Available online at www.sciencedirect.com
SciVerse ScienceDirect
Journal of Hydro-environment Research 6 (2012) 239–247
Journal of Hydro-environment Research
www.elsevier.com/locate/jher

Research paper

Spatial and temporal variations in algal blooms in the coastal waters of the western South China Sea

ChunLi Liu [a], DanLing Tang [b,*]

[a] Marine college, Shandong University at Weihai, 180 West Wenhua Road, Weihai 264209, PR China
[b] Center of Remote Sensing on Marine Ecology/Environment, South China Sea Institute of Oceanology, Chinese Academy of Sciences, 164 West Xingan Road, Guangzhou 510301, PR China

Received 14 January 2009; revised 11 May 2011; accepted 3 February 2012

Abstract

Algal blooms occur frequently in the coastal waters of the western South China Sea (SCS). This paper reports spatial and temporal variations of algal bloom events in these waters from 1993 to 2007. Twenty-five algal bloom events occurred in summer in the coastal waters of South and Central Vietnam where they were associated with wind-induced, coastal, nutrient upwelling and river discharges; a further eight events occurred in the coastal waters of North Vietnam. A greater number of algal bloom events were observed in 1999 and 2002, and were accompanied by several previously unobserved species for the study period. These events may be related to the El Niño events of 1998 and 2002. Furthermore, the bloom-causative species *Trichodesmium erythraeum* (Cyanophyta) entirely dominated the phytoplankton community of algal blooms during 1993–1999 whereas the species *Phaeocystis globosa* (Haptophyta) dominated blooms after 2002. This study establishes a basis for further long-term research of algal bloom event variations, and provides a compiled scientific reference that may be used for later prediction of Harmful algal blooms (HABs).

Keywords: South China Sea; Algal blooms; Spatial and temporal variations; Upwelling; Sea surface temperature

1. Introduction

During the latter part of the twentieth century and the beginning of the twenty-first century, the occurrence of algal blooms has generally increased in global coastal waters (Glibert et al., 2005) and specifically in the coastal waters of the western South China Sea (SCS). In coastal waters of Binh Thuan Province (BTP), blooms of *Phaeocystis globosa* have been recorded in 2002 and between 2005 and 2008.

Knowing the conditions that may have caused past algal blooms may help in predicting future events. For example, an extensive spatial and temporal study of blooms occurring in 2007–2008 connected their development with changes in plankton communities and nutrient stoichiometry (Doan-Nhu et al., 2010). It would be advantageous to be able to use remote sensing to detect these changing conditions to predict and/or detect algal blooms within large areas (Cullen et al., 1997) Combining past reports of the distribution patterns of algal bloom events and concurrent satellite information could refine the mapping of HABs from remotely sensed data (Dien et al., 2003; Tang et al., 2003, 2004a, 2004b). Therefore, we present spatial and temporal variations of algal bloom events with relevant remotely sensed data.

2. Study area and data

2.1. Study area

The study area was in the coastal waters of the western SCS (Fig. 1A, red box in Fig. 1B), within which the Vietnamese

* Corresponding author. Tel./fax: +86 20 89023203.
E-mail addresses: chunliliu@sdu.edu.cn (ChunLi Liu), lingzistdl@126.com, liuchunli@china.com.cn (DanLing Tang).

1570-6443/$ - see front matter © 2012 International Association for Hydro-environment Engineering and Research, Asia Pacific Division. Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.jher.2012.02.002

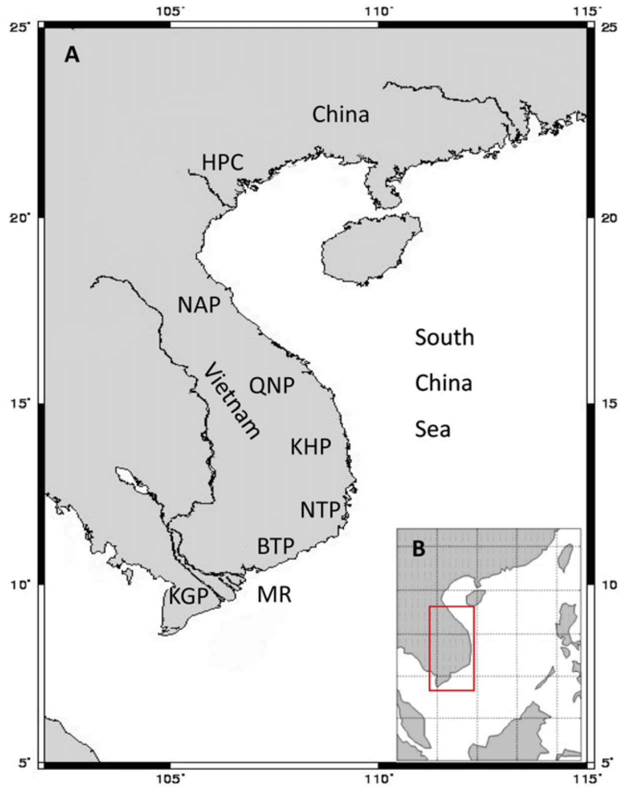

Fig. 1. (A) Geographical location of coastal waters of the western South China Sea (SCS). HPC, Hai Phong City; NAP, Nghe An Province; QNP, Quang Ngai Province; KHP, Khanh Hoa Province; NTP, Ninh Thuan Province; BTP, Binh Thuan Province; KGP, Kien Giang Province; MR, Mekong River mouth. (B) The location of our study area in the western SCS (Rectangular box).

marine waters, bordering a long coastline, merge with the SCS. The seasonally reversing monsoon wind of this East Asian monsoon region affects the local hydrology (Pan et al., 2002); the southwest (summer) monsoon lasts from June to September, while the stronger northeast (winter) monsoon occurs from November to March and is known to vary with the Southern Oscillation Index (Zhang et al., 1997).

2.2. Data

2.2.1. Algal blooms data collection and analysis

Official records of algal bloom events may be incomplete but we compiled a total of 33 historical algal bloom events occurring between 1993 and 2007 (Table 1), from various sources including symposia reports, research journals, Chinese and Vietnamese government statistics and other public data sources. Reported algal bloom events often give no exact record of the size of the affected area. Therefore, we considered only the occurrence within a broad region, the seasonal frequency, and the causative species of the algal blooms.

2.2.2. SeaWiFS-derived Chl-a

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) derived Chl-a images, with 1×1 km^2 monthly and seasonal spatial resolution, were processed with the SeaWiFS Data Analysis System (SeaDAS) using the Ocean Color 4-band algorithm (O'Reilly et al., 1998). The SeaWiFS Chlorophyll a Algorithms were used to validate with *in situ* data in SCS. For Chl-a between 0.1 and 10 mg m^{-3}, SeaWiFS agreed well with *in situ* data (Zhang et al., 2006; Pan et al., 2010). In the study, to investigate the temporal variation of Chl-a, we processed a series of monthly and seasonally averaged Chl-a images for the study area.

3. Results

3.1. Spatial distribution of algal blooms

The spatial distribution of algal bloom events varied considerably among the sampling sites from 1993 to 2007 (Fig. 2 and Table 1). Among the seven regions where the algal bloom events occurred, the highest frequency, with nine events, was found in the coastal waters of BTP. The second most frequent occurrence, with seven events, was observed in the coastal waters of NTP and Hai Phong City (HPC). The least frequent, with just one event, was observed in the coastal waters of Nghe An Province (NAP). In general, most algal bloom events (25) occurred in the coastal waters of South and Central Vietnam, where algal blooms have been reported in many previous studies (Nguyen et al., 1997; Nguyen, 1999; Tang et al., 2004b), while fewer events (eight) occurred in the coastal waters of North Vietnam. During the period of 1993–1999, the algal bloom events mainly occurred in the coastal waters of BTP in the South and Central Vietnamese region and those of HPC in the North Vietnamese region (Fig. 3A). This contrasts with the years 2002–2007, when many algal blooms were observed in the coastal waters of NTP in the South Central Vietnamese region (Fig. 3B).

Furthermore, the occurrence of algal bloom events had different seasonal distributions regionally (Fig. 3A and B). In the coastal waters of North Vietnam, algal bloom events were recorded throughout the year. However, in the coastal waters of South Central Vietnam, the algal bloom events were mainly observed during the March to July period with the exception of the coastal waters of Kien Giang Province (KGP).

3.2. Yearly variation of algal blooms

Not every year had reported sightings of algal blooms (Fig. 4). The most frequent annual algal bloom occurrences (nine events) were in 1999 and 2002, and these occurrences accounted for more than half of all the events recorded in the study period. Notably, algal bloom events were not observed in the intervening years of 2000 and 2001.

3.3. Seasonal variation of algal blooms and chl-a

The algal bloom events were observed in every month except in October (Fig. 5A). The highest monthly frequency (nine events) occurred in July, and the second highest (six events) in March. Among the nine algal blooms that occurred in 1999, one event occurred in March in each of the coastal waters of BTP, NTP and Quang Ngai Province (QNP) while

Table 1
Algal bloom events during 1993–2007.

Event	Year	Month	Location	Species	Phylum
1	1993	March	Binh Thuan Province	*Trichodesmium erythraeum*	Cyanophyta
2	1995	February	Khanh Hoa Province	*Noctiluca scintillans*	Dinophyta
3	1995	February	Khanh Hoa Province	*Noctiluca scintillans*	Bacillariophyta
4	1995	May	Binh Thuan Province	*Trichodesmium erythraeum*	Cyanophyta
5	1996	March	Binh Thuan Province	*Trichodesmium erythraeum*	Cyanophyta
6	1996	March	Khanh Hoa Province	*Noctiluca scintillans*	Dinophyta
7	1996	April	Binh Thuan Province	*Trichodesmium erythraeum*	Dinophyta
8	1996	May	Binh Thuan Province	*Trichodesmium erythraeum*	Dinophyta
9	1996	June	Binh Thuan Province	*Trichodesmium erythraeum*	Haptophytes
10	1996	July	Binh Thuan Province	*Trichodesmium erythraeum*	Dinophyta
11	1998	July	Hai Pong City	*Skeletonema costatum*	Xanthophyta
12	1999	January	Hai Pong City	*Skeletonema costatum*	Xanthophyta
13	1999	March	Binh Thuan Province	*Trichodesmium erythraeum Trichodesmium thiebautii*	Cyanophyta
14	1999	March	Ninh Thuan Province	*Trichodesmium erythraeum; Trichodesmium thiebautii*	Cyanophyta
15	1999	March	Quang Ninh Province	*Dinophysis caudata*	Dinophyta
16	1999	May	Hai Pong City	*Prorocentrum minimum*	Dinophyta
17	1999	May	Quang Ninh Province	*Prorocentrum minimum*	Dinophyta
18	1999	July	Hai Pong City	*Skeletonema costatum*	Xanthophyta
19	1999	November	Hai Pong City	*Guinardia delicat ula*	
20	1999	December	Hai Pong City	*Prorocentrum minimum*	Dinophyta
21	2002	January	Hai Pong City	*Prorocentrum minimum*	Dinophyta
22	2002	June	Ninh Thuan Province	*Phaeocystis globosa*	Haptophyta
23	2002	July	Binh Thuan Province	*Phaeocystis globosa*	Haptophyta
24	2002	July	Nghe An Province	*Ceratium furca*	Dinophyta
25	2002	July	Quang Ninh Province	*Ceratium furca*	Dinophyta
26	2002	July	Khanh Hoa Province	*Heterosigma sp*	Xanthophyta
27	2002	July	Ninh Thuan Province	*Phaeocystis globosa*	Haptophyta
28	2002	July	Ninh Thuan Province	*Phaeocystis globosa*	Haptophyta
29	2002	December	Kien Giang Province	*Microcystis sp*	Cyanophyta
30	2003	August	Kien Giang Province	*Microcystis sp*	Cyanophyta
31	2005	August	Ninh Thuan Province	*Phaeocystis globosa*	Haptophyta
32	2006	August	Ninh Thuan Province	*Phaeocystis globosa*	Haptophyta
33	2007	September	Ninh Thuan Province	*Phaeocystis globosa*	Haptophyta

Sources: Doan et al. (2002), Nguyen and Doan (1996), Nguyen (1999), Nguyen et al., (2003), Tang et al., (2004a), Wang et al., (2008).

one event occurred in May in the waters of HPC and QNP. The remaining four events occurred in January, July, November, and December, and all occurred in the coastal waters of HPC. In 2002, when nine algal bloom events were also observed, five individual events occurred in July in the coastal waters of BTP, NAP, QNP, Khanh Hoa Province (KHP), and NTP, while one was noted in January (HPC), one in June (NTP), and one in December (KGP).

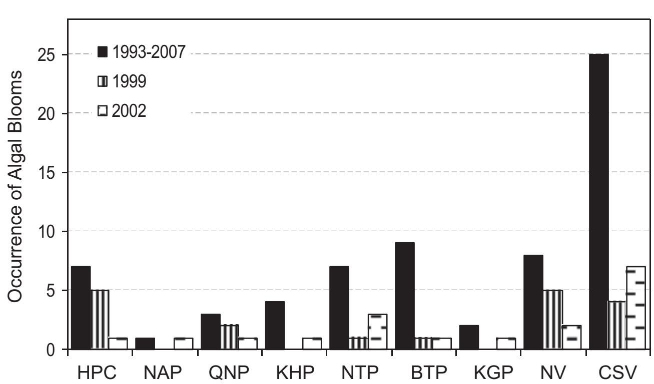

Fig. 2. Algal blooms frequencies for different regions during the entire period from 1993 to 2007, and during the years 1999 and 2002 separately. NV, North Vietnam (consisting of Hai Phong City (HPC) and Nghe An Province (NAP)); SCV, South Central Vietnam (consisting of the provinces of Quang Ngai (QNP), Khanh Hoa (KHP), Ninh Thuan (NTP), Binh Thuan (BTP) and Kien Giang (KGP)).

Monthly averaged SeaWiFS Chl-a images (Fig. 6) revealed significant associations with the reported bloom data (Table 1). For example, high Chl-a concentrations are notable for March, 1999, in the coastal waters of BTP, NTP and QNP (Fig. 6A) in which waters blooms had been reported for that time (Table 1). Similarly, the image for May, 1999, shows relatively higher Chl-a concentrations in the coastal waters of HPC and QNP (Fig. 6B) coinciding with reported blooms (Table 1). Similarly, in July and December, 1999, the higher Chl-a concentrations in the waters of HPC corresponded to two observed blooms and in July, 2002, high Chl-a concentrations in the waters of BTP, KHP and NTP coincide with the time and places of observed HAB occurrences.

Seasonally, occurrences of the 33 algal blooms (Fig. 5B) were more likely in summer (14) (June to August), and then spring (11) (March to May), winter (6) (December to February) and autumn (2) (September to November). Images of seasonally averaged Chl-a concentrations for 1999 and 2002 (Fig. 7) showed obvious seasonal variations in the western SCS. In the summer, bands of high concentrations of Chl-a are evident that occurred parallel to the coastline and

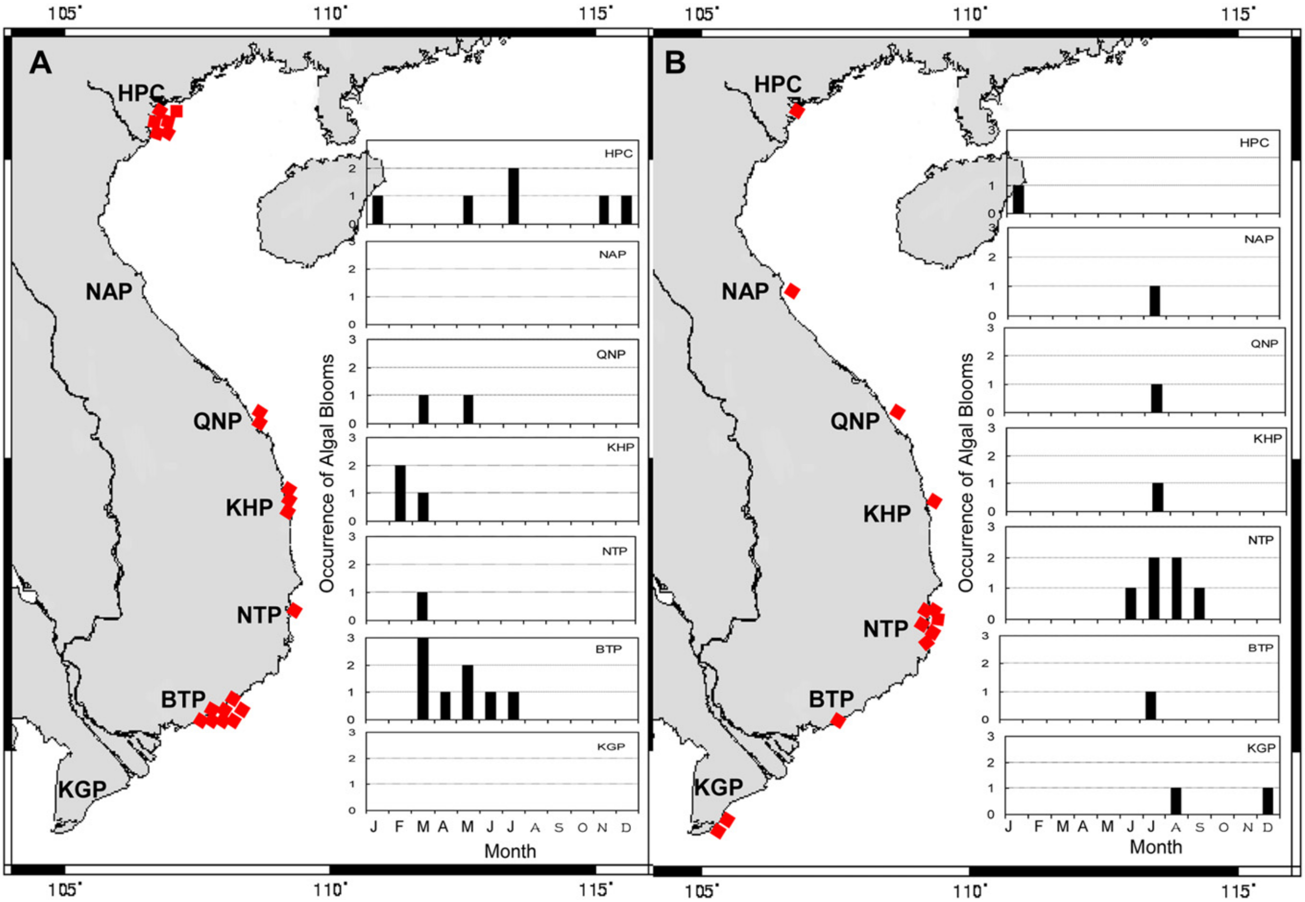

Fig. 3. (A) Monthly frequency of algal bloom events for the various coastal regions during 1993–1999 (Each map symbol represents one algal blooms event); (B) Monthly frequency of algal blooms events for the various coastal regions during 2002–2007 (Each map symbol represents one algal bloom event). HPC, Hai Phong City; NAP, Nghe An Province; QNP, Quang Ngai Province; KHP, Khanh Hoa Province; NTP, Ninh Thuan Province; BTP, Binh Thuan Province; KGP, Kien Giang Province.

projected into the open sea, within a range of 200 km, near the coastal waters of BTP to NTP (red arrow in Fig. 7B and F). These projected bands had largely dissipated in the autumn and were undetectable in the spring. In addition, Chl-a concentrations in the summer of 1999 (Fig. 7B) were lower than those in 2002 (Fig. 7F).

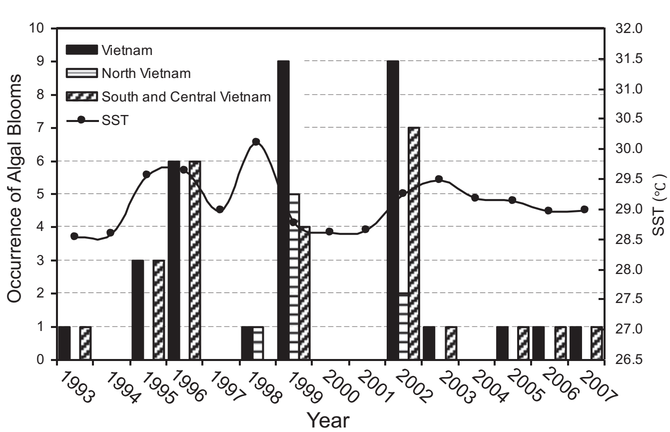

Fig. 4. Annual variation in the number of algal bloom occurences and in Sea Surface Temperature (SST) along the Vietnamese coast for the period of 1993–2007.

3.4. Species changes

During the study period, a total of 11 algal species were reported (Table 1). Several new species, those that had not previously been observed in the study area, occurred in 1999 and 2002, and relatively few new species were observed in other years. From 1993 to 1999, *Trichodesmium erythraeum* was the most frequently occurring bloom species, dominating 40% of the algal bloom events. However, the nature of the bloom species changed in the subsequent years. None of the algal bloom species reported in the earlier events were observed and, thus, the blooms occurring since 2002 were all caused by newly observed species. More importantly, *P. globosa* had become the principal bloom-causative species, dominating 54% of the blooms during 2002–2007.

4. Discussion

4.1. Nutrients

Our results indicated that algal blooms occurred frequently in the coastal waters of South and Central Vietnam in spring and summer (Table 1 and Fig. 5B). Nutrients were the primary factor that determined the growth of phytoplankton, since solar radiation, light penetration, and sea water temperatures were not limiting factors in the western SCS (Tang et al., 2003). Tang et al. (2004b) reported an extensive *P. globosa* bloom lasting for 6 weeks in the coastal waters of BTP in July 2002 and concluded that the algal bloom was supported by the process of the upwelling of nutrients that was caused by the southwesterly winds in the study area. This wind-induced upwelling transported nutrients from lower water layers to the surface layers, as well as from coastal waters to the open sea, inducing an increase in phytoplankton biomass and thus accounting for the higher algal bloom event frequency.

River discharges can be another important factor responsible for the frequent occurrence of algal blooms due to eutrophication. The location of BTP faced the open sea and was 200 km from the Mekong River mouth. The high nutrients discharge associated with this river results in increased nitrate and ammonium concentrations along the coast (Zhu et al., 2003) and enhanced biological activity. These factors cause higher phytoplankton biomass around the discharge area (Tang et al., 2004a). The nutrients discharged from the river would be expected to be rapidly diluted as the river water mixed with sea water, and thus the effect of the river discharge diminishes with the distance along the coastline.

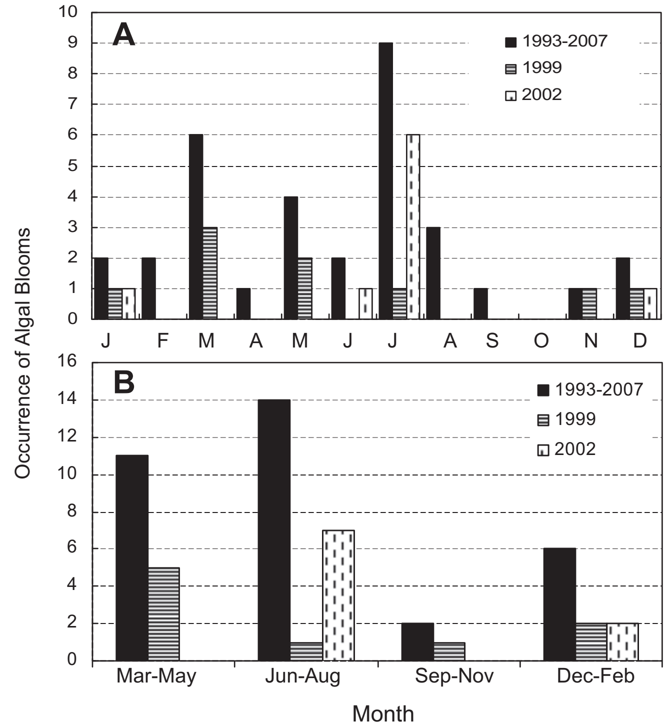

Fig. 5. (A) Monthly variation in the number of algal bloom occurrences during the entire period from 1993 to 2007, and during the years 1999 and 2002 separately. (B) Seasonal variation in the number algal bloom occurrences during the entire period from 1993 to 2007, and during the years 1999 and 2002 separately.

4.2. Sea surface temperature

More algal bloom events occurred in 1999 and 2002 (Fig. 4) compared with relatively fewer events in the other years of our study period. Fig. 4 shows that there was a clear SST spike in 1998, which lasted for more months than in other years, with a maximum value of about 31 °C, followed by a significant fall in SST in 1999. We attributed this phenomenon to the strong El Niño event, which occurred from April, 1997, to June, 1998. Similarly, the monthly averaged SSTs of 2002 became a little higher than the climatologic mean due to the impact of the moderate 2002–2003 El Niño event. Although the SST's of 1999 and 2002 were slightly elevated when compared with some of the other proximal years, this does not appear to make them atypical. Therefore, we can conclude that SST alone is not a dominant causative factor in producing algal bloom events. It is possible that there are complex interactions between SST and other environmental factors but we were unable to identify them from our limited dataset.

4.3. Seasonal characteristics

In the western SCS coastal waters, the largest number of HAB events in the study period occurred in March and July (Fig. 5A), and HAB were also very frequent in the seasons between these two months (Fig. 5B). In March, the temperature was 16–28 °C. During this month, the rainy season begins, the wind velocity generally becomes weaker and the air pressure becomes lower (Qi et al., 2004). This is a consequence of the northeast monsoon begins to change to the southwest monsoon, which is also associated with the gradual rise in temperatures (Wang et al., 2008). These conditions are ideal for phytoplankton growth. Therefore, we conclude that these ideal conditions resulted in the higher frequencies of algal bloom events observed in March.

During the summer season, the strong southwest monsoon winds begin to prevail and get stronger in July, coinciding with anticyclonic circulation leading to an upwelling plume. When this Ekman transport induced strong upwelling (Tang et al., 2004a), which delivered inorganic nutrients and subsurface phytoplankton to the surface waters thus creating favorable conditions for phytoplankton blooms (Tang et al., 2004b), the July and summer blooms occurred.

4.4. Changes of bloom species

Significant changes in bloom species occurred in the study period. From 1993 to 1999, the bloom was dominated by *T. erythraeum*. However, from 2002, the principal species was *P. globosa*. Phytoplankton life cycles, physiology and various environmental parameters would influence the blooming of a specific species (Yamamoto et al., 2002). The blooms of *T. erythraeum* are particularly abundant in tropical oligotrophic surface waters (Lugomela et al., 2002). In our study area, a possible effect of the El Niño event in 1998 was to diminish upwelling in 1999, which induced the low nutrients conditions of the surface waters in which *T. erythraeum* flourishes. At the beginning of the more moderate 2002 El Niño event, it is possible the upwelling close to the NTP waters was still

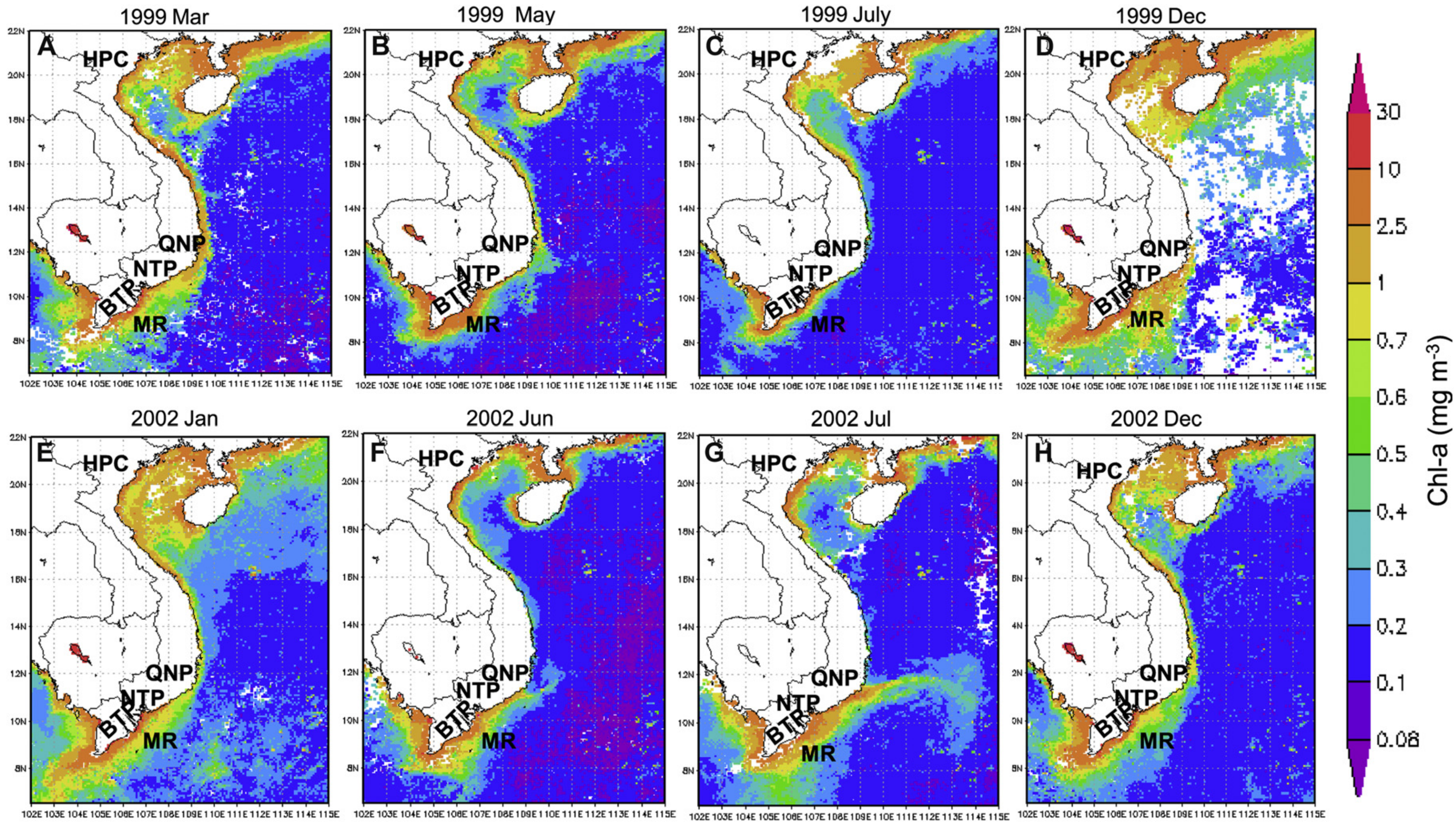

Fig. 6. Sea-viewing Wide Field-of-view Sensor (SeaWiFS) images showing the spatial distribution of various monthly averaged chlorophyll-a (Chl-a) concentrations in 1999 and in 2002 in the coastal waters of Vietnam. HPC, Hai Phong City; QNP, Quang Ngai Province; NTP, Ninh Thuan Province; BTP, Binh Thuan Province; MR, Mekong River mouth.

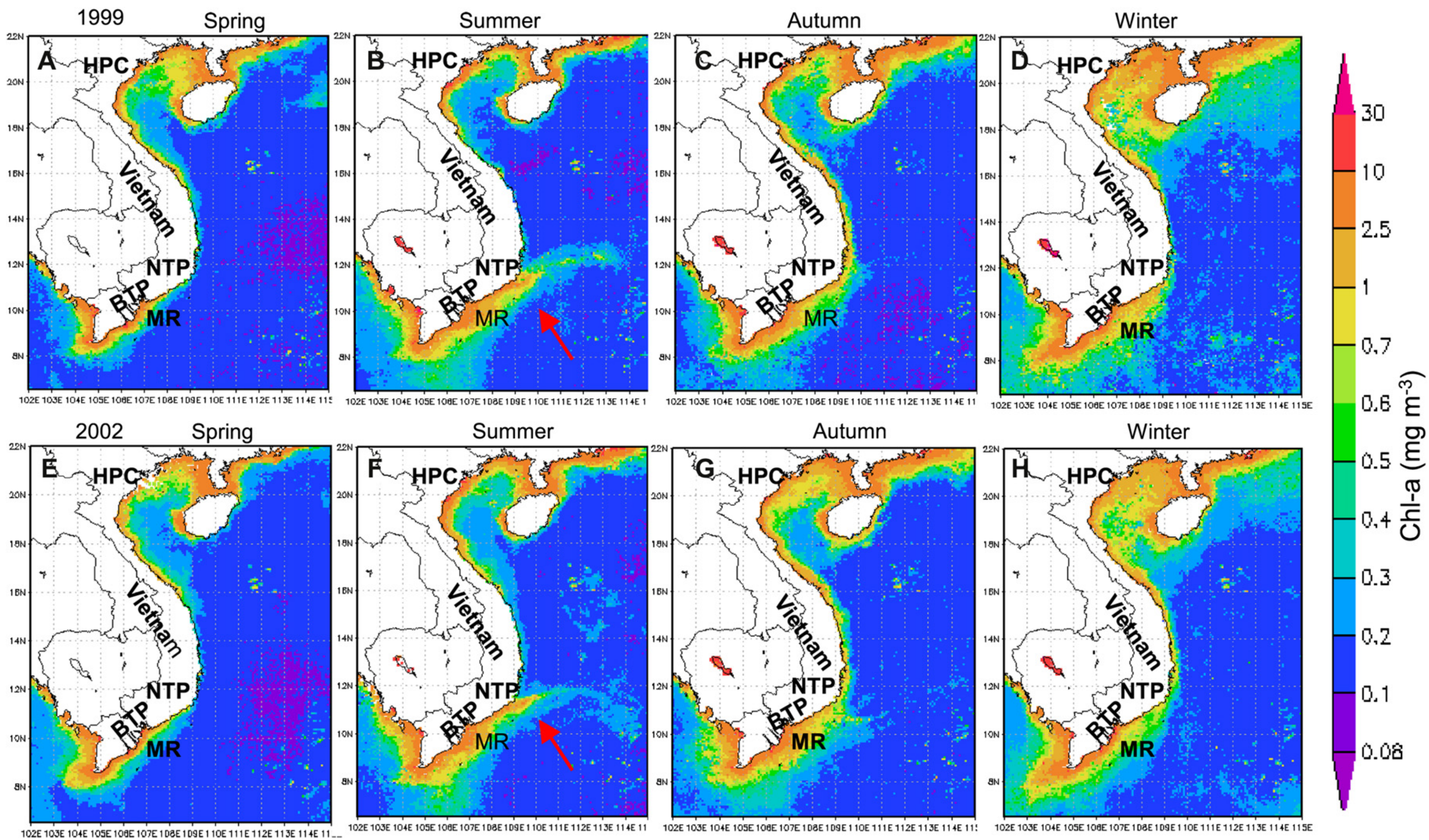

Fig. 7. Sea-viewing Wide Field-of-view Sensor (SeaWiFS) images showing the spatial distribution of seasonally averaged chlorophyll-a (Chl-a) concentrations in 1999 and in 2002 in the coastal waters of Vietnam. HPC, Hai Phong City; NTP, Ninh Thuan Province; BTP, Binh Thuan Province; MR, Mekong River mouth.

intensive, which transported the nutrients from the lower to the surface water layers that created eutrophic surface water conditions. The *T. erythraeum* species, well-adapted to oligotrophic conditions, therefore ceased to be observed in our study area and the *P. globosa* species, well-adapted to eutrophic conditions, appeared in these waters. In addition, *P. globosa*, being a flagellated unicellular species, may have had a better capability for reproduction, thus enhancing its capacity to rapidly dominate the later blooms.

5. Conclusions

This study showed that the spatial and temporal variations in algal blooms in the coastal waters of the western SCS during the study period were influenced by river water and wind-induced, upwelling sources. The major findings are summarized as follows:

1. Large temporal variations and regional species distributions were the most obvious characteristics of the algal bloom events occurring in the coastal waters of the western SCS. Most algal blooms occurred in the waters of South Central Vietnam in the summer, which was associated with wind-induced, coastal, nutrient upwelling.
2. July had the largest frequency of monthly algal bloom occurrences, which were induced by the southwest (summer) monsoon. March also had a large number of algal bloom events, which were mainly affected by the northeast (winter) monsoon.
3. There were two years of peak algal bloom occurrence in 1999 and 2002. The cause of this increase in algal bloom event intensity has yet to be definitively determined. However, several hypotheses may be advanced: e.g., decreases in nutrients loading from upwelling and/or an increase of sea surface temperature, which may have been affected by the 1998 and 2002 El Niño events of differing degrees.
4. The species *T. erythraeum* (Cyanophyta) dominated the phytoplankton community of algal blooms during 1993–1999, whereas the species *P. globosa* (Haptophytes) dominated blooms after 2002.

This study should provide a basis for further research on the long-term variability of algal blooms, and a scientific reference with which to assist in the prediction of HABs.

Acknowledgements

The presented work was supported by the following research grants: (1) The National Natural Science Foundation of China (NSFC40976091, 31061160190); (2) Foundation of Key Laboratory of Marine Biology (LMB/LAMB and LMM) (LMB081004) and State Key Laboratory of Tropical Oceanography (LTO0801) of Chinese Academy of Sciences; (3) Key Project of Knowledge Innovation Program, Chinese Academy of Sciences (kzcx2-yw-226); (4) Guangdong Natural Science Foundation, China (8351030101000002, 2010B031900041). We would like to thank Mr David Warrington of the State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau for his advice in preparing the manuscript. We also would like to thank anonymous reviewers for their useful suggestions and comments.

References

Cullen, J.J., Ciotti, A.M., Davis, A.F., Lewis, M.R., 1997. Optical detection and assessment of algal blooms. Limnology and Oceanography 42 (5, part2), 1223–1229.

Dien, T.V., Tang, D.L., Kawamura, H., 2003. Validation SeaWiFS-derived ocean color data and using for study distribution chlorophyll-a concentration in the Vietnam waters. In: Proceedings of Regional Conference on Digital GMS, 26–28 February. Bangkok, Thailand, p.75–87.

Doan, N.H., Nguyen, N.L., Nguyen, C., Ho, V.T., Nguyen, T.A., 2002. Plankton assemblage during the red tide in the Northern coast of Binh Thuan Province in July 2002, Abstract Presented at 10th International Conference on Harmful Algae. Intergovernmental Oceanographic Commission of UNESCO, St. Petersburg, Fla. Available at: http://www.xhab2002.com/.

Doan-Nhu, H.,D.N., Hguyen-Ngoc, L.,N.N., Dippner, J.W., 2010. Development of *phaeocystis globosa* blooms in the upwelling water of the South Central coast of Vietnam. Journal of Marine Systems 83, 253–261.

Glibert, P.M., Seitzinger, S., Heil, C.A., Burkholder, J.M., Parrow, M.W., Codispoti, L.A., Kelly, V., 2005. The role of eutrophication in the global proliferation of harmful algal blooms: new perspectives and new approaches. Oceanography 18, 198–209.

Lugomela, C., Lyimo, T.J., Bryceson, I., Semesi, A.K., Bergman, B., 2002. *Trichodesmium* in coastal waters of Tanzania: diversity, seasonality, nitrogen and carbon fixation. Hydrobiologia 477, 1–13.

Nguyen, N.L., 1999. *Trichodesmium erythraeum* bloom. Harmful Algae News 19 (13). Available at: http://ioc.unesco.org/iocweb/IOCpub/iocpdf/han19.pdf.

Nguyen, N.L., Doan, N.H., 1996. Harmful marine phytoplankton in Vietnam waters. In: Yasumoto, T., Oshima, Y., Fukuyo, Y. (Eds.), Harmful and Toxic Algal Blooms. Intergovernmental Oceanographic Commission of UNESCO, Paris, pp. 45–48.

Nguyen, N.L., Doan, N.H., Nguyen, T.M.A., Ho, V.T., 2003. A summary of HAB studies in Vietnam, Paper Presented at Workshop on Red Tide Monitoring in Asian Coastal Waters. University of Tokyo, Tokyo.

Nguyen, N.L., Doan, N.H., Pham, T.V., 1997. Outbreak of *Noctiluca scintillans* (Mac.) Ehr. related to eutrophication in Vanphong-Bengoi Bay, Central Vietnam. In: Viger, G., Ong, K.S., McPherson, C., Millson, N., Watson, I., Tang, A. (Eds.), Proceeding of the ASEAN–Canada Technical Conference on Marine Science (24–28 June, 1996), Penang, Malaysia. EVS Environment Consultant, North Vancouver and Department of Fisheries Malaysia: ASEAN Marine Environment Management: Quality Criteria and Monitoring for Aquatic Life and Human Health Protection, pp. IX-29–35.

O'Reilly, J.E., Maritorena, S., Mitchell, B.G., Siegel, D.A., Carder, K.L., Garver, S.A., Kahru, M., McClain, C., 1998. Ocean color chlorophyll algorithms for SeaWiFS. Journal of Geophysical Research 24, 937–953.

Pan, J., Yan, X.H., Zheng, Q., Liu, W.T., Klemas, V.V., 2002. Interpretation of scatterometer ocean surface wind vector EOFs over the northwestern Pacific. Remote Sensing of Environment 84, 53–68.

Pan, Y.L., Tang, D.L., Weng, D.H., 2010. Evaluation of the SeaWiFS and MODIS chlorophyll a algorithms used for the Northern South China Sea during the summer season. Terrestrial Atmospheric and Ocean Science 21, 997–1005.

Qi, Y.Z., Chen, J.F., Wang, Z.H., Xu, N., Wang, Y., Shen, P.P., 2004. Some observations on harmful algal bloom (HAB) events along the coast of Guangdong, southern China in 1998. Hydrobiologia 512, 209−214.

Tang, D.L., Kawamura, H., Lee, M.A., Dien, T.V., 2003. Seasonal and spatial distribution of chlorophyll a and water conditions in the Gulf of Tonkin, South China sea. Remote Sensing of Environment 85, 475−483.

Tang, D.L., Kawamura, H., Dien, T.V., Lee, M.A., 2004a. Offshore phytoplankton biomass increase and its oceanographic causes in the South China Sea. Marine Ecology Progress Series 268, 31−41.

Tang, D.L., Kawamura, H., Doan-Nhu, H., Takahashi, W., 2004b. Remote sensing oceanography of a harmful algal bloom off the coast of southeastern Vietnam. Journal of Geophysical Research. doi:10.1029/2003JC002045.

Wang, S.F., Tang, D.L., He, F., Fukuyo, L.Y., Azanza, R.V., 2008. Occurrences of harmful algal blooms (HAB) associated with ocean environments in the South China Sea. Hydrobiologia 596, 79−93.

Yamamoto, T., Hashimoto, T., Tarutani, K., Kotani, Y., 2002. Effects of winds, tides and river water runoff on the formation and disappearance of the *Alexandrium tamarense* bloom in Hiroshima Bay, Japan. Harmful Algae 1, 301−312.

Zhang, Y., Sperber, K.R., Boyle, J.S., 1997. Climatology and interannual variation of the East Asian winter monsoon: results from the 1979−1995 NCEP/NCAR reanalysis. Monthly Weather Review 125, 2605−2619.

Zhang, C.Y., Hu, C.M., Shang, S.L., Müller-Karger, F.E., Li, Y., Dai, M.H., Huang, B.Q., Ning, X.R., Hong, H.S., 2006. Bridging between SeaWiFS and MODIS for continuity of chlorophyll-a concentration assessments off Southeastern China. Remote Sensing of Environment 102, 250−263.

Zhu, G.H., Ning, X.R., Cai, Y.M., Liu, Z.L., Liu, Z.G., 2003. Studies on species composition and abundance distribution of phytoplankton in the South China Sea. Acta Oceanologica Sinica 25, 8−23 (in Chinese).