	Cyanophyceae	Chroococcales	<i>Anabaena flos-aquae</i> <i>Anabaena spiroides</i> <i>Microcystis aeruginosa</i>
Cryptophyta	Cryptophyceae	Cryptomonadales	<i>Chroomonas salina</i>
Dinophyta	Dinophyceae	Prorocentrales	<i>Prorocentrum balticum</i> <i>Prorocentrum dentatum</i> <i>Prorocentrum micans</i> <i>Prorocentrum minimum</i> <i>Prorocentrum triestinum</i>
		Gymnodiniales	<i>Cochlodinium polykrikoides</i> <i>Gyrodinium fissum</i> <i>Gymnodinium mikimotoi</i> (= <i>G.nagasakiense</i> ) <i>Gymnodinium sanguineum</i> <i>Pheopolykrikos hartmannii</i>
		Noctilucales	<i>Noctiluca scintillans</i>
		Gonyaulacales	<i>Alexandrium affine</i> <i>Alexandrium fraterculus</i> <i>Alexandrium tamarense</i> <i>Ceratium furca</i> <i>Ceratium fusus</i> <i>Lingulodinium polyedra</i> (= <i>G. polyedra</i> )
		Peridiniales	<i>Heterocapsa triquetra</i> <i>Scrippsiella trochoidea</i>
Chrysophyta	Bacillariophyceae	Centrales	<i>Chaetoceros curvisetus</i> <i>Leptocylindrus danicus</i> <i>Rhizosolenia alata</i> <i>Skeletonema costatum</i> <i>Thalassiosira allenii</i> <i>Thalassiosira conferta</i> <i>Thalassiosira lundiana</i> <i>Thalassiosira nordenskioeldii</i>
		Pennales	<i>Asterionella</i> sp. <i>Cylindrotheca closterium</i> <i>Pseudo-nitzschia pungens</i> <i>Pseudo-nitzschia australis</i> <i>Navicula</i> spp.
	Raphidophyceae	Raphidomonadales	<i>Chattonella</i> sp. <i>Fibrocapsa japonica</i> <i>Heterosigma akashiwo</i> (= <i>H. carterae</i> )
	Chrysophyceae	Dictyochales	<i>Dictyocha fibula</i>
Euglenophyta	Euglenophyceae	Eutreptiales	<i>Eutreptiella gymnastica</i>
Protozoa Ciliophora	Kinetofrag minophorea	Prostomatida	<i>Mesodinium rubrum</i>

Reviewing the annual fluctuations of HABs for the last two decades, four stages can be identified according to species toxicity, spatial distribution, density and duration as follows: the first - before the 1980s, the second stage - from 1981 to 1988, the third - four years from 1989 to 1992, and the last - five years since 1993.

As shown in Table 9, in the first stage the causative species were harmless, and the area was only partially affected by localized algal blooms. Bloom density was approximately 1,000 cells ml<sup>-1</sup>. The second stage, from 1981 to 1988, was a

transition stage from harmless to harmful species. The blooms occurred either in partial areas or sometimes widespread and lasted one or less than two weeks. From the third stage on, harmful species were chiefly responsible for the blooms, and they became widespread in whole coastal South Sea. The density sometimes reached 10,000 cells ml<sup>-1</sup>, quite lethal to aquatic animals. The duration of algal blooms was less than 3 weeks until 1992, but in 1995, it continued for nearly two months. From 1996 to 1998, the *Cochlodinium* bloom occurred every August and persisted for about one month.

**Table 9** Recent HABs in southern Korean coastal waters.

Terms	Before 1980	1981-1988	1989-1992	1993-1997
Species toxicity	Harmless	Harmless/harmful	Harmful	Harmful
Affected area	Partial area	Partial/wide area	Widespread/South Sea	Widespread overall coast
Bloom density (cells/ml)	1000	1000-5000	2000-10000	3000-30000
The longest duration	1 week	1-2 weeks	3 weeks (81)	8 weeks (1995)

#### **Dynamic modeling of harmful *Cochlodinium* blooms**

After *C. polykrikoides* blooms caused severe economic loss in 1995, dynamic modeling has been used to study the initiation and subsequent development of the blooms. From our recent work, it was found that *C. polykrikoides* species bloom when the thermocline is absent and water temperature overlying bottom sediment is 20°C or more. The population growth rate of *C. polykrikoides* is high at water temperatures of 24 - 26°C. It has proved that this species grows well in slightly eutrophic water similar to a chemical oxygen demand (COD) of 1 ppm. Warm and slightly eutrophic environment, is optimal for the growth of *C. polykrikoides*, forms in the South Sea in late August or early September when eutrophic coastal water is mixed with warm offshore water. This warm water is the intrusion of the Tsushima Warm Current.

When the *C. polykrikoides* bloom is fully developed, it gradually forms a plume-like patch and grows. Bloom movement and distribution is dependent on the wind direction and tidal currents. The bloom approaches the coast during flood currents when SW winds prevail, and vice versa during neap currents with a NW wind.

In order to build a virtual model for the initiation of *C. polykrikoides* blooms, we need to do in-depth studies to assess the influence of nutrient and COD-related factors on the growth rate, precise dormant period of this species, and temperature sensitivity of excystment and population growth. Furthermore, surface water temperature from NOAA images and chlorophyll- $\alpha$  concentrations from SeaWiFS images are also studied to predict subsequent evolution and horizontal distribution.

## **HABs management and mitigation strategies**

The Korean fisheries economy depends heavily upon the coastal zone for marine products and so it is especially sensitive to constraints from HABs. Resources must be used in the most efficient way and there is a need for sustainable, multiple-use management schemes.

There needs to be reasonable implementation and countermeasures to combat the environmental challenges such as those described above. The best way to minimize the damages is to detect HAB outbreaks at the initial stages and then take urgent action. The present action plan consists of regular monitoring and quick announcements to alert fishermen. Recently, a HAB alarm system and shield curtain for fish cages have been invented and can be commercially acquired. In addition, local self-government authorities sprinkle clay on the surface of the HAB-affected areas. If fisheries damages arise due to HABs, the government grants subsidies and relief bank loans for the sufferers.

### ***Hierarchical and television monitoring and announcement***

It is very necessary to forecast the outbreaks of blooms in order to take appropriate measures. Some fish killing dinoflagellates can devastate the farms. Most of the coastal fish farms cannot avoid the HABs due to fixed aquaculture facilities.

Regular coastal monitoring has been carried out since 1981, biweekly or monthly at 70 stations from March to November by the National Fisheries Research and Development Institute (NFRDI) to investigate the status of water quality and HAB outbreaks. Most of the coastal environmental parameters are monitored simultaneously.

When HABs occur, daily observations are made to indicate the subsequent development of HABs in the affected area and neighboring waters likely to be affected. Another 24 watch teams patrol the coast every day to detect red tides from May to October. There were 92 outposts along the coast in 1996. The patrolling periodicity is dependent on the frequency of red tide outbreaks in the last 5

years. They are divided into 3 grades, *i.e.*, daily, weekly and biweekly patrolling outposts. The main target phytoplankton are *C. polykrikoides*, *G. mikimotoi* and *Gyrodinium* sp.

With respect to the quick-detection and best-save measures, NFRDI is working to build a “remote televisual HAB monitoring network”. This is an image highway network for the telecommunication of microscopic image between local terminal laboratories and the central institute in Pusan. The expert in the central institute can identify phytoplankton species by telecommunicated microscopic image from the local laboratory. This way we can overcome the shortage of identification experts and a limited budget because this framework connects all the laboratories and outposts.

Most of the red tide information is distributed immediately to aquaculturists, fishermen and municipal administrative authorities by facsimile, internet (<http://www.nfrdi.re.kr>), and automated telephone response system that began service on May 6, 1996.

For the monitoring of shellfish poisoning, toxicological tests are run for PSP and DSP using bioassays and HPLC, and ASP using HPLC. The annual budget for the 1995 national red tide monitoring was about US\$250,000 exclusive of the personnel expenses and instrument purchase.

### ***Red tide alert system and alarm facilities***

To get early attention from fishermen and aquaculturists, NFRDI deploys an alert system. It consists of notification of “Red Tide Attention”, “Red Tide Alert” and “Lifting of the Warning”. The notices of attention and alert are issued when the density of *C. polykrikoides* exceed 300 cells/ml and 1,000 cells/ml, respectively. To prevent the intake of HABs into the fish culture tanks, practical HAB alarm techniques were invented in 1997. The HAB farm alarm system consists of sensor and alarm apparatus. The sensor can detect chlorophyll, temperature and turbidity. When it detects the possible HAB chlorophyll, it gives an alarm by sound during the day and light at night or both simultaneously. It is possible to stop the seawater supply into the tank automatically.

### **Mitigation strategies and scattering clays**

Mitigation strategies include cage movement to the outside of the affected area, diminution of feed supply, and early harvesting if the bloom develops to fatal levels. Another most important mitigation strategy is the scattering of clay. Clay has a capability to scavenge particles and carry them to bottom sediments. The removal efficiency of flocculent has been qualified in laboratory and field studies near TongYong fish farm using clay in September 1996. The removal efficiency was up to 80% using clay concentrations of 10 g l<sup>-1</sup>. No big difference was found between the laboratory and field test. In the field, dissolved inorganic nitrogen, chemical oxygen demand and chlorophyll- $\alpha$  concentration decreased slightly after dispersion. However, scattering clays into coastal farms has some impact on marine animals, especially on abalone, with no large effects on flatfish.

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