Hydrobiologia (2006)
DOI 10.1007/s10750-006-0108-1

Primary Research Paper

Spatial, seasonal and species variations of harmful algal blooms in the South Yellow Sea and East China Sea

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Received 08 May 2005; in revised form 27 January 2006; accepted 26 February 2006

Key words: harmful algal bloom, distribution, species variation, Yellow Sea and East China Sea

Abstract

The occurrences of harmful algal blooms (HABs), in terms of frequency and area in the Chinese coastal waters, have been increasing since 1980s and caused considerable economic losses. In the present study, we have analyzed spatial and seasonal characteristics of HAB events in the southern Yellow Sea and East China Sea along Chinese coast from 1933 to 2004. With a total 435 HAB records, the most frequent HAB occurrence area (FHA) is off the Yangtze River mouth and another two FHA areas are located south of the Yangtze River estuary along about isobaths of 30–60 m coastal water in the East China Sea. The time of HAB occurrence shifted during our study period: from autumn (August–October) before 1980s to July–August in 1980s, during May–July in 1990s, and May–June for the period of 2000–2004. Causative species were found to be different: *Noctiluca scintillans* and *Skeletonema costatum* were dominant causative species prior to 2000; and *Prorocentrum donghaiense* Lu was dominant from 2000 to 2004 and also caused large blooms in May. *Trichodesmium* sp. caused many HABs in autumn (August–October) prior to 1980s with only one HAB between 1980 and 2004. The changes of the dominant HAB species may have affected the timings of HAB occurrence, as well as the increasing HAB-affected areas in recent years.

Introduction

Harmful Algal blooms (HABs) are a serious marine problem and have increased in frequency, intensity, and geographic extent worldwide; this increase is not only a threat to marine aquaculture throughout the world but also a threat to human health (Anderson, 1997; Tang et al., 2003, 2004a, 2005). The first documented HAB event in China was caused by *Noctiluca scintillans* and *Skeletonema costatum* in Zhejiang coastal waters in 1933. It killed marine organisms such as razor clams and other shellfish species (Fei, 1952). From 1970s, HAB frequency increased three times every 10 years and sometimes led to large economic losses in Chinese coastal waters. Until 2001 at least 1800 persons had been poisoned totally and 30 people had died from toxins released by HAB species; from 1952 to 1998, a total of 322 HAB events had been observed in China (Zhou et al., 2001). In 2003 alone, the State Oceanic Administration of China (SOA) reported 119 HAB events in all Chinese coastal areas with a cumulative area of 14,550 km^2, of which 72% in frequency and 89% in area were in the East China Sea (SOA, 2004).

The environment of East China Sea has been affected by anthropogenic activities and population growth in the Yangtze River drainage basin and areas along the coasts; it ranked the most HAB prone in terms of the frequency and extent among all Chinese coastal areas in recent years (Xu et al., 1994). Earlier studies of HABs were carried out for the Yangtze River estuary and its adjacent areas; they found a high frequency area of HABs with total of 23 causative species at the Yangtze River mouth area (Xu et al., 1994; Zhou et al., 2001; Ye & Huang, 2003). One species, *Prorocentrum dentatum*, has been observed to cause large HAB blooms from 2000 in coastal waters of Zhejiang (Wang & Huang, 2003); this species later was named as *Prorocentrum donghainese* Lu (Lu et al., 2005).

The HABs have caused great economic losses by damaging mariculture. Shanghai municipality suffered greatly from HABs and its coastal ecology has been damaged by HABs (SOA, 2001). Fujian and Zhejiang provinces ranked the second and fifth, respectively, in mariculture production among all Chinese coastal areas, are also frequently threatened by HABs (Yang et al., 2004). The Three-Gorges Dam, the biggest dam in the world, would change the Yangtze River runoff from natural into man-made regulation that has serious impact on the nutrient output and sediments to the estuary and marine ecosystem. Therefore we are not only interested in the current distribution and frequency of HABs in the East China Sea related to coastal aquaculture, but also in the changes of oceanic primary production (pigment concentration) as well as fisheries recruitments after the completion of the dam. In the present study we analyze systematically historical HAB data from 1933 to 2004 in the South Yellow Sea and East China Sea to understand the HAB-affected area, and the frequency and seasonality of HAB occurrences in this area.

Materials and methods

Study area

Our study area (Box A, Fig. 1) is Chinese coastal waters in the northwest Pacific Ocean. The meteorological conditions in this region are influenced by monsoon winds (Tang et al., 2004b). The Southern Yellow Sea and East China Sea consist of various areas with different characteristics, with many studies on HABs having been carried out by different research groups. There is complicated topography and currents, the waters are influenced directly by the Yangtze River diluted water and Taiwan Strait warm current, and also are influenced indirectly by Kuroshio Current, cold water from the Yellow Sea as well as coastal waters along those provinces (Zhou et al., 2003). Therefore, an overall consideration of the monitoring of HABs that were studied by different groups in this region is necessary.

Historical records of HABs and data analysis

Since the first record of HABs in 1933 (Fei, 1952), Chinese scientists have conducted many HAB studies. One Chinese national HAB project was approved in 2001 and selected Yangtze River Estuary and coast of Zhejiang Province as the main study area and conducted the first cruise in May 2002. Until 2004, the SOA had established 11 HAB monitoring stations in East China Sea (SOA, 2004). All these previous research projects have established a good HAB database that provides important information for HAB research. We have collected a total of 435 historical HAB events from published papers, symposium documents and the China Oceanic Information Network of the SOA, as well as other public data sources for the southern Yellow Sea and the East China Sea during the period of 1933–2004. Some HAB events might not have been recorded in the early years; some HABs were reported as red or brown in color but without causative species. Some other HABs have neither records for spatial extent nor the size of affected area; for example, nine events before 1980s were only described as "large" or "small", without the exact bloom sizes.

From these 435 HAB cases, we have made comparisons for time of occurrence, location, causative species, and bloom area in four periods (before 1980, 1980s, 1990s, and 2000–2004). We then analyzed time series of HABs for these four periods.

Prorocentrum dentatum is a common HAB species in China, Korea, and Japan in recent years, and this species was renamed as *P. donghaiense* Lu

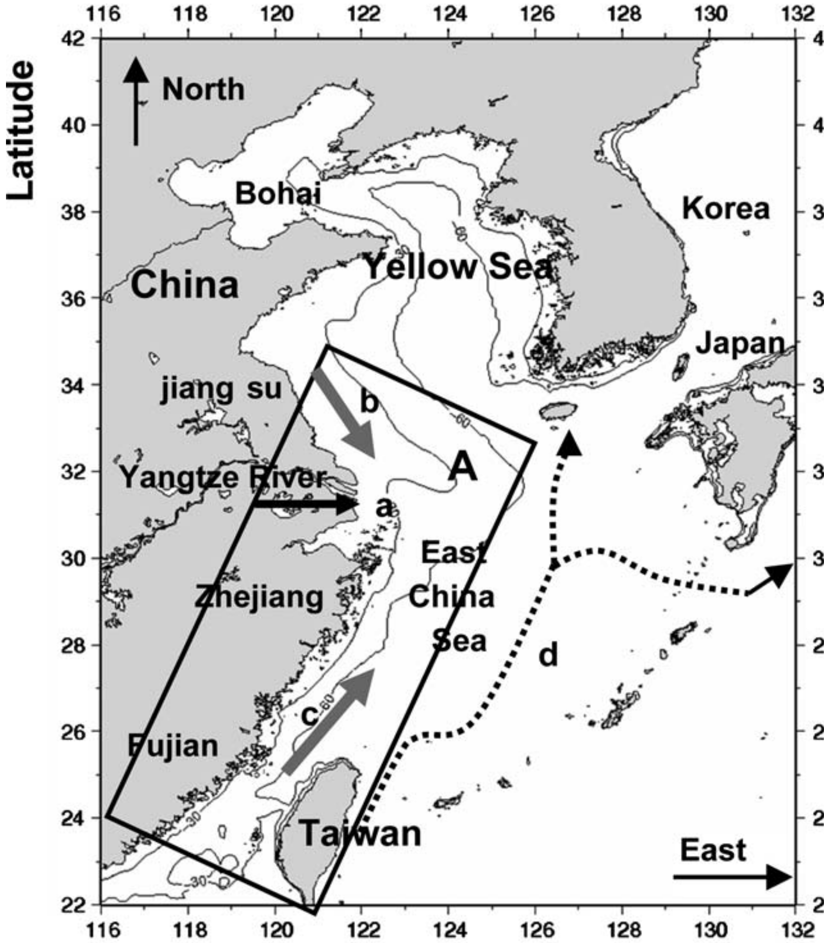

Figure 1. Study area. Box A shows our study area; Arrow a: Yangtze River diluted water; Arrow b: coastal water from the Yellow Sea; Arrow c: warm water of the Taiwan Strait; Arrow d: Kuroshio Current.

in 2005 in China (Lu et al., 2005). In our collected HAB data, most reports referred to *Prorocentrum dentatum*, except a few papers in China described it as *Prorocentrum donghainese*. In order to avoid missing any information as well as to make it easier in comparison with other HAB studies in the world, we now use "*Prorocentrum dentatum* (*donghaiense* Lu)" for both *Prorocentrum dentatum* and *P. donghaiense* Lu in our study.

Results

Frequent HAB occurrence area (FHA)

In our analysis, HABs appeared in almost all the coastal areas of the East China Sea from 1933 to 2004 (Fig. 2). In Fig. 2, asterisks denote HABs occurrences, and dashed circles indicate the most frequent HAB occurrence area (FHA) (30° 00′–31° 50′ N, 122° 00′–123° 00′ E). About 34% of HABs occurred in this area. Coastal waters of Zhejiang and Fujian provinces (Fig. 2(a), (b)) were also more vulnerable to HABs. A further 10 HABs occurred in the coastal area of Jiangsu province as indicated by shadow ellipses but their exact locations could not be identified (Fig. 2(c)). Those FHAs are mostly along isobaths of 30–60 m in the coastal water.

Dominant HAB causative species

The causative species of HABs changed from 1933 to 2004. A total of 205 HAB events were recorded,

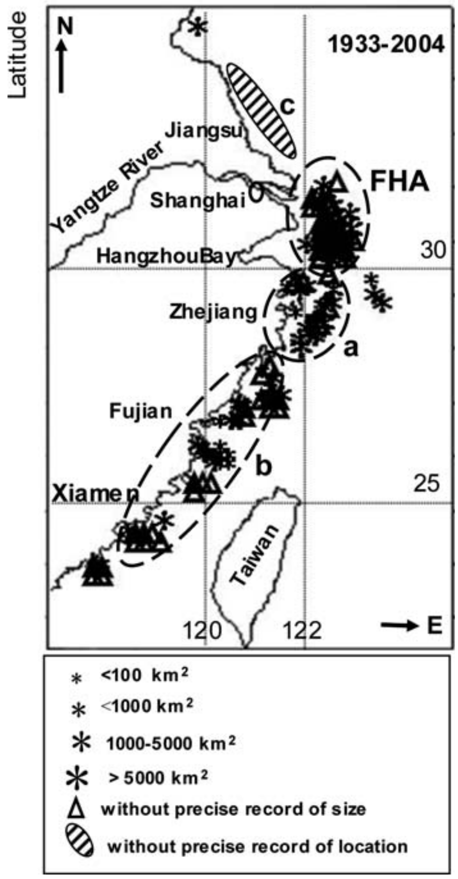

Figure 2. Locations of HAB events recorded during 1933–2004. FHA and circle "a" and "b" indicate area of frequent HAB occurrence; Each asterisk represents one HAB case, and the size of the asterisk corresponds to the size of HAB area. Each triangle depicts one HAB event without precise record of size. Shadow ellipse "c" indicates 10 HABs in the coastal waters of Jiangsu Province without precise record of the location.

with 32 causative species including three dominant HAB species: *Noctiluca scientillans, Skeletonema costatum* and *Prorocentrum dentatum* (*donghaiense* Lu). Some species were not identified to species but only to the family or genus level such as *Gymnodinium* sp. and *Cryptomonas* sp. that were grouped together as "other causative species" (Fig. 3)

Chronological analysis from these data, in 1980s, *Noctiluca scientillans* caused 39 events, ranking as the top of the recorded HAB causative species (Fig. 3(b)). In 1990s, *Skeletonema costatum* became the most frequent HAB causative species (Fig. 3(c)). These two species dominated for 73.2% of HAB events before 2000. However, from

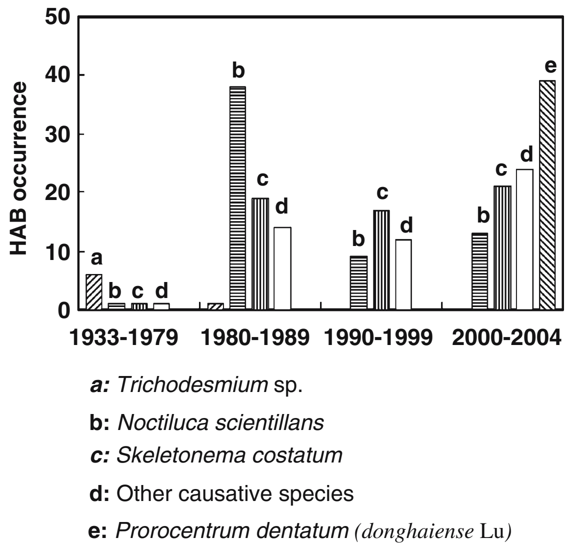

Figure 3. Number of HABs caused by five dominant species or groups in different periods.

2000 to 2004, *Prorocentrum dentatum* (*donghaiense* Lu) (Fig. 3(e)) contributed to the highest frequency of HABs including one HAB event with an area of 10,000 km^2 in 2004. This species was responsible for 39 HAB events and replaced both *Noctiluca scientillans* and *Skeletonema costatum*, becoming the most influential and frequent HAB causative species from 2000 to 2004.

Seasonal variations of HABs

Seasonal and monthly variations of HAB occurrences have been observed in our study. Prior to 1980, a total of 9 HABs were recorded mainly during autumn (August to October) (Fig. 4(a)). In 1980s, 15 HABs out of 78 events were in August and 12 HABs in July (Fig. 4(b)). Therefore, July to August was the frequent time period in 1980s that accounted for 34.6% of the total HABs in this decade.

There were 111 HAB records in 1990s, of which 35 were in May, 21 in June, and 23 in July (Fig. 4(c)). These accounted for 71.2% of the total recorded events in this decade, therefore, May–July was the frequent time in 1990s.

From 2000 to 2004, a total of 246 HABs was observed but only 126 were recorded with both time and location. May–June was the most frequent time with 95 HAB records responsible for 75.4% of these 126 recorded HABs (Fig. 4(d)).

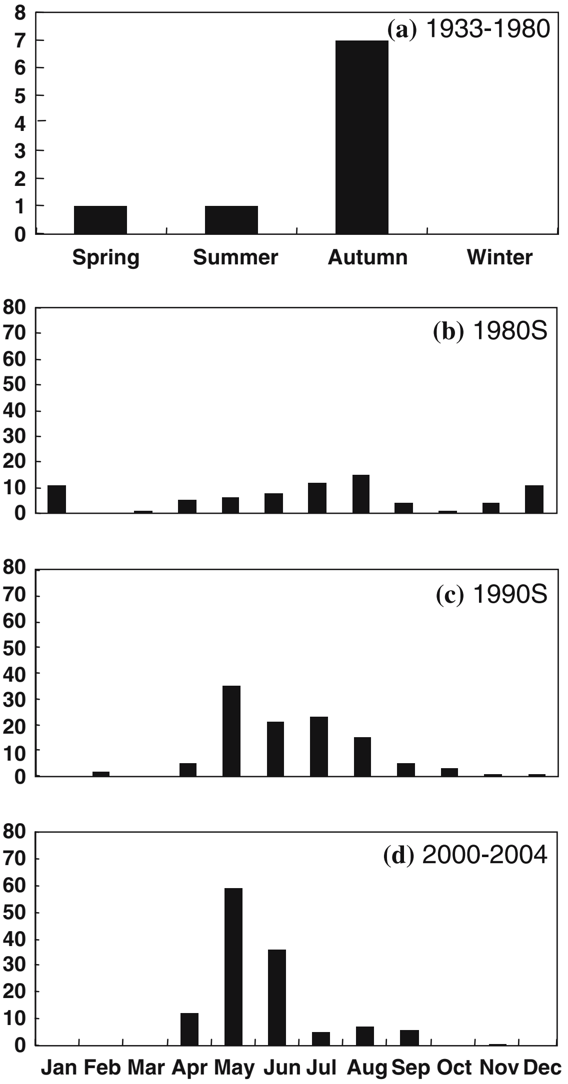

Figure 4. Monthly distribution of HABs in different periods during 1933–2004. Spring: February–April; Summer: May–July; Autumn: August–October; Winter: November–January.

Spatial distribution of HABs

Figure 5 shows the extent of spatial distribution of HABs in the coastal waters of the South Yellow Sea and the East China Sea. From 1933 to 1979, several HABs were observed in the Yangtze River estuary area and coastal waters of Fujian province (Fig. 5(a)). In 1980s and 1990s, a great number of events occurred along the coastal waters of Zhejiang province, especially outside the Hangzhou Bay (Fig. 5(b), (c)). From 2000 to 2004, HABs were observed in all East China Sea coastal waters (Fig. 5(d)).

Figure 6(a) shows enhancement of HAB frequency and affected areas annually. There were less than 19 HAB occurrences per year in 1980s and 35 or less in 1990s, but with a sharp increase from 16 to 86 per year from 2000 to 2004, with a peak in 2003. The total area of HAB occurrence was also found to be increasing. The 9 HABs before 1980s mainly occurred in the coastal areas of Fujian province and outside of the Yangtze River estuary. A total area of 14,133 km^2 was affected by HABs in 1980s, with another 11 occurrences recorded as large events. In 1990s, the total HAB area was 18,920 km^2 with another 18 recorded as large events. The HAB-affected area increased to 64,186 km^2 during the 5 years from 2000 to 2004.

The annual economic losses caused by HABs from 1998 to 2004 are found to vary (Fig. 6(b)), with the greatest loss in 2000.

Changes of causative species

Prorocentrum dentatum (*donghaiense* Lu) emerged as the dominant HAB species from 2000 to 2004 (Fig. 3(e)). A total of 39 blooms were caused by this species, and the duration and areas of HABs caused by *Prorocentrum dentatum* (*donghaiense* Lu) had increased, especially in May (Fig. 7).

Prorocentrum dentatum (*donghaiense* Lu) has been found to cause major blooms near Hangzhou Bay and in the coastal waters of Zhejiang province. These blooms lasted 1 week on average from 2000 to 2004, but sometimes they lasted more than 1 month. The blooms often spread to more than 1000 km^2 and the average size was about 847 km^2, but with one record of 10,000 km^2 in 2004.

Trichodesmium sp. caused many HABs before 1980s, and most HABs were in autumn (August–October). However, there is no record of this species causing HABs from 1990s to 2004 (Fig. 8).

Discussion

HAB occurrence area

Our results show one area of very high FHA (FHA, Fig. 2) and another two FHAs (Fig. 2(a), (b))

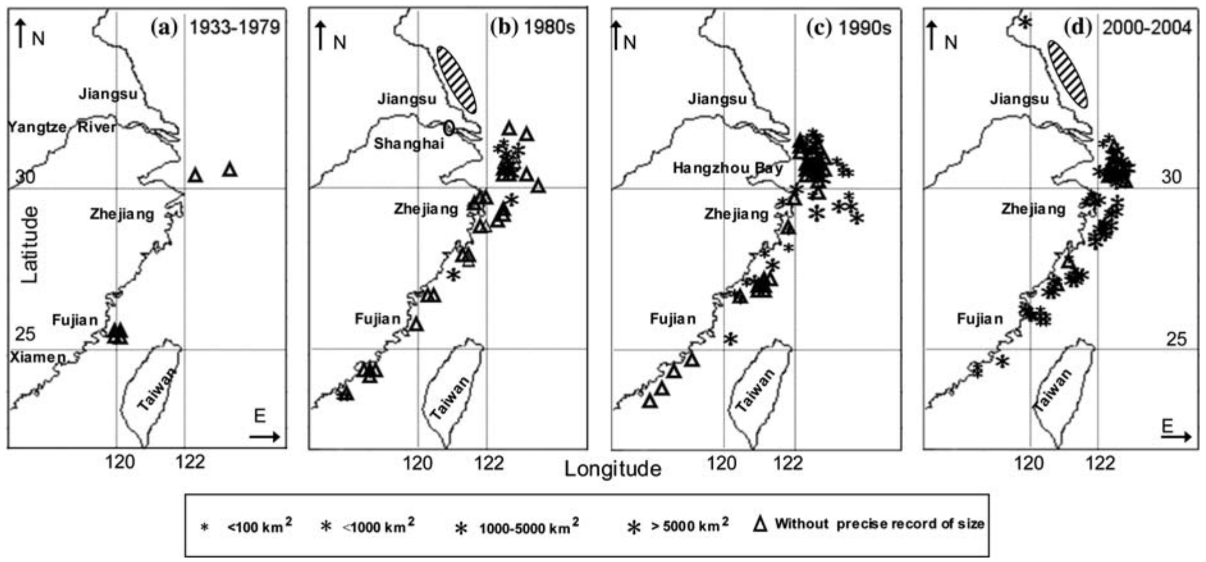

Figure 5. Sites of HAB events in periods from 1933 to 2004. Each star represents one HAB case, and the size of the star corresponds to the size of HAB area. Each triangle depicts a HAB event without precise record of size.

along isobaths of 30–60 m in the coastal waters, where environmental water conditions may have played an important role for bloom development.

First, the relatively serious eutrophication outside Yangtze River estuary in the East China Sea (SOA, 2000) is a likely inducement for the phytoplankton blooms and HAB occurrences (Pearl, 1997; Tang et al., 1998). The Yangtze River estuary and the Hangzhou Bay are the most eutrophic areas in the East China Sea (SOA, 2002). The Yangtze River, the longest one in China and the third largest in terms of volume in the world, takes tremendous amounts of nutrients into the East China Sea (Li et al., 2003; Zhou et al., 2003). The river nitrate concentration and flux have increased about 10-fold from 1968 to 1997 (Yan et al., 2003).

Second, the other two frequent HAB areas coincide with two upwelling zones along coastal waters of Zhejiang and Fujian provinces (Cao, 1986; Xu, 1986; Zhao, 1993; Tang et al., 1998, 2004b). Upwelling could provide rich inorganic nutrients for HABs to form; it might also make HABs last for a long period and cover large areas (Wang et al., 2000; Tang et al., 2002, 2004a).

Third, nutrient-rich water from Yangtze River meets with the warm water from Taiwan Strait to form a convergence zone that is usually favorable for the phytoplankton growth and HAB occurrences (Tang et al., 2003; Zhou et al., 2003).

Variations of HAB causative species and bloom season

The results show that the frequent period for HAB occurrence from 1933 to 2004 has shifted from autumn prior to 1980 to July–August in 1980s, May–July in 1990s and May–June from 2000 to 2004 (Fig. 4). One of the possible reasons for this change is due to the newly emerging species *Prorocentrum dentatum* (*donghaiense* Lu).

Prorocentrum dentatum (*donghaiense* Lu) appeared to cause HABs earlier than another dominant species *Skeletonema costatum*. Wang and Huang (2003) have found that the appearance and disappearance of *Prorocentrum dentatum* (*donghaiense* Lu) blooms matched with water temperature. *Prorocentrum dentatum* (*donghaiense* Lu) increases in May and mid-June but its populations decrease rapidly in late June in the Zhoushan area of Zhejiang province whereas *Skeletonema costatum* is found to be dominant when water temperatures reach 23 °C. Other experiments show that the most favorable temperature for *Skeletonema costatum* is 25 °C (Wang, 2002), which is a little higher than that of *Prorocentrum dentatum* (*donghaiense* Lu) of 18–22 °C (Wang & Huang, 2003).

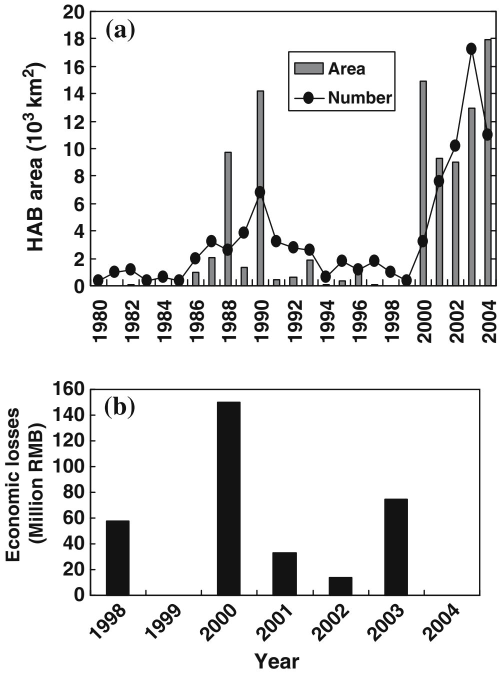

Figure 6. HAB occurrences and economic losses: 6(a) Annual HAB occurrences from 1980 to 2004. 6(b) Annual economic losses caused by HABs from 1998 to 2004.

Nutrients are one of the other important reasons for shifting of HAB occurrence time. In the Yangtze River estuary and its adjacent areas the total nitrogen to total phosphorus ratio is found to be very high and the phytoplankton growth is mainly limited by phosphate concentration rather than by nitrogen (Han et al., 2003). Previous experiments have shown that *Prorocentrum dentatum* (*donghaiense* Lu) has an advantage over *Skeletonema costatum* in such situations (Li et al., 2003). Li et al. (2003) have found that in May the phosphate concentration in the FHA is low and the growth of *Skeletonema costatum* may be affected whereas this may facilitate the growth of *Prorocentrum dentatum* (*donghaiense*). With the precipitation increase in June, nutrients, especially phosphorus, are supplemented by the diluted water from the Yangtze River and *Skeletonema costatum* may grow quickly (Li et al., 2003). For these reasons, *Prorocentrum dentatum* (*donghaiense* Lu) may be able to grow well in May due to the favorable temperature and nutrient conditions. More studies are required to find out why *Trichodesmium* sp. has disappeared in recent years.

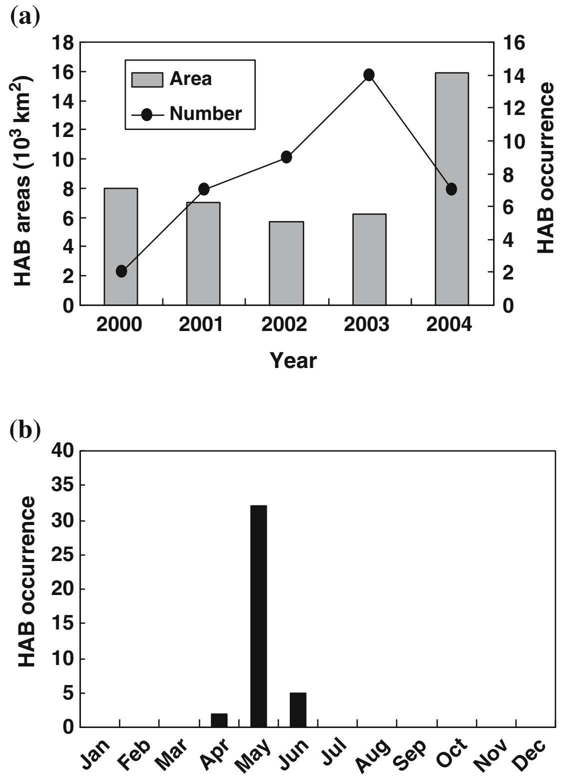

Figure 7. HAB occurrence caused by *Prorocentrum dentatum* (*donghaiense* Lu) from 1933 to 2004. (a) Number and area of HAB occurrence; (b) Season of HAB occurrence.

Future investigations and monitoring for HABs

Our results from a long-term investigation show that the following points should be considered for HAB studies and environmental monitoring.

(1) We should extend the HAB monitoring sites southward because HABs occurred almost through all the East China Sea coastal areas. More attention should be given to the FHA (Fig. 2), and the other two areas of frequent HAB occurrence in the coastal waters along Zhejiang and Fujian provinces.

(2) The monitoring timing should be adjusted. The frequent HAB occurrence timing has been found to shift in past decades from autumn prior to 1980 to May–June period from 2000 to 2004. Attention should be given to *Prorocentrum dentatum* (*donghaiense* Lu) that often causes large blooms particularly in recent years.

(3) HABs in the East China Sea are affected by Yangtze River discharges and northward Taiwan Warm Water Current. Kuroshio Current passes by this area and moves toward Korean and Japanese waters, therefore, cooperative research among China, Korea, Japan, and Taiwan would benefit HAB studies in this region.

Conclusion

From the present study, we have found one area with very high HAB occurrences off the Yangtze River mouth (FHA in Fig. 2); the other two frequent areas coincide with two upwelling zones along coastal waters of East China Sea.

The dominant causative species was found to vary. Occurrence time of HABs was found to shift from July–August in 1980s to May–July during 1990s, and May–June during 2000–2004.

In summary, the HAB occurrence frequency has been accelerated and HAB affected areas have also been enlarged; consequently, the economic losses caused by HABs have also increased with the highest loss in 2000.

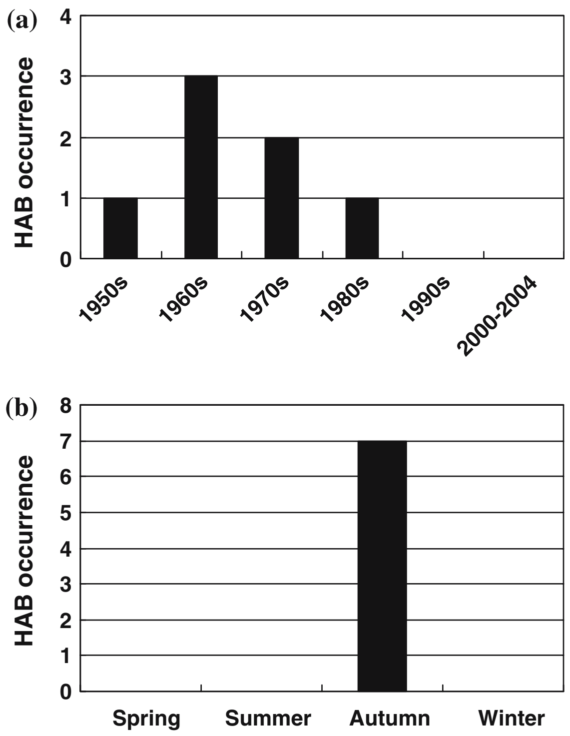

Figure 8. HABs caused by *Trichodesmium* sp. from 1933 to 2004.

Acknowledgements

This research was jointly supported by the following research grants awarded to DanLing TANG: (a) "One Hundred Talents Program of Chinese Academy of Science" Ybjh0403; (b) Two Guangdong Natural Sciences Research Foundation (China) (04001306 and 05102008); (c) Key Research Project of Chinese Academy of Science (KZCX3-SW-227-3). This work is also partially supported by the Ministry of Maritime Affairs and Fisheries, Republic of Korea through a Project (PM34700; Project for a Development of Communication, Ocean and Atmospheric Satellite) and the Science Council in Taiwan (NSC 93-2313-B-019-016) on long-term monitoring study in Taiwan Strait. Appreciations are given to: Professor Yasuwo Fukuyo, Graduate School of Agricultural and Life Sciences, University of Tokyo; Mr. Zheng Guangming of SCSIO; Professor Ramesh Singh, Department of Civil Engineering Indian Institute of Technology; and Professor Qi YuZao of Jinan University, for their help, comments and suggestions on this study.

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