Available online at www.sciencedirect.com

SCIENCE DIRECT®

Advances in Space Research 37 (2006) 681–689

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

Satellite evidence of harmful algal blooms and related oceanographic features in the Bohai Sea during autumn 1998

DanLing Tang [a,*], Hiroshi Kawamura [b], Im Sang Oh [c], Joe Baker [d]

[a] *LED, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China*
[b] *Center for Atmospheric and Oceanic Studies, Graduate School of Science, Tohoku University, Japan*
[c] *Research Institute of Oceanography and School of Earth and Environmental Sciences, Seoul National University, Republic of Korea*
[d] *Office of Chief Scientist, DPI, Queensland, Australia*

Received 11 September 2004; received in revised form 12 April 2005; accepted 12 April 2005

Abstract

Harmful algal blooms (HABs) are truly global marine phenomena of increasing significance. Some HAB occurrences are different to observe because of their high spatial and temporal variability and their advection, once formed, by surface currents. A serious HAB occurred in the Bohai Sea during autumn 1998, causing the largest fisheries economic loss. The present study analyzes the formation, distribution, and advection of HAB using satellite SeaWiFS ocean color data and other oceanographic data. The results show that the bloom originated in the western coastal waters of the Bohai Sea in early September, and developed southeastward when sea surface temperature (SST) increased to 25–26 °C. The bloom with a high Chl-*a* concentration (6.5 mg m^{-3}) in center portion covered an area of 60×65 km^2. At the end of September, the bloom decayed when SST decreased to 22–23 °C. The HAB may have been initiated by a combination of the river discharge nutrients in the west coastal waters and the increase of SST; afterwards it may have been transported eastward by the local circulation that was enhanced by northwesterly winds in late September and early October.

Keywords: Harmful algal bloom (HAB); Satellite remote sensing; Oceanographic feature; Chl-*a*; SeaWiFS; Bohai Sea; China

1. Introduction

Harmful algal blooms (HABs) are regarded as one of serious marine disasters throughout the world. Some HABs can produce toxins that accumulate in shellfish and fish, which are unsuitable for human consumption. The toxins in some HABs do not threaten human health, but do harm marine organisms such as fish. Other HAB species are not toxic, but they may cause marine organisms to die due to mechanical damage to gills or due to depletion of dissolved oxygen in water. The nature and extent of the problems associated with HABs have become more prominent over the last several decades. However, it is difficult to quantify such outbreaks in order to document trends since there are so many different types of blooms with so many different effects (Anderson, 1989). High spatial and temporal variability of algal blooms make it difficult to monitor HABs by ship surveys alone. Insufficient oceanographic studies have limited our understanding of HABs.

The numbers of HAB events are recently found to be increasing in Chinese coastal waters in recent years. During autumn 1998, the largest HAB events were observed in the Bohai Sea (Figs. 1(A) and (C)) by water monitoring and aerial-photography in the northeastern waters of China; the HABs affected a large area of up to 8000 km^2 and caused the biggest economic loss in

* Corresponding author. Tel./fax: +86 20 89023203.
E-mail addresses: lingzistdl@yahoo.com, lingzistdl@126.cm (D.L. Tang).
URL: http://lingzis.51.net/ (D. Tang).

0273-1177/$30 © 2005 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2005.04.045

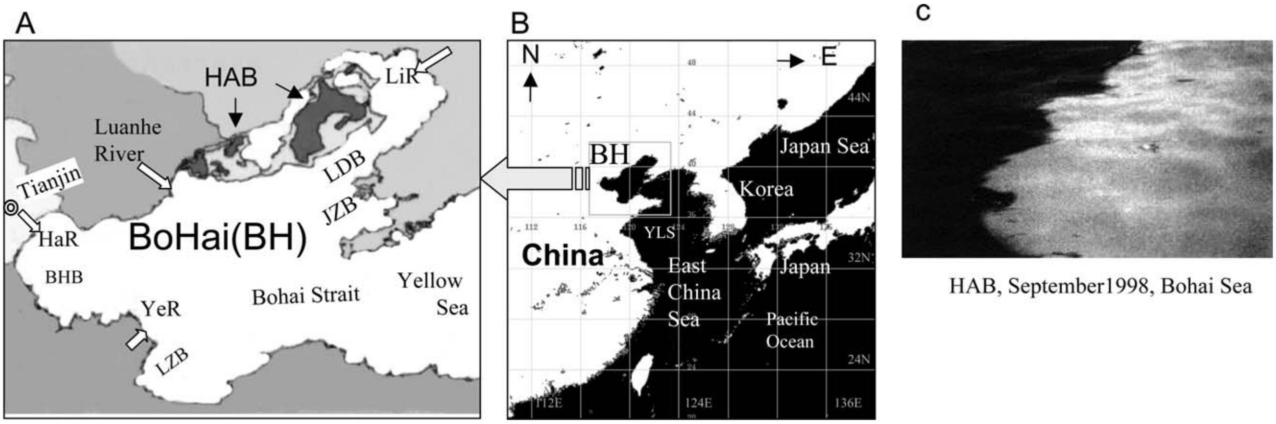

Fig. 1. (A) Location of HAB in the Bohai Sea in September 1998 (Redrawn from SOAC, 2003). Four rivers are identified and marked with white arrows: LiR: Liaohe River; LuR: Luanhe River; HaR: Haihe River; YeR: Yellow River. (B) The location of the Bohai Sea (small box BH). (C) HAB in Bohai Sea in September 1998 (Photographed by Fu, WC).

fisheries that has been recorded in the Bohai Sea, by killing fish and damaging aquaculture (NMDIS, 1998). During September–October, 1998, HABs covered an area more than 5000 km^2 in the northern Bohai Sea (HAB in Fig. 1(A); Hui, 2002), causing an economic loss of 12 million RMB (SOAC, 2001); During September 18–October 15, 1998, in the Bohai Sea, HABs covered an area of 5000 km^2 area caused an economic loss of 500 million RMB (EQB, 2000). During September 18–30, 1998, HAB was found to cover an area of 3000 km^2 in the Jinzhou Bay (NMDIS, 1998); On October 3, 1998, a large area of HABs (800 km^2) was observed in the Bohai Bay (NMDIS, 1998). Zhao et al. (2000) have reported HAB that lasted about two months from August 14 to October 19 in the Bohai Bay. We have found that some of these HAB events in the Bohai Sea are caused by the same algae species, *Ceratium furca*. Due to limited studies, it was not possible to understand the formation, evolution, and decomposition of algal blooms; and therefore we need detailed investigation for the entire area for a long period, for at least 2 months.

Remote sensing has long been considered an obvious tool for studying the distribution of HAB organisms over larger spatial scales and longer time scales than what is possible with ship-based sampling (Tester et al., 1991; Keafer and Anderson, 1993; Tang et al., 2003a,b, 2004a,b). A winter algal bloom was observed in the southwestern Luzon Strait by using Coastal Zone Color Scanner (CZCS) imagery (Tang et al., 1999); short-time variability of a phytoplankton bloom in the Arabian Sea was reported using Chlorophyll-*a* (Chl-*a*) images derived from the ocean color and temperature sensor (OCTS) (Tang et al., 2002). SeaWiFS-derived Chl-*a* data and sea surface temperature (SST) derived from the advanced very high resolution radiometer (AVHRR) were also utilized to monitor HABs in Hong Kong waters (Tang et al., 2003a), the South China Sea (Tang et al., 2004a), the Gulf of Mexico (Stumpf et al., 2003), and in New Zealand waters (Chang et al., 2003). The present study traced biological oceanic progress of these HABs by utilizing satellite remote sensing data together with oceanographic data. We took measurements over a time-frame long enough to show the relationships between some of the previously separate reports. Such an examination over the entire Bohai Sea for a relatively long period may enhance our knowledge of the formation, advection, and breakdown of HABs.

2. Methods and data

2.1. Study area

The Bohai Sea (Fig. 1(A)) has four major bays, with its east–west width about 300 km and north–south length about 550 km and an area of about 77,000 km^2. It exchanges waters with the northern Yellow Sea through a narrow strait called the Bohai Strait (Figs. 1(A) and (B)). The Bohai Sea is relatively shallow with an average depth of 20 m; the deepest part is in the Bohai Strait where the depth reaches 70 m. Four large rivers carry industrial and domestic wastewater discharged from several large cities in China, such as Tianjin (Fig. 1(A)). In the Bohai Bay, the coastal waters show moderate eutrophication throughout year, but the northern waters show heavy eutrophication in summer (Tao, 2002), and most HABs occur in this season.

The weather influencing the Bohai Sea is dominated by a strong northerly monsoon wind from late November to March that has an average speed of approximately 10 m s^{-1} in the month of January (Yuan and Su, 1984). In the Bohai Sea, seasonal water stratification appears early in April and breaks down at the end of

September. The circulation in the Bohai Sea is fairly complicated due to the temporal and spatial variation of forcing factors, i.e., tide, wind, and baroclinicity (Guan, 1994). In September, a decrease of SST usually results from the vertical mixing of water columns which is caused by the strong seasonal wind and the strong local tidal current in the Bohai Sea.

2.2. SeaWiFS ocean color images

The ocean color 4-band algorithm (OC4) (O'Reilly et al., 1998) has been used in the SeaWiFS Data Analysis System (SeaDAS) (version 4) to process available SeaWiFS-derived Chl-*a* images (1×1 km^2 spatial resolution) for the Bohai Sea for September 1998 when the HAB events occurred. We know that OC4 may not be adequate for quantitative analysis to coastal water, such as in the Bohai Sea, we focused our attention on HAB movement in the offshore waters. Masks (such as land masks and cloud mask) have been applied for every image, and flags have been considered as well.

2.3. AVHRR SST data from NOAA satellite

AVHRR SST data are processed for the period of the bloom in the Bohai Sea. These are images of local coverage with 1×1 km^2 spatial resolution processed through the MCSST algorithm (McClain et al., 1985) at Tohoku University (Sakaida et al., 2000). We selected the dates to match with Chl-*a* images that are processed for the HAB bloom.

2.4. Sea surface wind

Wind speed and direction over the ocean surface are retrieved from measurement of the QuikScat backscattered power (Wentz et al., 2001). QuikScat wind vector data are originally provided by the NOAA-CIRES Climate Diagnostics Center Boulder, Colorado, USA (NOAA, 2003); we processed weekly and monthly wind images for the period from August to November 1998, by using generic mapping tools graphics (GMT) (Wessel and Smith, 2002). The resolution of QuikScat wind vector is 100 km × 100 km for the open sea, and the size of Bohai Sea is 300 km by 550 km; With such limited wind data we can only get general information.

3. Results

3.1. Harmful algal blooms in the Bohai Sea

The Routine Water Monitoring Mission of the State Oceanic Administration of China (SOAC) and other Chinese institutions have observed several HAB outbreaks in the Bohai Sea by analyzing hydrographic data and aerial photographs. These records enabled us to compile a summary of HAB occurrences during autumn 1998 (Table 1) when there was a significant loss of commercial fish. The number of actual HAB events may be larger than those are given in Table 1 because some blooms, particularly the offshore blooms, may not have been observed by the hydrographic data and aerial photographs.

An extensive HAB (Fig. 1(A)), which was dominated by the marine dinoflagellate *Ceratium furca*, was reported by SOAC (2001) in western Liaodong Bay. We were able to obtain one SeaWiFS image (Fig. 2(C)) on September 15. High Chl-*a* concentrations (white arrow) are found in the HAB area (Fig. 2(C)), which matches well with the HAB reported in terms of location and date (Fig. 1(A)). The outbreak of *Ceratium furca* may reduce oxygen levels in the water, which may, in turn, lead to fish kills.

3.2. Spatial distribution of the algal bloom

We were able to obtain a series of SeaWiFS images for September 1998 (Fig. 2). At the beginning of September, Chl-*a* concentrations are found to be low in the entire Bohai Sea and somewhat higher along the coastal waters (Fig. 2(A)). On September 11, an algal plume (white arrow in Fig. 2(B)) appeared near the Luanhe River mouth (LuR, Fig. 2(B)). On September 15, this algal plume extended offshore, and the Chl-*a* concentration increased along the coast at the same time (Fig. 2(C)). The location of the bloom in Liaodong Bay matched well with in situ observations (Fig. 1(A); No. 7 in Table 1).

The algal bloom subsequently intensified and migrated in an offshore direction. An extensive bloom with high Chl-*a* concentrations is observed in the central portion of the northern sea on September 16 (Fig. 2(D)); it covers an area of about 60×65 km^2. The bloom moved eastward on 21 September (Fig. 2(E)). On the same day, a large algal bloom near the Jinzhou Bay (arrow in Fig. 2(E)) is detected based on Chl-*a* concentrations, and that also matches with the in situ data (No. 8 in Table 1). At the end of September, the bloom is found to disappear (Fig. 2(F)) and Chl-*a* concentrations decrease in the study area. This suggests that this HAB started from the west coastal water in the Bohai Sea. SeaWiFS images showing HAB events match well with the in situ observations.

3.3. Wind velocities and water temperature

Weekly wind data (Fig. 3) shows weak south to south–west winds (<3 m s^{-1}) in the last week of August 1998 (Fig. 3(A)), but Fig. 3(B) shows north-east winds in the first week of September. In the second week of September, the wind speed became higher by about 7 m s^{-1}

Table 1
Harmful algal blooms recorded by field surveys in the Bohai Sea during autumn 1998

No.	Match with Fig. 2	Time period	Location	Area (km^2)	Algal species	Cell/Chl-*a* concentration	Economic loss	References
1		August	Bohai Bay		*Chaetoceros* sp., *Coscinodiscus* sp., *Prorocentrum micans*	1.55×10^9 (cells m^{-3})		Tao (2002)
2		September 2	Laizhou Bay	300	*Ceratium furca*			SOAC (2002); Chang (2000)
3		August 15–September 10	Near Bohai Strait		*Gymnodinium* sp.		A lot	SOAC (2002)
4	B–E	September 16–October 19	Bohai		*Ceratium furca* (Ehrenberg)		12 million RMB	SOAC (2002)
5	B–E	September 18–30	Northern Bohai Sea	3000	*Ceratium furca* (Ehrenberg)			SOAC (2003)
6	B–E	September–October	Northern Bohai Sea	5000		Chl-*a*: 6.25 (mg m^{-3})		Hui (2002); Chang (2000)
7	D–E	September 29	Liaodong Bay		*Ceratium furca* (Ehrenberg)			SOAC (2002)
8	E	September 18–30	East area of Jinzhou Bay	3000	*Ceratium furca*			NMDIS (1998)
9	B–F	September 18–October 15	Bohai Sea	5000			500 million RMB (60 million US $)	EQB (2000)
10		October 3	Tianjin New Harbor	8000	*Ceratium furca* (Ehrenberg), and *Gonyaulax* sp.			NMDIS (1998)
11		October	Bohai Bay			0.2×10^9 (cells m^{-3})		Tao (2002)
12	A–F	August 14–October 19	West of West of Liaodong Bay to middle of Liodong Bay	10000	*Ceratium furca*	1.25×10^9 (cells m^{-3})		Zhao et al. (2000)

(Fig. 3(C)), and the direction change from easterly to strong northeasterly in the 4th week of September (Fig. 3(D)). To understand the wind condition for the season, we analyzed monthly wind images (Fig. 4) for the period from August to November 1998. The wind direction is found to change significantly in the fall season in the Bohai Sea: Northeasterly wind was observed during September (Fig. 4(B)), but northwesterly wind appeared during October (Fig. 4(C)).

The SST was not uniform in the Bohai Sea during September 1998 (Fig. 5). In general, water temperatures are found to be higher in the south compared in the north. In early September, high SSTs are observed along the southwest coast ("a" in Fig. 5(A)) and low temperatures along the northeast ("b" in Fig. 5(A)). High temperature waters (yellow in Fig. 5, around 25–27 °C) are found around the mouth of the Luanhe River (LuR in Fig. 5(A)) and the area with SST $\geqslant$ 25 °C expanded from the west coast to the central area (arrow in Fig. 5(A)). The SST is found to increase throughout the Bohai Sea from September 1 (Fig. 5(A)) to September 10 (26–27 °C) (Fig. 5(B)). The SST subsequently decreased along the east coast, and reached the lowest temperature (22 °C) at the end of September (Fig. 5(C)–(E)). The SST of the algal bloom area is found to be 25–26 °C (Fig. 5(B)).

4. Discussion

4.1. Algal blooms and water conditions in autumn in the Bohai Sea

Algal blooms generally require adequate nutrient concentrations, enough sunlight, and warm water temperatures for a specific species (Guerra-Martínez et al., 1995; Tang et al., 1998, 2003a,b, 2004a). Earlier studies for the Bohai Sea have indicated that the seasonal and spatial variation of algae and Chl-*a* concentration was closely correlated with environmental factors; if light conditions are similar, the main factors are found to be related with water temperature and nutrient levels (Tao, 2002). Ship surveys in the Bohai Sea during 1981 and 1982 have shown occurrence of highest pigment concentration during autumn (Lui et al., 1984); Ecological investigations in the year 1998 (Li and Tao, 2000) also show higher mean abundance of algal cells during August in the Bohai Bay. *Ceratium furca* is found as a typical marine dinoflagellate (Smalley and Coate, 2002), which is also found in a coastal lagoon of Mexico (Guerra-Martínez et al., 1995), where the cell abundance increased in brackish conditions (13–35‰) and at high temperature (30–34 °C). HABs of *Ceratium furca* have occurred several times along the coastal waters in China; cell concentration reached 6×10^4 L^{-1} in an HAB in southern China (Zhou and Lin, 1995).

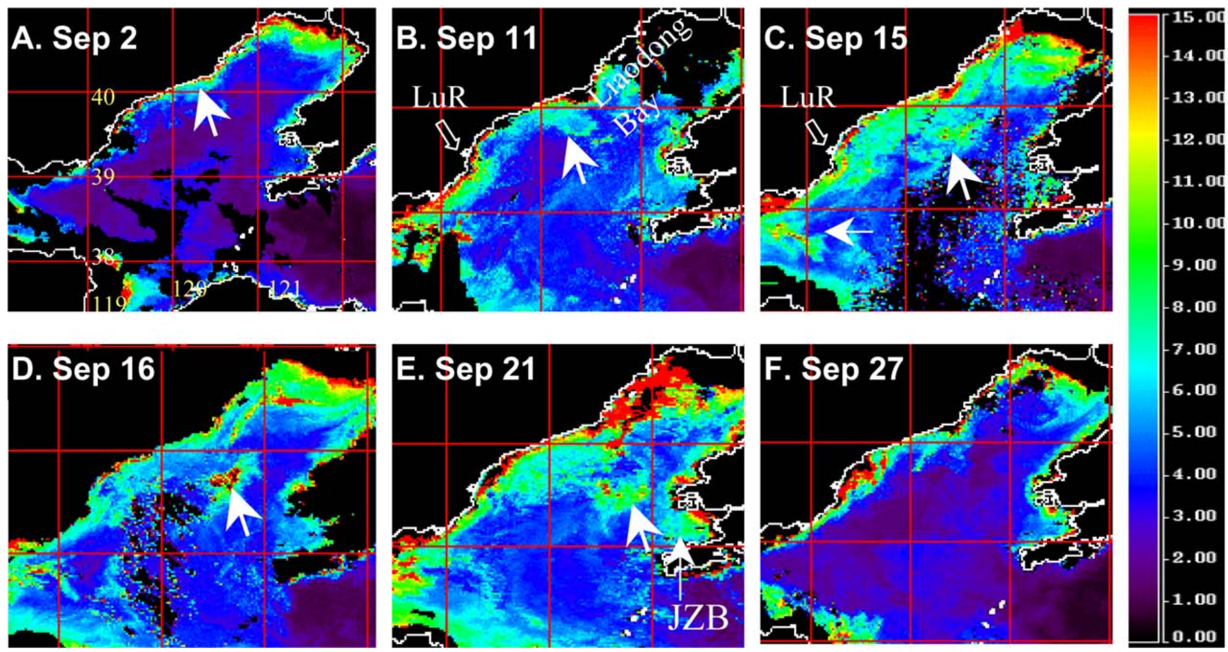

Fig. 2. (A–H). SeaWiFS images showing HAB with high Chl-*a* concentrations (white arrows) from west to east in the Bohai Sea in September 1998. LuR: Luanhe River.

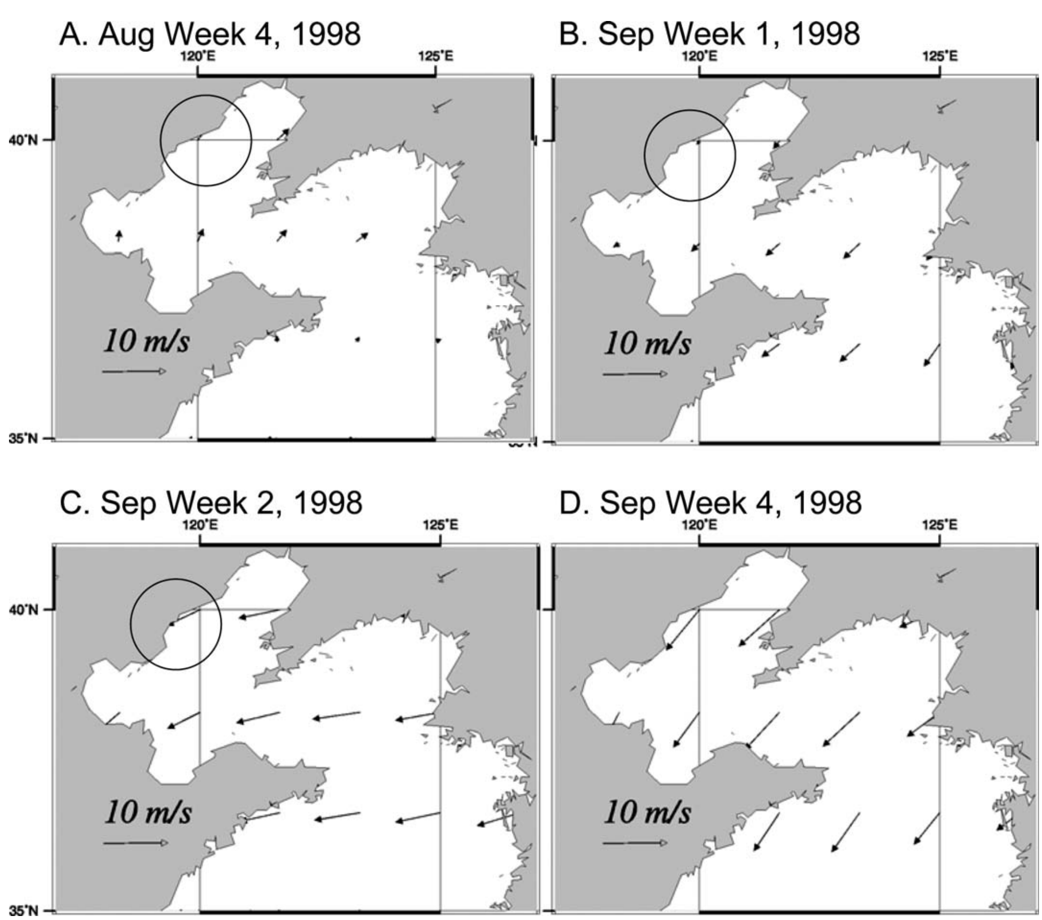

Fig. 3. Weekly wind images derived from QuikScat for the Bohai Sea in 1998, showing the wind changes in the HAB area. Arrows show wind speed and direction.

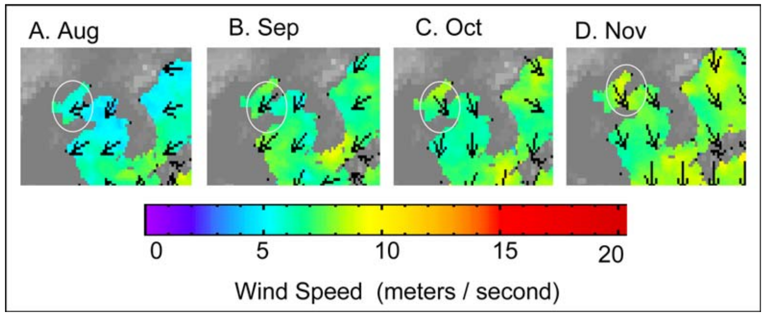

Fig. 4. Monthly wind conditions derived from QuikScat for the Bohai Sea in 1998, showing the transition of wind directions. Arrows show wind direction and colors display wind speed.

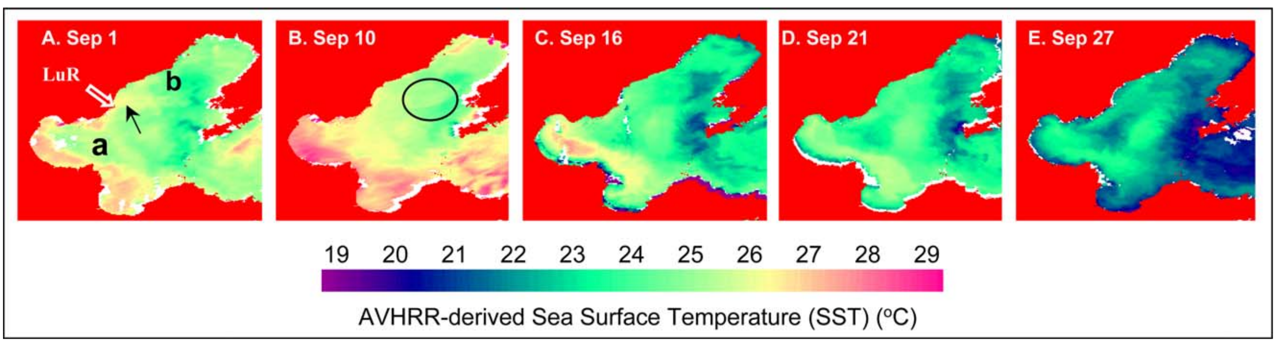

Fig. 5. SST maps in the Bohai Sea in 1998. Color bars show temperature, land is shown in red.

The historic record shows the averaged monthly discharge of the Luanhe river to be about 35.81 $m^3 s^{-1}$, with the highest discharge 82.88 $m^3 s^{-1}$ during June, and about 47.75 $m^3 s^{-1}$ during August from 1980 to 1983 (CSGE, 2003). The present results show that the 1998 HAB initiated along the coast near the Luanhe River mouth (Fig. 2(A) and (B)) in the Bohai Sea. When the Luanhe river water discharged into the west coastal waters of the semi-enclosed Bohai Sea, and the seawater temperature increased to 25–26 °C (Fig. 5(B)), the algal bloom occurred near the river mouth area and adjacent coastal waters (Fig. 2(B) and (C)), probably due to high eutrophication and bloom-favorable environmental conditions. Concentrations of N, P, and COD have high seasonality in the Bohai Sea; the highest level of inorganic N (0.2 mg L^{-1}) was observed during August to September (Zhou and Zhang, 2003). Earlier study made by Tang et al. (1998) has shown that the Bohai Sea, the only semi-enclosed sea, has the highest concentrations of pigments (Chl-*a*) during 1979–1986 compared to the East China Sea and the South China Sea. Additionally, because of the change of wind direction and the increase of wind speed (Fig. 3), stratification was broken down in the second half of September in the Bohai Sea (Huang et al., 1999), and therefore nutrients might have been brought to the surface causing expansion and intensification of the algal bloom (Figs. 2(C)–(E)).

Stable and high level SST is one of the reasons for the algal bloom. At the end of September, the SST is found to decrease to about 22–23 °C (Fig. 5(E)) due to the strong northeasterly wind, and as a result, the bloom decayed. We know that sea water temperature has a high correlation with air temperature. During 1998 in the Bohai Sea area, air temperatures in the months of late August and early September was found to be higher compared to other years (Zhou et al., 1997; Gong et al., 2000). But at the end of September, low sea water temperature (Fig. 5(E)) due to strong vertical mixing of water column induced by the northwesterly wind (Figs. 3(D) and 4(B)) may reduce the phytoplankton bloom. The other possibility is that the depletion of available nutrients may also limit phytoplankton bloom in the offshore waters of the Bohai Sea at the end of September (Fig. 2(F)).

4.2. Algal bloom distribution from west to east

The present study shows the algal blooming from the west coast to the east of the Bohai Sea during 1998, and lasted more than 1 month. The Bohai Sea circulation consists of three components, namely, the warm current extension (WCE) entering the Bohai Sea from the northern Yellow Sea, the Liaodong Coastal Current, and the Southern Bohai Coastal Current (Guan, 1994) (Fig. 6). The WCE is a leading component of the circulation. It

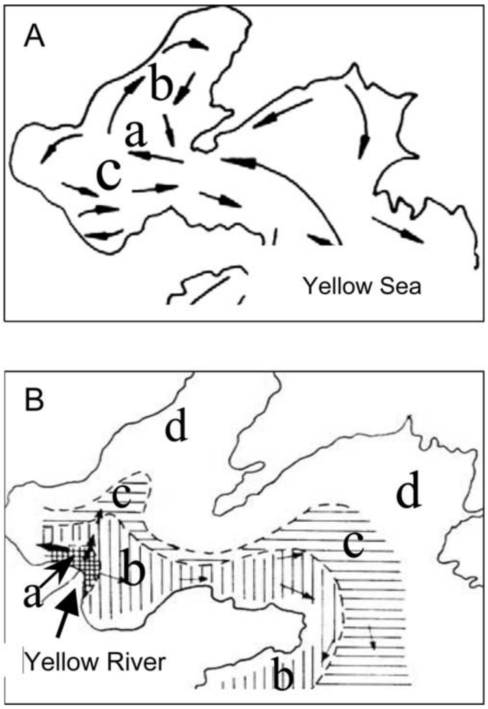

Fig. 6. (A) Bohai Sea Circulation in the Bohai Sea (Redrawn from Guan, 1994). (a) Warm Current Extension (WCE); (b) Liaodong Coastal Current; (c) Southern Bohai Coastal Current. (B) Distribution of sediment loads discharged from Yellow River (Redrawn from Qin, 1994). (a) strong; (b) medium; (c) weak; (d) no influence. Arrows indicate direction of sediment transport.

enters the Bohai Sea like a jet ("a" in Fig. 6), moves westward along the central part of the Bohai before encountering the coast, and separates into two branches. One branch moves toward the Liaodong Bay to form an anti-cyclonic gyre ("b" in Fig. 6(A)), and the other branch moves toward the Bohai Sea to form a cyclonic gyre ("c" in Fig. 6(A)). The long-term conditions are controlled by clockwise circulation (Guan and Chen, 1964). In the northern Bohai Sea, HAB may occur eastward from the currents and disappear when the available nutrients are exhausted.

The frontal zone between river discharge water and seawater may provide suitable conditions for an algal bloom. A "frontal HAB" between Pearl River discharge water and the South China Sea water was observed in the northern South China Sea (Tang et al., 2003b). In the present observation, algal bloom occurred and moved along with the frontal waters between the Luanhe River discharge plume and the coastal current (Fig. 2).

4.3. Tracing the movement of HAB by satellite

In many cases, it is difficult to trace algal blooms from the data by ship survey as we have discussed in Sections 1 and 4.1. Some HAB events, particularly offshore blooms, might not be identified. A single moving bloom might be recorded as multiple blooms; there were also some other separate HABs, such as the bloom in October in the Bohai Bay. The present study shows a series of Chl-*a* images that coincided with HABs reported by various in situ observations (Table 1).

The ocean color of coastal waters are influenced not only by algae and related particles, but also by other substances. The SeaWiFS-derived color values may also vary independently of algae, notably due to inorganic particles in suspension and yellow substances particularly in the river mouth (Sathyendranath, 2000; Tang et al., 2004). In the Bohai Sea, the Yellow River (YeR in Fig. 1(A)), located in the southern Bohai Sea, is a major source of sediment into the sea (Fig. 6(B)) (Qin, 1994). Its influence is greater in the Yellow River mouth area and along the south coastal water than that in the northern Bohai Sea (Figs. 1(A) and 6(B)). The HAB during 1998 occurred in the northern sea and moved to offshore waters (Figs. 2 and 3), satellite images are comparable with in-situ observation in terms of location and Chl-*a* concentration level (Table 1). The present study clearly shows an advantage of satellite images in mapping the development of HABs in offshore waters.

5. Conclusion

SeaWiFS-derived Chl-*a* data have been applied successfully in mapping of HABs in the Bohai Sea during autumn 1998. A series of images have revealed the development, distribution, and movement of HABs, comparable with ship observations. This represented examples of evidence of HAB and related oceanographic features by satellite imagery. The present study suggests that the high SST and weak wind may be important for the algal bloom, and HAB biomass could be transported distances in the sea.

Acknowledgements

This research was jointly supported by (1)"One Hundred Talents Program" of the Chinese Academy of Sciences, China; (2) Guangdon Nature Science Foundation (China) (04001306) to Dr. D.L. Tang; and (3) Special Coordination Found For Promoting Science and Technology "Red-Tide Watches", MEXT, Japan. QuikScat data were produced by the Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team. Dr. F. Sakaida, Tohoku University has helped in making SST data available to us.

References

Anderson, D.M. Toxic algal blooms and red tides: a global perspective. in: Okaichi, T., Anderson, D.M., Nemoto, T. (Eds.), Red

Tides: Biology Environmental Science and Toxicology. Elsevier, N.Y., pp. 11–16, 1989.

Chang, F.H., Richardson, K., Pinkerton, M., Uddstrom, M. Feasibility of monitoring of major HAB events in New Zealand using satellite remote ocean color and SST images, in: Workshop on Red Tide Monitoring in Asian Coastal Waters, Tokyo University, Japan, pp. 106–108, 2003.

Chang, Z. Chinese Marine Disaster Bulletin. The State Oceanic Administration of China, 2000.

CSGE (Center for Sustainability and the Global Environment). River Discharge Database. Gaylord Nelson Institute of Environment Studies, University of Wisconsin-Madison, 2003. Available from: <http://www.sage.wisc.edu/riverdata/>.

EQB. Environment Quality Bulletin, Beijing, China, 2000 (in Chinese).

Fu, W.C. Available from: <www.people.com.cn/GB/huanbao/56/20020208/643421.html>.

Gong, Q., Zhan, S., Liu, Y., Han, X.S. Study on red tide occurred in Bohai Bay in 1998 and relationship between red tide and the weather conditions. in: Zao, D.Z. (Ed.), Paper Collection of Red Tide Research for the Bohai Sea. China Ocean Press, Beijing, pp. 71–76, 2000 (in Chinese).

Guan, B.X., Chen, S.J. The Current System in the Near-sea of China Seas, pp.1–85, 1964 (in Chinese).

Guan, B.X. Patterns and structures of the currents in Bohai, Huanghai and East China Sea. in: Zhou, D., Liang, Y.B., Zhen, C.K. (Eds.), Oceanology of China Seas, vol. 1. Kluwer Academic Publishers, AA Dordrecht, The Netherland, pp. 17–26, 1994.

Guerra-Martínez, Sandra Luz Lara-Villa, Miguel Angel. Florecimiento de *Ceratium furca* (Peridiniales: Ceratiaceae) en un ambiente salobre: Laguna de Sontecomapan, México, 1995.

Huang, D.J., Su, J.L., Backhaus, J.O. Modeling the seasonal thermal stratification and baroclinic circulation in the Bohai Sea. Cont. Shelf Res. 19, 1489–1505, 1999.

Hui, S.T. The progress of China ocean harmful algal blooms monitoring technology, in: Proceedings of the International Workshop on Coastal Eutrophication, Tianjin University, pp. 48–66, 2002.

Keafer, B.A., Anderson, D.M. Use of remotely-sensed sea surface temperatures in studies of *Alexandrium tamarense* bloom dynamics. in: Smayda, T.M., Shimizu, Y. (Eds.), Toxic Phytoplankton in the Sea, Proceedings of the 5th International Conference. Elsevier, Amsterdam, pp. 763–768, 1993.

Li, Q.X., Tao, J.H. Studies on ecological characteristics of phytoplankton in waters near Tianjin. J. Tianjin University 33 (4), 464–469, 2000 (in Chinese).

Lui, P.D., Fei, Z.L., Mao, X.H., Zhu, M.Y., Zhan, C., Wong, Y.X., Lee, B.H., Xia, B. Estimation of primary productivity and distribution of Chlorophyll-*a* in Bohai. Acta Oceanol. Sin. 6 (1), 90–98, 1984 (in Chinese).

McClain, E.P., Pichel, W.G., Walton, C.C. Comparative performance of AVHRR-based multichannel sea surface temperatures. J. Geophys. Res. 90, 11587–11601, 1985.

NMDIS (National Marine Date and Information Service). Chinese Marine Disaster Bulletin, Tianjin, China, 1998. Available from: <http://www.pemsea-bohai.net.cn/zhxx/1998p.htm>.

NOAA, 2003. Availabe from: <http://www.cdc.noaa.gov/>.

O'Reilly, J.E., Maritorena, S., Mitchell, B.G., Siegel, D.A., Carder, K.L., Garver, S.A., Kahru, M., McClain, C. Ocean color chlorophyll algorithms for SeaWiFS. J. Geophys. Res. 103, 24937–24953, 1998.

Qin, Y.-S. Sedimentation in northern China Seas. in: Zhou, D., Liang, Y.B., Zhen, C.K. (Eds.), Oceanology of China Seas, vol. 1. Kluwer Academic Publishers, AA Dordrecht, The Netherland, pp. 395–406, 1994.

Sakaida, F., Kudoh, J.-I., Kawamura, H. A-highers – The system to produce the high spatial resolution sea surface temperature maps of the western North Pacific using the AVHRR/NOAA. J. Oceanogr. 56, 707–716, 2000.

Sathyendranath, S. General introduction. in: Sathyendranath, S. (Ed.), Remote Sensing of Ocean Color in Coastal, and Other Optically Complex Waters. International Ocean-Color Coordinating Group, Nova Scotia, Canada, pp. 5–21, 2000.

Smalley, G.W., Coate, D.W. Ecology of the red-tide dinoflagellate *Ceratium furca*: distribution, mixotrophy, and grazing impact on ciliate populations of Chesapeake Bay. J. Eukaryot. Microbiol. 49 (1), 63–73, 2002.

SOAC. China Ocean Yearbook 1999–2000. The State Oceanic Administration of China. China Ocean Press, Beijing, pp. 349–350, 2001 (in Chinese).

SOAC. Available from: http://www.soa.gov.cn/chichao/2002hyzh/index.html, 2002.

SOAC. Available from: <http://www.china-hab.ac.cn/english/ccls/sjtp.htm>, 2003.

Stumpf, R.P., Culver, M.E., Tester, P.A., Tomlinson, M., Kirkpatrick, G.J., Pederson, B.A., Truby, E., Ransibrahmanakul, V., Soracco, M. Monitoring *Karenia brecis* blooms in the Gulf of Mexico using satellite ocean color imagery and other data. Harmful Algae 35, 1–14, 2003.

Tang, D.L., Kawamura, H., Lee, M.A., Dien, T.V. Seasonal and spatial distribution of chlorophyll-*a* concentrations and water conditions in the Gulf of Tonkin, South Chins Sea. Remote Sens. Environ. 85 (4), 475–483, 2003a.

Tang, D.L., Kawamura, H., Doan-Nhu, H., Takahashi, W. Remote sensing oceanography of a harmful algal bloom (HAB) off the coast of southeastern Vietnam. J. Geophys. Res. (Ocean) 19, 2004a.

Tang, D.L., Kester, D.R., Ni, I.-H., Qi, Y.Z., Kawamura, H. In situ and satellite observations of a harmful algal bloom and water condition at the Pearl River Estuary in late autumn 1998. Harmful Algae 2, 89–99, 2003b.

Tang, D.L., Kawamura, H., Luis, A.J. Short-term variability of phytoplankton blooms associated with a cold eddy on the North-western Arabian Sea. Remote Sens. Environ. 81 (1), 82–89, 2002.

Tang, D.L., Ni, I.-H., Müller-Karger, F.E., Liu, Z.J. Analysis of annual and spatial patterns of CZCS-derived pigment concentrations on the continental shelf of China. Cont. Shelf Res. 18, 1493–1515, 1998.

Tang, D.L., Ni, I.-H., Kester, D.R., Müller-Karger, F.E. Remote sensing observation of winter phytoplankton blooms southwest of the Luzon Strait in the South China Sea. Mar. Ecol.-Prog. Ser. 191, 43–51, 1999.

Tang, D.L., Ni, I-H., Müller-Karger, F.E., Oh, I.S. Monthly variation of pigment concentrations and seasonal winds in China's marginal seas. Hydrobiologia 511, 1–15, 2004b.

Tao, J.H. Eco-hydrodynamic characters of Bohai Bay, in: Proceedings of Second International Workshop on Coastal Eutrophication, Tianjin University, pp. 15–24, 2002.

Tester, P.A., Stumpf, R.P., Vukovich, F.M., Fowler, P.K., Turner, J.T. An expatriate red tide bloom: transport, distribution, and persistence. Limnol. Oceanogr. 36, 1953–1961, 1991.

Wentz, F.J., Smith, D.K., Mears, C.A., Gentemann, C.L. Advanced Algorithms for QuikScat and SeaWinds/AMSR. in: IGARSS'01 Proceedings 2001. NASA, USA, 2001.

Wessel, P., Smith, W.H.F. The Generic Mapping Tools, Version 3.4.1. A Map-Making Tutorial. NOAA/NESDIS/NODC, USA, pp. 1–33, 2002.

Yuan, Y., Su, J. Numerical modelling of the circulation in the East China Sea. in: Ichiy, T. (Ed.), Ocean Hydrodynamics of the Japan and East China Seas, Elsevier Oceanogr. Ser., vol. 39. Elsevier, New York, pp. 167–186, 1984.

Zhao, D.Z., Cong, P.F., Zhao, L., Zhang, F.S., Guo, H., Cheng, Z.L., Fu, Y. Study on the behaviour process of the Bohai Sea red tide in

1998. in: Zao, D.Z. (Ed.), Paper Collection of Red Tide Research for the Bohai Sea. China Ocean Press, Beijing, pp. 60–66, 2003 (in Chinese).

Zhou, J.M., Lin, Y.S. HAB in Dapeng Bay. in: Proceedings (I) of SCOR-IOC. China Ocean Press, Beijing, China, 1995 (in Chinese).

Zhou, J.Z., Zhang, C. Bohai Bay. in: Qi, Y., et al. (Eds.), Harmful Algae Bloom in China Coast. Science Press, Beijing, China, pp. 104–115, 2003 (in Chinese).

Zhou, S.L, Chen, J.F, Ma, S.S., Zhao, J. The Hydrological environment and variation feature of environment in Bohai Sea. Mar. Fish. Res. 18 (2), 86–100, 1997.