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# In situ and satellite observations of a harmful algal bloom and water condition at the Pearl River estuary in late autumn 1998

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## Abstract

Harmful algal blooms (HABs) have posed a serious threat to the aquaculture and fisheries industries in recent years, especially in Asia. During 1998 there were several particularly serious blooms in the coastal waters of south China, which caused a serious damage to aquaculture. We report a massive dinoflagellate bloom near the mouth of Pearl River in November 1998 with analyses of data from both in situ sea water measurements and satellites. A multi-parameter environmental mapping system was used to obtain real-time measurements of water quality properties and wind data through the algal bloom area, which allow us to compare water measurements from inside and outside of the bloom areas. This bloom with high concentrations of algal cells was evident as a series of red colored parallel bands of surface water that were 100–300 m long and 10–30 m wide with a total area of about 20–30 $km^2$ by visual. The algal density reached $3.8 \times 10^7$ cells $l^{-1}$ and the surface chlorophyll-a (Chl-a) concentration was high. The algal species has been identified as *Gymnodinium* cf. *catenatum* Graham. The water column in the bloom area was stratified, where the surface temperature was 24–25 °C, the salinity was 18–20%, and the northern wind was about 3–4 m $s^{-1}$ in the bloom area. The SeaWiFS image has shown high Chl-a area coinciding with the bloom area. The sea surface temperature (SST) image of the Pearl River estuary combined with the in situ measurements indicated that the bloom occurred along a mixing front between cooler lower salinity river water and warmer higher saline South China Sea (SCS) water.


*Keywords:* AVHRR; China; Dinoflagellate; Harmful algal bloom (HAB); In situ measurement; Pearl River estuary; SeaWiFS

## 1. Introduction

Over the past two decades, harmful algal blooms (HABs) appear to have increased in frequency, intensity and geographic distribution worldwide. This increase is not only a threat to the coastal fish/shellfish aquaculture throughout the world, but it is also of great concern to human health (Anderson, 1998; Hallegreaff et al., 1995). It is, however, difficult to quantify such outbreaks in order to document trends since there are so many different types of blooms with so many different impacts (Anderson, 1998). In November 1998 we obtained a set of water quality data near the mouth of the Pearl River estuary in the northern of South China Sea (SCS) (Fig. 1) at a time when there was a massive algal bloom. This study reports our observations and findings of this autumn algal bloom with analyses of in situ water column measurements supplemented by

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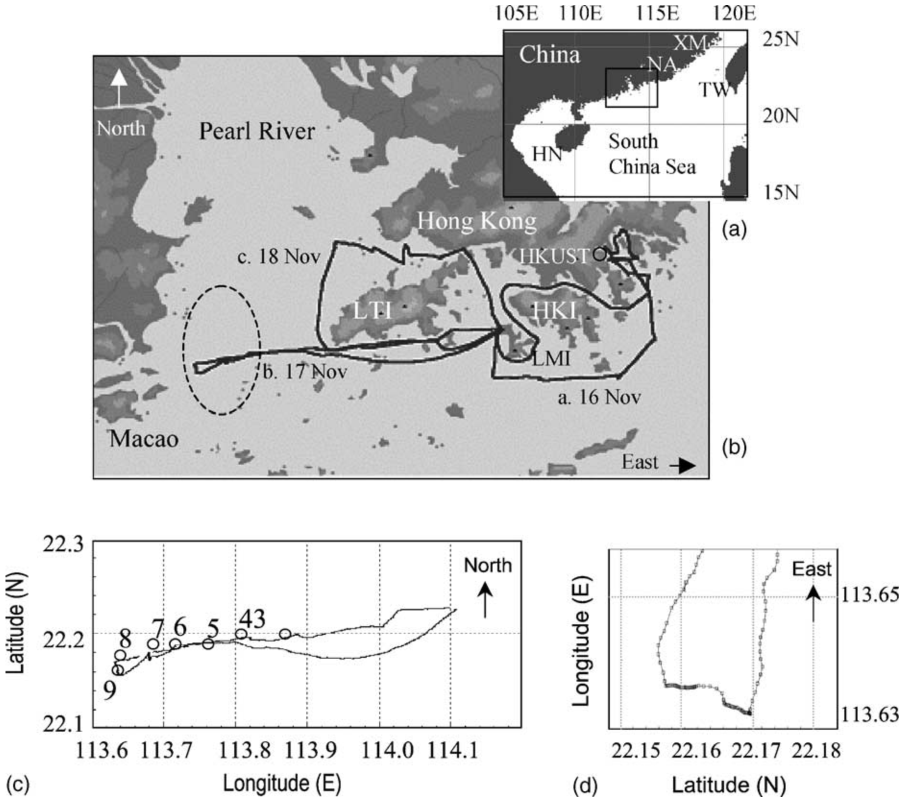


Fig. 1. The northern South China Sea. (a) Small box indicates the study area: HN, Hainan Island; NA, Nanao; TW, Taiwan; XM, Xiamen. (b) A set of boat cruise transects (transects a., b. and c.) for in situ water measurements in the Pearl River estuary (a) waters on 16, 17 and 18 November 1998. The algal bloom area is indicated by a dashed circle near Macao: HKI, Hong Kong Island; HKUST, Hong Kong University of Science and Technology; LMI, Lamma Island; LTI, Lantau Island. (c) Location of the cruise in the mouth of Pearl River on 17 November 1998 (b). Number 3–9 in the figure indicates sampling stations. The algal bloom was observed around station 9. (d) Detailed location of the north-south transect in the cruise (c).

satellite images. This examination of the algal bloom with physical and chemical water column measurements would enhance our knowledge of water conditions during a HAB.

China has the highest fishery production in the world and over 50% of the fishery products are from aquaculture (Qian, 1994). The rapid increase in coastal aquaculture production has created serious problems because marine pollution and eutrophication are unavoidable by-products of the marine aquaculture system (Stewart, 1997). The resulting intensified HABs have posed very serious threats to the fisheries and aquaculture industries along the Chinese coast (Lam and Ho, 1988; Qi et al., 1995, 1996a). Consequently, the introduction of management measures to mitigate deteriorating coastal water quality and the adverse environmental impacts of aquaculture development have become urgent matters to the region (Chua et al., 1989). Over 146 red tides events have been recorded in the South China Sea since 1981 (Qi et al., 1996b). The actual incidence of such blooms may be even greater because of the lack of a regular monitoring system. The frequency of HAB occurrences was high during late 1997 to early 1999 particularly in Hong Kong waters. A series of HABs of *Phaeocystis globosa* occurred along the coast of the southeast China, from the beginning of October 1997 in Fujian to February 1998 in Shanwei (Lu and Huang, 1999). These HABs caused tremendous damage to the coastal aquaculture industry in China.

Hong Kong also experienced a series HABs during March–April 1998 (Dickman and Tang, 1999). It was the worst outbreak of HABs of the decade, wiping out 1500 tonnes of farmed fish, which was equivalent to half of the entire Hong Kong aquacultural production of 1997 (Anderson, 1998). In the past, most studies on those HABs were mainly focused on species identification and toxin effect; here is lacking of oceanography study for HABs in this area.

Satellite remote sensing data have been used to study pigment concentration and sea surface temperature (SST) in the coastal areas of China (Tang et al., 1998, 1999, 2003a,b). By examining satellite ocean color data and sea surface temperature, Tang et al. (1999, 2002) reported winter phytoplankton blooms near the Luzon Strait in the South China Sea, and observed short-term variability of phytoplankton blooms in the northern Arabian Sea. SST images can be used to determine water temperature in nearshore areas (Fox et al., 2000; Tang et al., 2003a). SST and SeaWiFS images have also been applied for a HAB (*Gymnodinium catenatum*) study in New Zealand waters (Chang et al., 2001). At the present, we are unable to detect the species of HAB by using satellite ocean color image, therefore we call for more in situ study between HAB and satellite remote sensing for further application of satellite technology on HABs.

Most of the algal blooms occurred in spring in many small bays in the east side of Hong Kong, where locations are also mariculture fish farm with water of entrophication. We observed a massive algal bloom when we carried out a research cruises in November 1998 near the mouth of the Pearl River in the west side of Hong Kong (Fig. 1b). The present paper presents the examination of this autumn algal bloom from three different aspects: (1) What is the species for this autumn phytoplankton bloom? (2) What is the water condition in the mouth of the river? (3) What kind of information we could obtain from satellite image?

## 2. Material and methods

### 2.1. Study area and cruise measurements

The study area is located in the northern part of South China Sea (Fig. 1a), where Macao is in the west side and Hong Kong in the east side (Fig. 1b). The Pearl River discharges into the river estuary. On 16–18 November 1998, a series of 23 stations were sampled to provide vertical profiles of the physical and chemical properties of the waters in this region (Fig. 1b). A multi-parameter environmental sensor system (YSI model 6000) was used to obtain real-time underway measurements of surface water quality properties, including water temperature, salinity, turbidity, oxygen, and chlorophyll-a (Chl-a). A differential GPS electronic charting system was used to track the location of the vessel. Measurements were made every minute along the cruise track. A massive algal bloom was observed at station 9 between Lantau Island and Macau (Fig. 1b) on 17 November. Locations of sampling stations 3–9 are displayed in Fig. 1c. Fig. 1d shows details of the north-south transect in Fig. 1c. We measured Chl-a concentrations along this transect. Algae were sampled, fixed with Lugol's solution (Sournia, 1978) and examined under a microscope in laboratory. Water measurements from inside and outside the bloom areas were compared.

### 2.2. Satellite remote sensing data

NOAA series satellites have a near-polar sun-synchronous orbit at a height of about 850 km (Schumacher et al., 1991). The advanced very high resolution radiometer (AVHRR) has five channels that cover the visible and infrared (IR) spectrum; it detects the SST. This study analysis images from AVHRR local data at $1.1 \times 1.1\,km^2$ resolution from the receiving station at the Hong Kong University of Science and Technology (HKUST) (Tang et al., 2003a). The TerraScan SST algorithm is MCSST-based (McClain et al., 1985). One SST image of the Hong Kong region was found useful in this consideration of a HAB. We then extracted water temperature values along a transect T (T in Fig. 6a) from this SST image.

SeaWiFS data were also received by HKUST; Chl-a image is processed through SeaWiFS data analysis system (SeaDAS) by ocean color 4-band algorithm (OC4) (O'Reilly et al., 2000) at Asian I-Lac project (Tang and Kawamura, 2002; Tang et al., 2003b).

### 2.3. HAB events in the Hong Kong waters

There were a series of HABs during 1998 in Hong Kong waters. All incidences with algal species and dates of occurrence in Hong Kong waters has been provided by Hong Kong Agriculture, Fisheries and Conservation Department (HKAFCD) that enabled us to compile a summary of these events.

## 3. Results

### 3.1. Algal bloom and in situ measurements

The algal bloom with a deep-red color was observed on 17 November 1998 around station 9 near the mouth of the Pearl River (Fig. 1b and c). It was located near Macao. The bloom area appeared as many parallel strips of 100–300 m long and 10–30 m wide, with a total area at least 20–30 $km^2$ (Fig. 2a). The algal cell concentrations reached $3.8 \times 10^7\,l^{-1}$. The species was a chain-forming unarmored dinoflagellate (Fig. 2b) with distinguishing characteristic of its conspicuous sulcus that could be easily seen. The sulcus extended from the antapex to the apex and the girdle showed a descending spiral that was up to one-fifth of the cell length. The cells contained numerous chloroplasts with remarkable pyrenoids and were spherical cysts with size ranging from about 45 μm long and 40 μm wide (Fig. 2c). This species is identified as *Gymnodinium* cf. *catenatum* Graham. A definitive verification of the species has not been possible with the available samples.

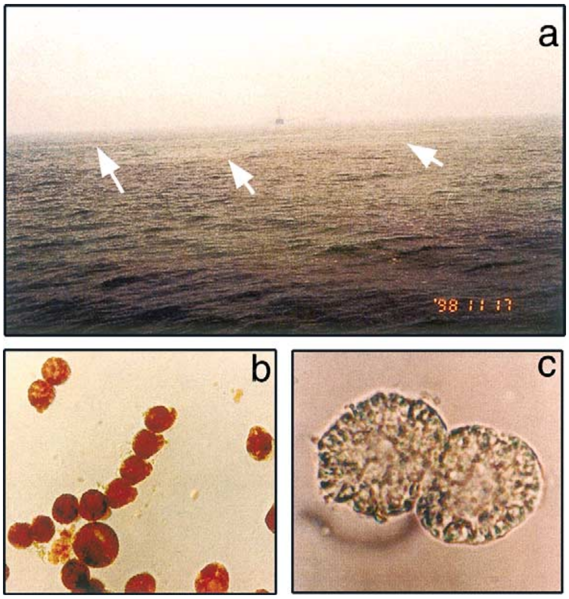


Fig. 2. (a) Deep-red color paths of the algal bloom near the mouth of the Pearl River on 17 November 1998. (b) Chains of *Gymnodinium* cf. *catenatum* cells. (c) Two algal cells of *Gymnodinium* cf. *catenatum*.

A portion of the underway measurements from 22.15 to 22.18 N (Fig. 1c and d) is shown in Fig. 3. Surface Chl-a fluorescence values along the north-south transect (Fig. 1d) are indicated by the voltage output of the fluorometer in Fig. 3a. The Chl-a concentration in surface reached high level and highly variable as we crossed two big strips of about 1000 m wide (22.156–22.164 N) (Fig. 3a). This matches with visual observation in the field (Fig. 2). The water temperature was between 24 and 25.0 °C in the area with the algal bloom (Fig. 3b). Salinity decreased from east (22‰) to west (17.2‰) as we approached the algal bloom region (Fig. 3c). Oxygen saturations on the surface reached 130% in the bloom area (Fig. 3d). These results also indicate a spatial variation of water condition from east to west in the month of the Pearl River. The wind was from the northeast at about 3–4 $m\,s^{-1}$ (Fig. 4).

The vertical structure of the water column inside and outside the bloom is shown in Fig. 5. The algal bloom, which occurred around station 9, was concentrated at the surface with Chl-a values of 15 $\mu g\,l^{-1}$ decreasing to 8 $\mu g\,l^{-1}$ at a depth of 2 m (Fig. 5a). The salinity was low (around 19‰) on the surface and increased to 29‰ at a depth of 3–4 m (Fig. 5b). Surface oxygen (Fig. 5c) saturations were 125% at several stations, reaching 140% in one of the bands of concentrated algal cells. The water column was highly stratified at the time of these observations.

### 3.2. Water temperature and Chl-a distribution in the river estuary

There was no NOAA SST data or SeaWiFS images from 17 to 20 November 1998 because the sensors were turned off due to a meteor shower. The SST image (Fig. 6a) closest to 17 November 1998 was obtained on 23 November. SST values were extracted from the image along transect T (approximately east-west) (T in Fig. 6a) to illustrate the gradients and magnitudes for comparison with the shipboard surface temperatures measured 6 days earlier. There

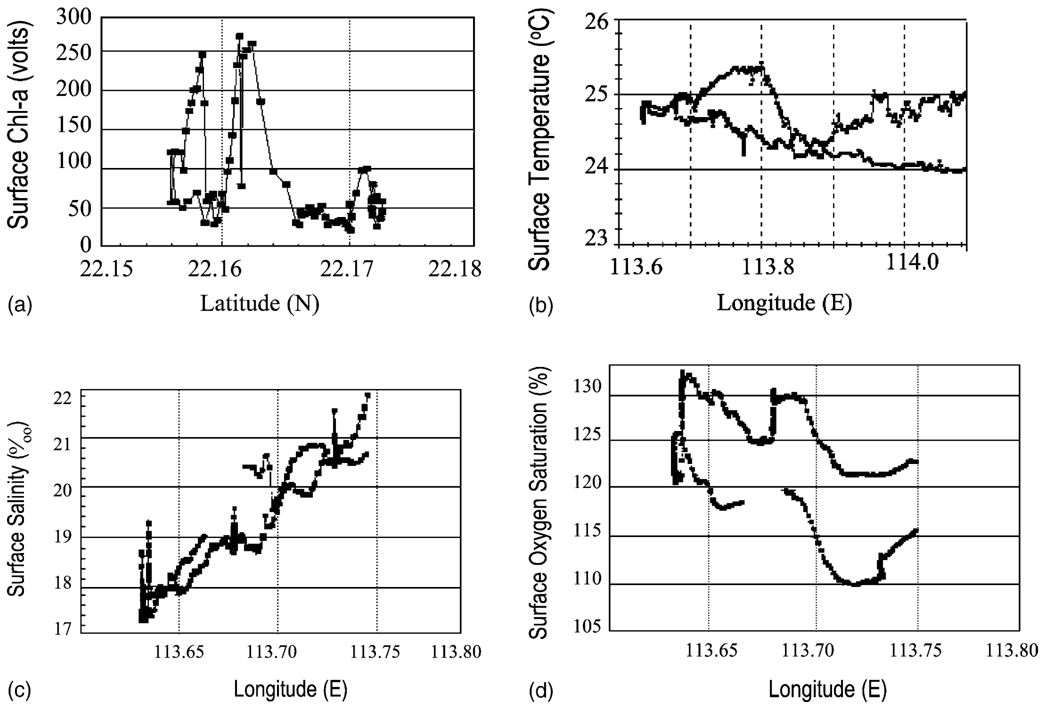


Fig. 3. Flowcell measurements of surface waters on 17 November 1998 (Fig. 1b and c): (a) Chl-a concentrations (along a north-south transect in Fig. 1d); (b) water temperature; (c) salinity; (d) oxygen saturations.

were 58 pixels obtained from transect T. The cool pixels in this image corresponding to SST values of less than 24 °C appear as a green fringe near the land. This green band represents pixels in which the SST value is contaminated by the cooler values from the land. The area of yellow pixels (SST ≥ 24 °C) on the western side of the estuary (arrow a), however, is consistent with the pattern we usually observe for fresh waters that are discharged from a series of outlets of the Pearl River. The warmer waters on the east side (arrow b) of the estuary and south of Hong Kong are typical from the South China Sea; the lower SST values are associated with lower salinity mixtures of Pearl River and SCS waters on the west side of the estuary. The discharge of the Pearl River reaches a maximum during June and July (the wet summer monsoon), and during November the discharge is approaching the annual minimum flow of January and February (the dry winter monsoon).

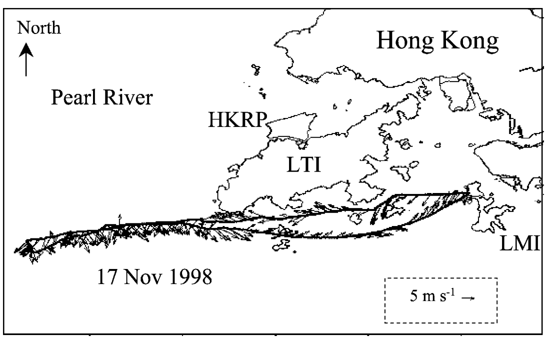


Fig. 4. Wind strength and direction along our cruise transect (b. in Fig. 1b and c) on 17 November: HKRP, Hong Kong Airport; LTI, Lantau Island.

The SST image taken on 23 November 1998 shows a thermal gradient extending from 24.2 °C in the west to 24.8 °C on the western side of the estuary. The surface temperature we measured in the bloom area on 17 November 1998 was 24.7–24.9 °C. Assuming that the pattern observed in the SST image on 23 November is characteristic of the pattern of

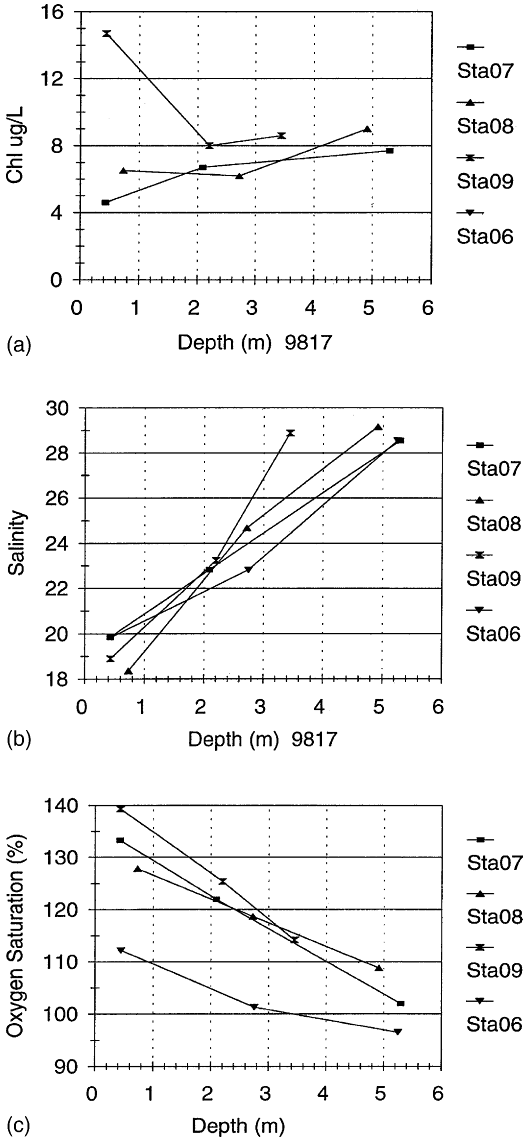


Fig. 5. Vertical water measurements at stations 6–9 (Fig. 1c) on 17 November 1998 displaying the water profile from surface to 6 m deep in the red tide area: (a) Chl-a concentration; (b) salinity; (c) oxygen saturation.

surface waters observed the preceding week, we can infer that the location of the bloom we observed on 17 November was associated with the mixing front of SCS and Pearl River discharge waters, at the point where they achieved a salinity of 17–18‰.

Fig. 7 is a SeaWiFS derived Chl-a obtained on 23 November 1998. Although there are mask out pixels in the west coast water in this image, we observe higher Chl-a concentrations (>1.5 gm m$^{-3}$) between Macao and the Lamma Island (LTI) than the surrounding waters coinciding with the location we meet bloom during our cruise. High Chl-a in a belt shape was between Macao and Lamma Island, where can be compared with the thermal gradient on the SST image in term of location (Fig. 6a).

### 3.3. HABs in Hong Kong waters in 1998

Thirty-seven incidences of HABs in 1998 with algal species and dates of occurrence in Hong Kong waters are compiled in Table 1. There was a total of 23 species plus a few species that have not yet been identified. The bloom described in this study is number 33 on the list. The locations of those HABs that occurred in November 1998 are shown in Fig. 8. Most of these HABs were in the east part of Hong Kong. The algal bloom we report in this study was in west of Hong Kong near Macao. It was outside of Hong Kong territorial water and there it was not included in Hong Kong Government HAB database to be show in this map.

## 4. Discussion

### 4.1. Harmful algal blooms in 1998

About 90 species have been identified that cause HABs in the coastal areas of China (Qi et al., 1991). In 1998, HABs were unusually more frequent reported first from the northeast (coast of Xiamen (XM) in Fig. 1a) and then extended to the southwest (Hong Kong and Macao waters) along the northern coast of the South China Sea from March to April. Were they the same algal species? Did these blooms propagate from northeast to southwest? The first report of *Phaeocystis globosa* came from an upwelling area off the coast between Xiamen and Nanao (NA in Fig. 1a) in east China, in some initial reports *Phaeocystis* was incorrectly identified as *Gymnodinum* (Dickman and Tang, 1999). In early March, a *Gyrodinium digitatum edom* bloom occurred in the northeast corner of Hong

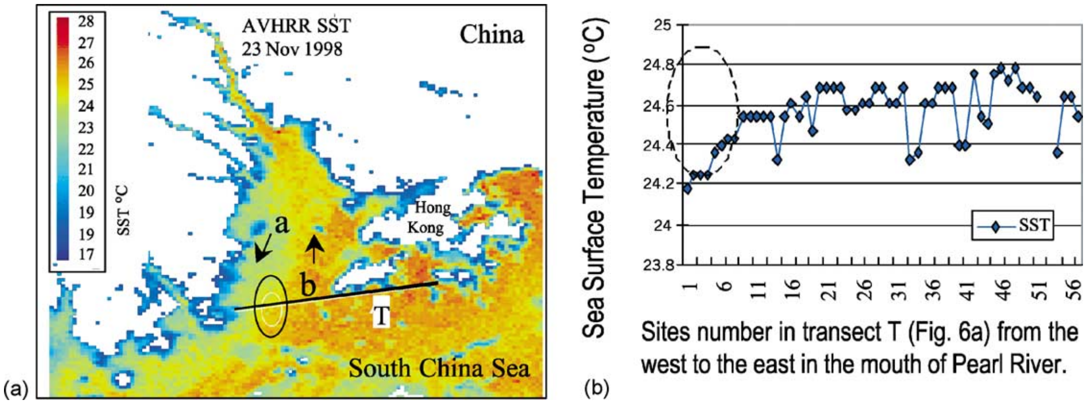


Fig. 6. (a) AVHRR image shows SST on 23 November 1998 (color bar indicates temperature). (b) SST values along a transect T (a) from west (Macao) to east (LKM).

Kong (Kat-ou) (Fig. 8). It swept eastward and then southward into Port Shelter along the south side of Hong Kong Island. In the middle of April, *Gyrodinium* HK2 reached Lamma and Lantau islands and then extended up into the Pearl River estuary to Zhuhai. It then extended westward into the Yanjian area. There were numerous species of HABs that bloomed in Hong Kong waters in 1998, but none of these were the same species as we report in the present study (Table 1 and Fig. 8).

*Gymnodinium catenatum* Graham produces paralytic shellfish poisoning (PSP) toxins, it has been found throughout the world, including Japan, North and South America, Australia (Fukuyo et al., 1990), and European countries (Hallegreaff et al., 1995), also bloomed in New Zealand waters in 2000 (Chang et al., 2001). Before 1995, it had been found in China only in Dapeng Bay (Qi et al., 1995, 1996a). Our study is the first reported occurrence of a *Gymnodinium* cf. *catenatum* bloom near the mouth of the Pearl River along with the associated water column properties in late autumn of 1998. The algal bloom species composition has been found changed from 1980s to 1990s. Paul Harrison (personal communication) has suggested the nitrogen enrichment from sewage discharge in recent years may affect surface/volume ratio of algal species that could be the key factor for the species composition changes. Although there was no reported fish kill within the Pearl River estuary by this observed HAB bloom, our study may provided in situ measurements and satellite remote sensing and serve as an early warning that a fall PSP outbreak in this area could be occurred again in the future.

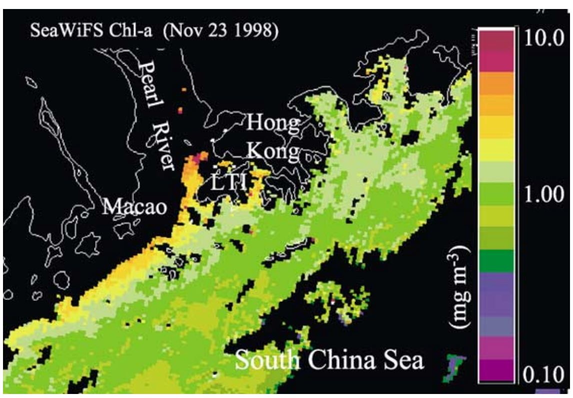


Fig. 7. SeaWiFS-derived Chl-a image on 23 November 1998. Color bar indicates Chl-a concentration.

### 4.2. Water condition in the HAB area

As we summarized in Table 1 and Fig. 8, most of the algal blooms occurred in spring in some small bays in the east side of Hong Kong (Fig. 1b), where are sites of fishing farms with waters of entrophication. What was the water condition concerning an autumn algal bloom in the Pearl River estuary? Although the specific conditions that trigger blooms are difficult to differentiate, we can identify some important factors from this study.

Table 1
Harmful algal blooms (HABs) recorded in Hong Kong waters in 1998 (data source: HKAFCD)

| No. | Date from | Date end | Location | Species |
|---|---|---|---|---|
| 1 | 20 February 1998 | 20 February 1998 | Turtle Cove Beach | *Noctiluca scintillans* |
| 2 | 20 February 1998 | 20 February 1998 | Repulse Bay Beach | *Noctiluca scintillans* |
| 3 | 13 March 1998 | 13 March 1998 | Little Palm Beach | *Noctiluca scintillans* |
| 4 | 16 March 1998 | 20 March 1998 | Silverstrand | *Noctiluca scintillans* |
| 5 | 18 March 1998 | 30 March 1998 | O Pui Tong, Kat O Hoi, Yan Chau Tong | *Gyrodinium* sp. HK98 |
| 6 | 17 March 1998 | 17 March 1998 | Tai Long Sai Wan | Undetermined |
| 7 | 23 March 1998 | 26 March 1998 | Leung Shuen Wan, Kau Sai | *Gyrodinium* sp. HK98 |
| 8 | 25 March 1998 | 31 March 1998 | Yim Tin Tsai Fcz, Inner Tolo Harbour | *Chaetoceros* spp., *Prorocentrum* spp., *Noctiluca scintillans* |
| 9 | 25 March 1998 | 27 March 1998 | Silverstrand | *Noctiluca scintillans* |
| 10 | 1 April 1998 | 1 April 1998 | Chung Hom Kok Beach | *Chaetoceros curvisetus*, *Noctiluca scintillans* |
| 11 | 2 April 1998 | 2 April 1998 | Yim Tin Tsai Fcz, Yung Shue Au Fcz | *Prorocentrum minimum* |
| 12 | 3 April 1998 | 3 April 1998 | Kat O Fcz, O Pui Tong Fcz | *Gyrodinium* sp. HK98 |
| 13 | 3 April 1998 | 4 April 1998 | Kai Lung Wan Fcz, Tai Tau Chau Fcz | *Gyrodinium* sp. HK98 |
| 14 | 7 April 1998 | 12 April 1998 | Shatin Hoi, Island House | *Prorocentrum minimum* |
| 15 | 9 April 1998 | 16 April 1998 | Cheung Sha Wan Fcz, Ma Wan Fcz, Sok Kwu Wan Fcz | *Gyrodinium* sp. HK98 |
| 16 | 10 April 1998 | 16 April 1998 | Sham Wan Fcz, Tap Mun Fcz | *Gyrodinium* sp. HK98 |
| 17 | 11 April 1998 | 17 April 1998 | Yim Tin Tsai (east and west) Fcz, Yung Shue Au Fcz | *Gyrodinium* sp. HK98, *Prorocentrum minimum* |
| 18 | 17 April 1998 | 17 April 1998 | Shek O Beach | *Noctiluca scintillans* |
| 19 | 24 April 1998 | 25 April 1998 | Repulse Bay Beach, Chung Hom Kok Beach | *Cochlodinium polykrikoides* |
| 20 | 25 April 1998 | 25 April 1998 | Sha Chau, Lung Kwu Chau, Tap Shek Kok | *Gymnodinium sanguineum* |
| 21 | 29 April 1998 | 1 May 1998 | Butterfly Beach, Cafeteria New Beach | *Gyrodinium instriatum* |
| 22 | 2 May 1998 | 12 May 1998 | Silver Mine Bay Beach, Pui O Beach, Tong Fuk Beach | *Gymnodinium* sp.1 |
| 23 | 5 May 1998 | 6 May 1998 | Deep Water Bay, near Ocean Park | *Cochlodinium polykrikoides* |
| 24 | 9 May 1998 | 11 May 1998 | Silver Mine Bay Beach | *Gyrodinium spirale* |
| 25 | 20 May 1998 | 21 May 1998 | Yim Tin Tsai Fcz, Inner Tolo Harbour | *Heterocapsa circularisquama* |
| 26 | 28 May 1998 | 1 June 1998 | Yim Tin Tsai (east and west) Fcz | *Leptocylindrus minimus*, *Skeletonema costatum*, *Thalassiosira* spp. |
| 27 | 5 June 1998 | 5 June 1998 | Cheung Sha Wan Fcz | *Thalassiosira* spp. |
| 28 | 15 June 1998 | 17 June 1998 | Cheung Sha Wan Fcz, Lo Tik Wan Fcz, East Lamma Channel | *Skeletonema costatum*, *Thalassiosira* spp. |
| 29 | 30 June 1998 | 30 June 1998 | Lo Tik Wan Fcz, East Lamma Channel | *Skeletonema costatum* |
| 30 | 24 August 1998 | 20 October 1998 | Port Shelter, Rocky Harbour | *Ceratium furca* |
| 31 | 16 September 1998 | 2 November 1998 | Inner Mirs Bay, Crooked Harbour, Double Haven | *Ceratium furca* |
| 32 | 1 November 1998 | 17 November 1998 | Beaches at Shek-O, Deep Water Bay, Tai Long Wan, Hair Pin Wan | *Mesodinium rubrum* |
| 33[a] | 17 November 1998 | – | Near the Pearl River mouth | *Gymnodinium* cf. *catenatum Graham* |
| 34 | 2 December 1998 | 3 December 1998 | Kat O Fisheries Department Substation | *Prorocentrum dentatum*, *Noctiluca scintillans* |
| 35 | 18 December 1998 | 26 December 1998 | Kat O Fisheries Department Substation, O Pui Tong Fcz | *Prorocentrum dentatum* |
| 36 | 18 December 1998 | 6 January 1999 | Sham Wan Fcz, Wong Shek Pier (Kau Tong Hau) | *Prorocentrum dentatum* |
| 37 | 21 December 1998 | 3 January 1999 | Yim Tin Tsai Fcz, Tai Po Hoi | *Cerataulina pelagica* |

[a] Number 33 is the algal bloom on 17 November reported in the present study.

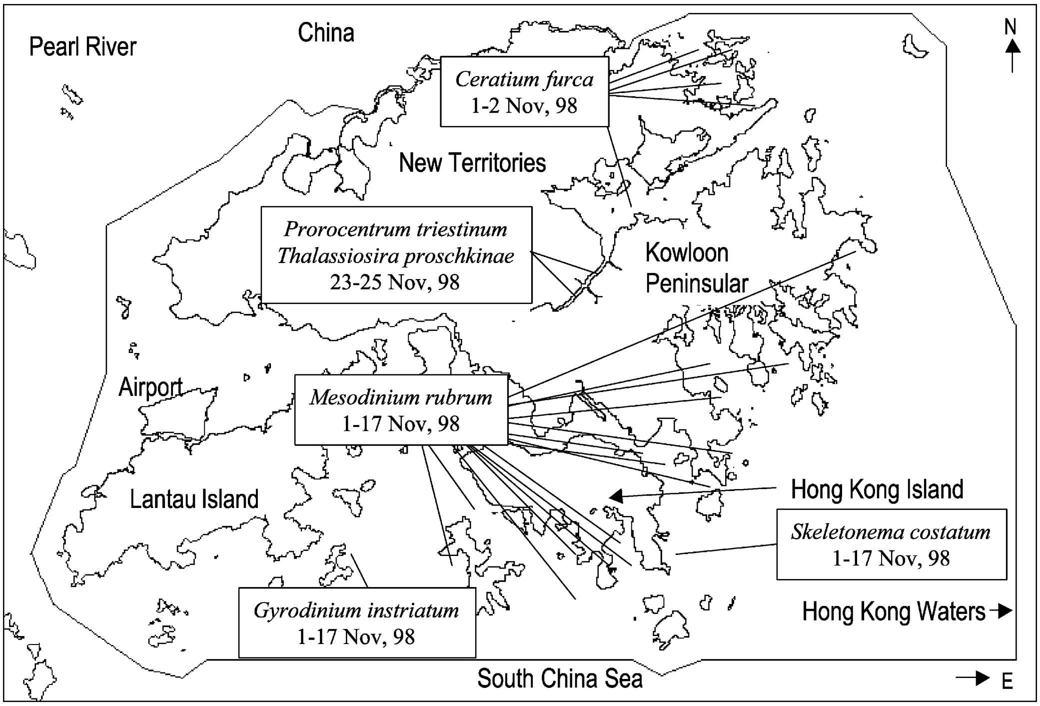


Fig. 8. Map of HABs distribution in Hong Kong waters in November 1998. The algal bloom we describe in this study was in the west to the Hong Kong waters (near Macao), which is not included in this map.

Phytoplankton blooms generally require adequate nutrient concentrations in the euphotic portions of the water column. Dinoflagellates, such as *Gymnodinium* cf. *catenatum*, as a group are capable of diel vertical migration, and are able to exploit nutrient-rich water below the euphotic zone, particularly when nutrient in the upper water column were depleted (Chang et al., 2001). Hong Kong lies on the coastal shelf of the northern South China Sea; the hydrography is mainly influenced by three factors: monsoon-affected ocean currents, Pearl River discharges, and tidal currents. Therefore, near the mouth of the Pearl River, nutrients are not a limiting factor because of high nutrient discharges from the Pearl River; water temperature plays an important role in the growth of phytoplankton. Algae usually have a spring peak when the water temperature increases from 24 to 25 °C. Yanagi et al. (1994) reported that it was at 25 °C when *Gymnodinium mikimotoi* bloomed in Japan. In this study, a dinoflagellate, *Gymnodinium* cf. *catenatum* bloomed in November when the water temperature was 24–25 °C, these bands were aligned in the north-south direction similar to the wind direction in the mixing front of Pearl River discharge waters with rich nutrients and the South China Sea waters with high temperature. The direction and speed of the wind may have been important factors in forming the linear bands of highly concentrated algal cells.

Water mass stratification has been considered the essential physical condition that dinoflagelltes require to bloom (Smayda, 2002). *Gymnodinium catenatum* bloom in New Zealand waters in 2000 coincided with the development of warm and presumable relatively stable surface water (Chang et al., 2001). The present study again supports these statements. In addition these physical and chemical features of the environment have also complicated biological factors influencing phytoplankton blooms as well as determining species that will dominate in the algal blooms. Our in situ measurements of Chl-a, temperature, salinity and oxygen show variations from the surface to depths of 6 m (Fig. 5), indicating stratified on this occasion. This stratification may be cause by freshwater input from the Pearl River; additionally, there were no strong winds during the algal bloom period that may also contribute to the water stratification.

### 4.3. Satellite remote sensing on HAB research

HABs have been reported in the Pearl River estuary but we need more evidence of the meteorological and oceanographic conditions that are associated with these HABs. Satellite imagery can provide records of environmental changes before, during, and after the algal bloom incidences. It can offer better interpretation of field survey in the context of overall temporal spatial patterns that may have rapidly varying conditions (Richard and Megan, 1997; Tang et al., 1999, 2002, 2003b). In the present study, the SST data are compatible with in situ measurements to determine the distribution of water properties in a larger area, indicating the HAB in front water area.

In this SeaWiFS image (Fig. 7), some pixels in the bloom area were masked out, and we are unable to establish a relationship between this bloom and features in the ocean color image. SeaWiFS imagery currently cannot discriminate between different algal classes and that the elevated Chl-a concentrations seen in the river plume are most likely contaminated by high concentration of colored dissolved organic mater. However, satellite images could help to detect the location and to estimate the spatial extend of the bloom with in situ measurements (Tang et al., 2002). This kind of research between in situ HAB observation and satellite data analysis is necessary. Satellite derived Chl-a data can be reprocessed by improved algorithms and new products may provide more information for HAB research in turbid coastal waters.

## 5. Conclusions

We observed a dinoflagellate *Gymnodinium* cf. *catenatum* Graham bloom at the Pearl River estuary in late autumn 1998 by analysis of in situ and satellite measurements. The bloom occurred along a mixing front between cold Peril River discharge water with rich nutrient and warmer SCS water with high salinity, where the water were stratified. The bloom area was about 20–30 $km^2$ with high density of $3.8 \times 10^7$ cells $l^{-1}$. Satellite images are helpful for observing the spatial variation of water temperature and the spatial extend of the bloom. This study may serve as an early warning that autumn PSP outbreak within the Pearl River estuary in fall could be possible in the future. Summary of HABs events in 1998 indicates more HABs occurred in the east water than in the west water in Hong Kong.

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