Postprint: Current Status, Evolutionary Trends, and Response Strategies for Algal Bloom Disasters in China' s Coastal Waters

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Abstract

Harmful algal blooms (HABs) are common disastrous ecological anomalies in coastal waters, encompassing not only "red tides" and "brown tides" formed by microalgae, but also "green tides" formed by macroalgae. In many sea areas, once the problem of harmful algal blooms emerges, it persists for a considerable duration, posing threats to mariculture, ecological security, and human health. In China, harmful algal blooms have become a prominent marine ecological disaster issue. The Bohai Sea, the Yangtze River estuary and its adjacent waters, and the coastal waters of the South China Sea represent three typical high-incidence areas for red tides. Large-scale outbreaks of red tides have caused severe damage to the mariculture industry and also threaten marine ecological security and human health. Recently, disastrous harmful algal bloom phenomena such as green tides and brown tides have also emerged in the South Yellow Sea and Bohai Sea, attracting considerable attention. Comprehensive analysis of harmful algal bloom issues in China' s coastal waters reveals that causative species of algal blooms in China' s coastal areas exhibit evolutionary trends of diversification, increasing harmfulness, and miniaturization, which presents numerous difficulties for the monitoring and management of algal blooms. To effectively prevent and control harmful algal blooms, it is necessary to strengthen basic research on harmful algal blooms, elucidating fundamental issues such as the diversity status of causative species, the relationship between bloom occurrence and ecosystem health, the evolutionary trends of algal blooms and their driving factors, and the potential ecological effects of algal bloom evolution. Simultaneously, capabilities for observation, early warning, control, and prevention of algal blooms should be further enhanced.

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Special Topic: Coastal Science and Sustainable Development

Harmful Algal Bloom Disasters in China' s Coastal Waters: Current Status, Evolution Trends, and Response Strategies

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Abstract

Harmful algal blooms (HABs) are common disastrous ecological anomalies in coastal waters, encompassing not only "red tides" and "brown tides" formed by microalgae but also "green tides" formed by macroalgae. Once HABs emerge in many sea areas, they tend to persist for extended periods, posing threats to mariculture, ecological security, and human health. In China, HABs have become a prominent marine ecological disaster problem. The Bohai Sea, the Yangtze River estuary and its adjacent waters, and the coastal waters of the South China Sea represent three typical high-incidence regions for red tides. Large-scale red tides have caused severe damage to mariculture and threatened marine ecological security and human health. Recently, disastrous HAB phenomena such as green tides and brown tides have also appeared in the southern Yellow Sea and Bohai Sea, attracting significant attention. Comprehensive analysis of China' s coastal HAB problems reveals that causative species are exhibiting diversification, harmfulness, and miniaturization trends, creating numerous difficulties for monitoring and management. To effectively prevent and control HABs, it is necessary to strengthen basic research on harmful algal blooms to elucidate fundamental issues including the diversity of causative species, the relationship between bloom occurrence and ecosystem health, evolution trends and their driving factors, and potential ecological effects of these changes. Simultaneously, we should further enhance capabilities in HAB observation, early warning, control, and prevention.

Keywords: harmful algal bloom, red tide, green tide, brown tide
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Harmful algal bloom disasters are ecological disasters caused by the rapid proliferation or aggregation of microalgae or macroalgae forming harmful algal blooms

(HABs). Common marine HAB phenomena include "red tides" and "brown tides" formed by microalgae, as well as "green tides" formed by macroalgae. Algae forming HABs can harm marine life through multiple pathways, such as toxin production, damaging gill tissues of marine organisms, and altering water physicochemical environments, thereby endangering mariculture, human health, and ecological security. Consequently, HABs are consistently studied and managed as a category of marine ecological disaster. HAB phenomena commonly occur in coastal estuaries and bays, and many HAB events, once initiated, evolve into normalized phenomena that can persist for years or even decades. For instance, green tides have persisted for over 30 years in the coastal waters of Brittany, France [1], while green tides in the Venice Lagoon lasted nearly 20 years before gradually disappearing [2]. In recent years, as human activities and climate change have continued to intensify their impacts on the marine environment, the affected areas of HABs have continuously expanded, posing severe threats to the sustainable development of coastal aquaculture, human health, and marine ecological security, and have become a global ecological disaster issue. Research on the causes and hazards of HABs has also become one of the frontier fields in marine science.

In China, HABs represent one of the most prominent marine ecological disaster problems [3,4], with research and monitoring of harmful algal blooms receiving considerable attention. Since the 1970s, with support from the Ministry of Science and Technology, the National Natural Science Foundation of China, the Chinese Academy of Sciences, the State Oceanic Administration, and other agencies, research has been ongoing regarding the formation mechanisms, hazard mechanisms, monitoring technologies, and prevention strategies for harmful algal blooms in China' s coastal waters. More than 30 red tide monitoring zones have been established in China' s coastal waters for routine monitoring of red tide occurrences. However, the HAB problem in China' s coastal waters remains extremely serious, with both the frequency and affected area of HABs showing upward trends, causing enormous economic losses and social impacts.

1.1 Red Tide Disasters in China' s Coastal Waters

In China' s coastal waters, the Bohai Sea, the Yangtze River estuary and its adjacent waters, and the coastal waters of the South China Sea are three typical high-incidence regions for red tides.

In the Bohai Sea region, the three bays of Liaodong Bay, Laizhou Bay, and Bohai Bay have the most severe red tide problems, with multiple large-scale red tides historically occurring [5]. The Bohai Sea is an important spawning and nursery ground for economically important species, with numerous mariculture zones in its coastal waters. Red tides have caused tremendous damage to the mariculture industry in the Bohai Sea. In 1989, a *Gymnodinium* sp. red tide in Huanghua City, Hebei Province, dealt a devastating blow to the prawn aquaculture industry in the Bohai Bay area, causing direct economic losses of 240 million yuan. In 1998, a *Ceratium furca* red tide in the Bohai Sea severely damaged the aquaculture industries of Liaoning, Hebei, Shandong, and Tianjin, resulting in approximately 120 million yuan in economic losses. Between 2004 and 2006, large-scale *Phaeocystis* sp. red tides occurred consecutively in Bohai Bay, though they did not cause significant damage to aquaculture. More recently, brown tides caused by *Aureococcus anophagefferens* have been repeatedly recorded in the coastal waters of Qinhuangdao in the Bohai Sea, severely damaging the local scallop aquaculture industry. Particularly concerning is that toxic algal blooms have been recorded multiple times in the waters surrounding the Bohai Sea, with toxin contamination in cultured shellfish being very common, posing potential threats to consumers of seafood products. In 1998, a red tide formed by *Dinophysis* spp. (which can produce diarrhetic shellfish toxins, DSTs) together with *Ceratium furca* was followed by detection of diarrhetic shellfish toxin components in shellfish [6]. In 2006, an *Alexandrium* spp. red tide capable of producing paralytic shellfish toxins (PSTs) was recorded in the Changdao sea area of Shandong, causing massive mortality of cage-cultured fish.

The East China Sea region has the highest recorded number of red tide occurrences in China' s coastal waters. Red tides in this sea area mainly appear in spring and summer, with May through August being the high-incidence period. Since 2000, the frequency of red tides in the waters adjacent to the Yangtze River estuary has increased dramatically [Figure 1: see original paper], with large-scale red tides occurring frequently, affecting areas up to tens of thousands of square kilometers. Of particular concern is that the dominant red tide species are toxic and harmful dinoflagellates such as *Prorocentrum donghaiense*, *Karenia mikimotoi*, and *Alexandrium* spp., posing serious threats to aquaculture development, human health, and ecological security [7]. A *K. mikimotoi* red tide that occurred in 2005 in waters adjacent to the Yangtze River estuary caused massive mortality of cultured fish near Nanji Island, with direct economic losses exceeding 30 million yuan. In 2012, a large-scale *K. mikimotoi* red tide along the coast of Fujian Province caused massive mortality of cultured abalone, with preliminary estimates of economic losses exceeding 2 billion yuan, representing the most severe economic loss caused by harmful algal blooms in China' s history. Additionally, high densities of toxic *Alexandrium* spp. and toxic *Dinophysis* spp. have been observed multiple times in waters adjacent to the Yangtze River estuary, with *Alexandrium* cell densities reaching 10 –10 cells/L, meeting red tide levels. Analysis of phytoplankton and shellfish samples collected during red tides has detected various algal toxins including paralytic shellfish toxins and diarrhetic shellfish toxins.

The coastal waters of the South China Sea are also among China's high-incidence regions for red tides, with recorded red tide events second only to those in the East China Sea. Most red tides in the South China Sea occur in bays such as Dapeng Bay, Daya Bay, and Shenzhen Bay, as well as waters near the Pearl River estuary. Historically, red tide phenomena recorded in the South China Sea were not large in scale, but since the 1990s, large-scale red tides have begun to appear, particularly those formed by *Phaeocystis* sp. In November–December 1997, a large-scale *Phaeocystis* red tide occurred in Zhelin Bay, Raoping, Guangdong, causing massive mortality of cultured fish and economic losses exceeding 70 million yuan. In 1999, another *Phaeocystis* red tide occurred in the Raoping sea area, covering more than 3,000 km². In the Beibu Gulf of Guangxi, large-scale *Phaeocystis* red tides have also occurred consecutively in recent years. During the winters of 2014 and 2015, *Phaeocystis* red tides in the coastal waters of Guangxi covered the waters near Fangchenggang, Qinzhou Bay, and Beihai. Since *Phaeocystis* can form spherical colonies up to 2–3 cm in diameter during red tides, capable of clogging filter nets, they pose potential threats to the safety of cooling water systems at coastal nuclear power facilities.

1.2 Green Tide Disasters in the Yellow Sea

Compared with the Bohai Sea, East China Sea, and South China Sea, the red tide problem in the Yellow Sea is not severe. However, since 2007, large-scale green tides formed by the macroalga *Ulva prolifera* have occurred consecutively in the Yellow Sea for 10 years [Figure 2: see original paper] [Figure 3: see original paper]. During green tide events, the area covered by green algae has exceeded 1,000 km², making it the largest of its kind in the world. In the later stages of green tides, massive amounts of floating green algae accumulate along the coastline. In 2008 alone, the Qingdao municipal government removed over 1 million tons of green algae from the coastline. Since the accumulated green algae produce toxic gases such as H S and NH when decomposing, polluting the air and seawater and even causing biological asphyxiation, green tides have had enormous impacts on coastal tourism landscapes and mariculture. After the 2008 Yellow Sea green tide landed on the Shandong Peninsula, the decomposition of *Ulva* accumulated in culture ponds deteriorated water quality, devastating sea cucumber, abalone, raft-cultured scallop, and tidal flat shellfish aquaculture in Rushan, Haiyang, Jiaonan, and Rizhao, causing major economic losses of up to 800 million yuan to local aquaculture [8]. The 2009 Yellow Sea green tide also caused economic losses of up to 640 million yuan. Green tides not only threaten coastal landscapes and aquaculture but also raise serious concerns about impacts on the natural marine environment. During growth and decomposition, green algae absorb or release nutrients, altering the biogeochemical cycling of biogenic elements in the water and potentially causing phytoplankton blooms that result in secondary disasters [9].

In response to the consecutive occurrence of green tides, urgent problems to be solved include how to monitor and predict green tide occurrences timely and accurately, and how to respond to green tide disasters effectively. Currently, China's satellite remote sensing technology has achieved large-area, synchronous, and rapid monitoring of green tide disasters [10] [Figure 4: see original paper]. During *Ulva* blooms in the Yellow Sea, satellite data from China' s Fengyun MERSI, Environmental HJ/CCD, and Beijing-1 have been applied to monitor the drift paths of green algae [11]. However, numerical models for predicting the occurrence and development trends of green tides are still lacking. In terms of green tide response, passive manual and mechanical harvesting remains the primary approach. Although harvested green algae can be utilized as resources [12], this only partially compensates for economic losses caused by green tides. Controlling green tides at their source remains an urgent priority.

1.3 Brown Tide Disasters in the Yellow Sea and Bohai Sea

Brown tides are a newly emerged type of harmful algal bloom in China' s Yellow Sea and Bohai Sea in recent years. In summer 2009, a unique harmful algal bloom phenomenon appeared in the coastal waters of Qinhuangdao in the Bohai Sea. During the bloom, cultured bay scallops exhibited reduced feeding rates, growth stagnation, and even massive mortality, causing significant economic losses. Since then, similar harmful algal bloom phenomena have occurred consecutively each year. In 2010, the affected area reached 3,350 km^2, causing over 200 million yuan in economic losses. Because the causative species (the algal species forming the harmful bloom) are tiny, fragile, and difficult to preserve, making identification through morphological characteristics challenging, the bloom could only be generally termed a "picophytoplankton bloom." Pigment analysis revealed that phytoplankton during bloom periods contained 19' -butanoyloxyfucoxanthin (But-fuco), fucoxanthin (Fuco), diadinoxanthin (Diad), and chlorophyll *a* [13]. Molecular biological studies found that in clone libraries constructed using eukaryotic universal primers, a pelagophyte—*Aureococcus anophagefferens*—dominated. Combining pigment characteristics and molecular biological analysis confirmed that *A. anophagefferens* was the primary causative species [13]. This harmful algal bloom formed by *A. anophagefferens*, known internationally as "brown tide," was the first record in China. In addition to the coastal waters of Qinhuangdao in the Bohai Sea, similar "brown tide" phenomena also appeared in the Sangou Bay area of the North Yellow Sea in 2011.

The "brown tide" phenomenon had previously only been reported on the U.S. East Coast and in South Africa, representing a typical ecosystem disruptive algal bloom (EDAB) [14]. The coastal waters of the Yellow Sea and Bohai Sea are important shellfish aquaculture areas in China and also serve as spawning and nursery grounds for many important marine economic species. Due to the toxic effects of *A. anophagefferens*, the emergence of brown tides could further damage the ecological functions of coastal waters, affecting ecosystem health and the sustainable development of aquaculture. Both the Qinhuangdao coastal waters and Sangou Bay area are near the M2 tidal amphidromic point [15], where water bodies are relatively stable. The large number of rafts in shellfish aquaculture zones block seawater flow, further increasing water stability—an important reason for brown tide occurrence in these areas. However, the reasons for the sudden outbreak of "brown tides" in the coastal waters of the Yellow Sea and Bohai Sea remain unclear.

2 Evolution Trends of Harmful Algal Bloom Disasters in China' s Coastal Waters

2.1 Evolution Characteristics of Harmful Algal Bloom Disasters in China

In recent years, harmful algal blooms in China' s coastal waters have shown clear evolution trends, with continuously increasing occurrence frequency and expanding affected areas. Before the 1990s, recorded red tide events in China' s coastal waters were rare, and affected areas were small, rarely exceeding several hundred square kilometers. After 2000, the annual recorded number of red tide events has ranged between 50–80, with affected areas reaching thousands or even tens of thousands of square kilometers and durations lasting over a month. Additionally, causative species have shown significant changes, exhibiting evolution trends of "diversification, harmfulness, and miniaturization."

The "diversification" trend of causative species in China' s coastal waters is very evident. In coastal sea areas, there are not only microalgal red tides and brown tides but also macroalgal green tides. Regarding microalgae, common causative species in China' s coastal waters encompass many groups including diatoms, dinoflagellates, cyanobacteria, cryptophytes, haptophytes, raphidophytes, and pelagophytes. Studies on harmful algal blooms in waters adjacent to the Yangtze River estuary indicate that after 2000, causative species for red tides in this area changed significantly. In addition to diatoms such as *Skeletonema* spp., many large-scale red tides were formed by dinoflagellates including *Prorocentrum donghaiense*, *Karenia mikimotoi*, and *Alexandrium* spp. [7]. In the Bohai Sea and South China Sea waters, some previously unrecorded species such as *Aureococcus anophagefferens* and *Phaeocystis* spp. have also formed harmful algal blooms multiple times.

Causative species in China' s coastal waters also show an evolution trend toward "harmfulness." Since dinoflagellates and other flagellates can produce highly active toxic substances with toxic effects on marine organisms and even human health, the increasing number of red tides formed by dinoflagellates and other flagellates has continuously increased threats to mariculture development. Currently, more and more toxic algal species are being recorded in China' s coastal waters, with various algal toxins detected in many sea areas, including paralytic shellfish toxins, okadaic acid (OA), dinophysistoxins (DTXs), pectenotoxins (PTXs), yessotoxins (YTXs), azaspiracid (AZA), and cyclic imine toxins such as gymnodimine (GYM) and spirolide (SPX). Toxin contamination in cultured shellfish is common, and poisoning incidents from consuming contaminated shellfish have occurred repeatedly. In 2008, a poisoning incident involving seven people (with one death) was reported in Lianyungang, Jiangsu, caused by consumption of clams contaminated with paralytic shellfish toxins. In May 2011, over 200 people in Ningbo, Zhejiang and Ningde, Fujian were poisoned after consuming mussels, which were later found to contain high levels of okadaic acid and dinophysistoxins, with toxicity exceeding diarrhetic shellfish toxin food safety standards by more than 40 times [16]. In late April 2016, another mussel poisoning incident occurred in the Qinhuangdao area, with paralytic shellfish toxin levels far exceeding shellfish safety standards. The "harmfulness" of causative species not only threatens human health but also endangers marine ecological security. Studies have found that during *Prorocentrum donghaiense* red tides, the egg production rate of the key zooplankton species *Calanus sinicus* decreases significantly, with population densities declining markedly [17], potentially altering the fundamental food chain and causing changes in coastal ecosystem structure and function. Since the early 21st century, the increase in large-scale dinoflagellate red tides in China' s coastal waters has been accompanied by outbreaks of large jellyfish, which to some extent is related to changes in the species composition of basic food organisms.

In recent years, the "miniaturization" trend of causative species has also become prominent. Cells of species such as *Phaeocystis* and *Aureococcus anophagefferens* are extremely small. Although *Phaeocystis* can form spherical colonies several centimeters in diameter during red tides, its cell size is only 5-8 μm, while *A. anophagefferens* cells are only 2-3 μm. Such tiny algal cells create significant challenges for HAB research and monitoring based on traditional morphological approaches.

2.2 Driving Factors of Harmful Algal Bloom Evolution in China' s Coastal Waters

For the evolution of harmful algal blooms in China' s coastal waters, changes in the coastal environment caused by human activities should be the primary reason. Many studies have shown that HAB occurrence is closely related to eutrophication caused by nutrient pollution. In oligotrophic coastal waters, seagrass beds or benthic perennial macroalgae typically dominate. As eutrophication intensifies, primary producers gradually shift to fast-growing epiphytic macroalgae. In severely eutrophicated waters, harmful algal blooms such as green tides or red tides appear. With rapid population growth and socioeconomic development in China' s coastal regions, coupled with dramatic increases in fertilizer application in large river basins, large quantities of nutrients have entered the ocean through various pathways, causing continuous intensification of eutrophication in some of China' s coastal waters and sustained increases in nutrient concentrations, particularly evident in estuarine areas such as the Yangtze River estuary. Along with rising nutrient concentrations, eutrophicated waters have also experienced structural changes in nutrients such as high N/P ratios and high N/Si ratios. Many studies have shown that dinoflagellates often have competitive advantages under imbalanced nutrient conditions, so structural changes in coastal nutrients likely contribute to increased dinoflagellate red tides, thereby exacerbating harmful algal bloom problems. Additionally, increased concentrations of organic nitrogen and phosphorus nutrients are particularly concerning. In the coastal waters of Qinhuangdao in the Bohai Sea, coastal urbanization and aquaculture activities have significantly increased organic nitrogen concentrations, representing an important factor triggering brown tides in this area.

In addition to eutrophication, habitat alteration by human activities is another important reason for the intensifying harmful algal bloom problem. Studies on green tides in the Yellow Sea have found that the aquaculture area in the Subei Shoal is an important region for the early development of Yellow Sea green tides [10,17,18]. The Subesi Shoal is an important *Porphyra* aquaculture base in China, with cultivation areas reaching tens of thousands of hectares, and *Ulva* is a fouling green alga that attaches to *Porphyra* aquaculture rafts. Large quantities of aquaculture rafts provide important substrates for *Ulva* in the Subesi Shoal area, with *Ulva* attaching to *Porphyra* rafts in winter and proliferating massively as temperatures rise in spring, reaching biomasses of thousands of tons. After the aquaculture season ends, large amounts of fouling green algae are discarded into the sea, becoming the source of large-scale green tides in the Yellow Sea.

In addition to human-induced environmental changes in coastal waters, climate change is also an important factor affecting HAB occurrence. Against the background of global warming, seawater warming in China' s coastal waters is very prominent, potentially altering the distribution of algae in China' s coastal waters. Another particularly noteworthy issue is that regional climate events such as El Niño and La Niña may change current intensity, water stratification, and even nutrient transport fluxes in regional sea areas, thereby indirectly affecting the distribution, dynamics, and even harmful effects of HABs. However, current understanding in this area remains very limited and requires more in-depth research.

3 Response Strategies for Harmful Algal Bloom Disasters in China' s Coastal Waters

Regarding the rapidly changing harmful algal bloom problem in China' s coastal waters, our understanding remains relatively superficial, and there is an urgent need to strengthen research on the formation and evolution mechanisms of algal bloom disasters. Why do such diverse harmful algal bloom problems appear in China' s coastal waters? Does the occurrence of harmful algal blooms indicate degradation of China' s coastal ecosystem environment? Do various harmful algal bloom phenomena compete or succeed one another? How will harmful algal blooms in China' s coastal waters evolve in the future? Will such evolution impact marine ecosystem health and socioeconomic development in coastal regions? These questions require systematic basic research to fundamentally reveal the diversity of causative species, adaptive strategies of different algal species, the regulatory roles of environmental factors in bloom development and decline, and the pathways and mechanisms of harm caused by algal bloom disasters to ecosystems before scientific answers can be provided.

Addressing the diverse algal bloom disaster problems requires enhanced monitoring and early warning capabilities for harmful algal blooms. However, the diversification and miniaturization trends of causative species in China' s coastal waters pose higher demands on HAB monitoring and early warning. It is necessary to make full use of macro-scale remote sensing observation technology, combined with various technical means from taxonomy, analytical chemistry, and molecular biology, to continuously advance the application of in-situ observation technologies in harmful algal bloom research, and to fully realize the potential of numerical simulation methods in HAB research and prediction, thereby improving monitoring and early warning capabilities.

Regarding the harmful effects of algal bloom disasters, it is necessary to continuously improve prevention and control capabilities. The continuous emergence of harmful algal bloom phenomena in coastal waters poses threats to mariculture development, human health, tourism landscapes, ecological security, and even the safe operation of coastal large-scale facilities, requiring effective control technologies and response strategies. Currently, modified clay-based emergency response techniques have been effectively applied to control red tides and brown tides in China' s coastal waters, playing positive roles in protecting coastal tourism landscapes, mariculture, and safe operation of coastal facilities. However, in the long term, measures to control eutrophication and protect habitats are still needed to reduce harmful algal bloom events and prevent their harmful effects.

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Note: Figure translations are in progress. See original paper for figures.