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PRIMARY RESEARCH PAPER

Occurrences of harmful algal blooms (HABs) associated with ocean environments in the South China Sea

SuFen Wang · DanLing Tang · FangLiang He ·
Yasuwo Fukuyo · Rhodora V. Azanza

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Abstract Harmful algal blooms (HABs) occur frequently in the South China Sea (SCS), causing enormous economic losses in aquaculture. We analyzed historical HAB records during the period from 1980 to 2003 in SCS. We found that HABs-affected areas have expanded and the frequency of HABs varied during this period. The seasonal and annual variations, as well as causative algal species of HABs are different among the four regions. Areas with frequent HABs include the Pearl River Estuary (China), the Manila Bay (the Philippines), the Masinloc Bay (the Philippines), and the western coast of Sabah (Malaysia). HABs occurred frequently during March–May in the northern region of SCS, May–July in the eastern region, July in the western region, and year-round in the southern region. Among the species that cause HABs, *Noctiluca scintillans* dominated in the northern region, and *Pyrodinium bahamense* in the southern and eastern regions. Causative species also varied in different years for the entire SCS. Both *P. bahamense* and *N. scintillans* were the dominant species during 1980–2003. Some species not previously recorded formed blooms during 1991–2003, including *Phaeocystis globosa, Scrippsiella trochoidea, Heterosigma akashiwo*, and *Mesodinium rubrum*. Variations in HABs are related to various regional conditions, such as a reversed monsoon wind in the entire SCS, river discharges in the northern area, upwelling in Vietnam coastal waters during southwest winds and near Malaysia coastal waters during northeast winds, and eutrophication from coastal aquaculture in the Pearl River estuary, Manila Bay, and Masinloc Bay.

Keywords Harmful algal bloom (HAB) · Spatial and temporal variations · Management implications · Environmental change · South China Sea

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S. F. Wang · D. L. Tang (✉)
Remote Sensing and Marine Ecology Group, LED, South China Sea Institute of Oceanology, Chinese Academy of Sciences, 164 West Xingang Road, Guangzhou 510301, China
e-mails: lingzistdl@126.com; lingzis@scsio.ac.cn
URL: http://Lingzis.51.net

S. F. Wang · D. L. Tang
Graduate School of the Chinese Academy of Sciences, Beijing 100039, China

F. L. He
Department of Renewable Resources, University of Alberta, Edmonton, AB, Canada
e-mail: fhe@ualberta.ca

Y. Fukuyo
Asian Natural Environmental Science Center, Tokyo University, Tokyo, Japan

R. V. Azanza
University of the Philippines, Diliman, Philippines

Introduction

Harmful Algal Blooms (HABs) have spread worldwide and become a global problem causing enormous economic loss and serious impacts on human health (Anderson, 1997a, b). HABs have been reported from Florida (Philips et al., 2004), British Columbia (Taylor & Haigh, 1993), Norwegian waters (Dahl & Tangen, 1993; Vila et al., 2001), northeast Atlantic (Edwards & Johns, 2006), and the upwelling regions off South Africa (Pitcher & Calder, 2000). Detrimental ecosystem effects associated with HABs range from pelagic and benthic community mortalities to fish/shellfish aquaculture mortalities, attributable to both biomass losses (i.e., due to low-dissolved oxygen) and toxic effects for humans (Heil et al., 2005; Anderson et al., 1994). The worldwide increase in aquaculture is part of the problem, and has been blamed for pollution of the ecosystem (ICLARM, 1993; Stewart, 1997), especially in Asia (FAO/NACA, 1995). In a positive feedback cycle, the increasing frequency, intensity, and geographic distribution of HABs poses a serious threat to the coastal fish/shellfish aquaculture and fisheries (Anderson, 1998).

Intensive marine farming and rapid industrialization over the past two decades along the coast of the South China Sea have placed a heavy stress on the marine environment and greatly degraded marine ecosystems in the region. Massive mortality and devastating diseases as well as HABs in marine farms have already hampered the sustainable development of the marine-culture industry (Qi et al., 2004). The understanding of historical HAB distribution and concentration in the South China Sea offers a basis for urgent management measures required to mitigate deteriorating coastal water quality and the adverse environmental impacts on aquaculture development (Chua et al., 1989; FAO/NACA, 1995).

The South China Sea (SCS) is the largest semi-closed sea in the western tropical Pacific Ocean (Fig. 1A). It is surrounded by Malaysia, Thailand, Vietnam, Brunei, Indonesia, Philippines, and China. The coastal fringes of SCS are home to about 300 million people in 2000 (Fig. 1A) (Global Statistics, 2000). The SCS is a distinctive ecosystem, in which the combination of geology and climate produces a remarkable amount of biological

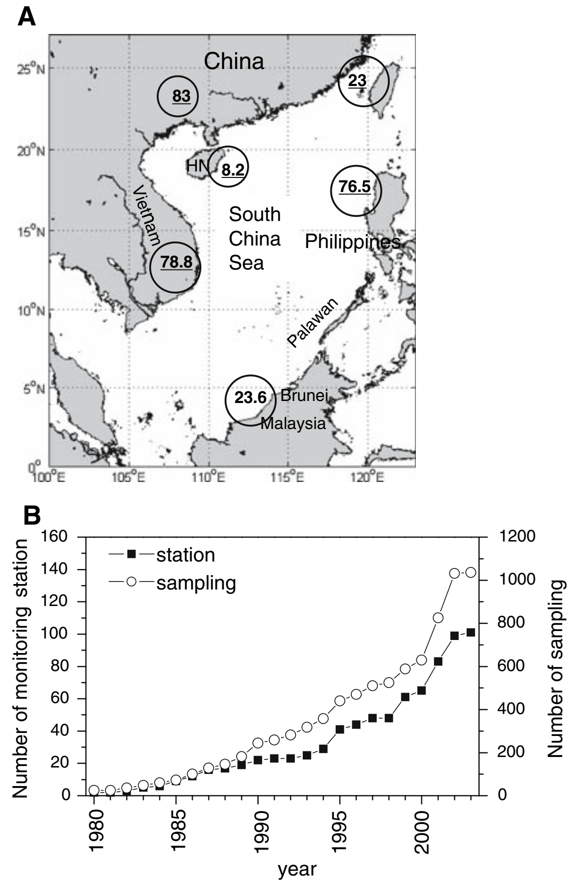

Fig. 1 (**A**) Study area—the South China Sea (SCS). Numbers in circles show human population (in million) of the local coastal regions. (**B**) The number of monitoring stations and routine sampling frequency for HABs in the SCS from 1980 to 2003

diversity and immense genetic resources (Roseberg, 1999).

The littoral countries of the SCS have similar coastal ecosystems and access to common marine resources, such as coastal cultivation of oysters and shrimp, and deep-sea fishing for tuna and other migratory species. The sea plays an important role in the economies of the coastal nations, by providing food and employment for the increasing population. About half of the coastal population's protein intake comes from the sea (Roseberg, 1999). The problems of environmental pollution around the SCS are primarily due to population growth and urbanization in coastal cities, economic growth and increased material consumption, and highly polluting technologies for energy production and primary resource extraction.

In the SCS, HABs have caused mass mortality of fishes and other ecosystem impacts (Qi et al., 2004; Xia & Wu, 1996; Tang et al., 2003a, b) in the past 20 years. For example, in November 1997, HABs off Raoping (Guangdong province, China) led to an estimated economic loss more than US$8 million (Qi et al., 2001). During March–April 1998, HABs in the mouth of the Pearl River in Guangdong province and Hong Kong caused economic losses estimated at over US$45 million (Qian et al., 2000; Tang et al., 2003a, b). In summer 1983, *Pyrodinium bahamens* bloomed in Magued Bay and the Samar Sea, Philippines, poisoning 700 people, killing 70 people, and causing economic losses up to US$500,000 (Maclean, 1989). In 2002, a *Prorocentrum minimum* bloom in the northern Philippines led to economic losses of US$120,000 (Azanza et al., 2005).

Local HAB studies in the SCS area have focused on algal species (Hodgkiss & Lu, 2004; Azanza et al., 2005; Masuda et al., 2001), environmental factors (Tang et al., 2003a, b; Usup et al., 2002; Yoshida et al., 2000), and oceanic dynamics (Tang et al., 2004a, b, 2006a) in association with upwelling that supports long-term phytoplankton blooms (Tang et al., 2004b).

Due to the extensive area of the SCS, many environmental factors, such as monsoon winds, weather, ocean circulation, upwelling, and human activities play roles in HAB formation (Han et al., 1995; Tang et al., 2004a). The aims of this study were to analyze the spatial and temporal dynamics of HAB occurrences from 1980 to 2003, and identify potential risk factors of HABs in the SCS. The study addresses the need to improve our understanding about the distribution of HABs and the conditions of HABs outbreaks in the region, thus enhancing our predictive ability.

Data and methods

Study area

With a total area of 3.5×10^6 km^2, the SCS is the largest marginal sea in the world (Fig. 1A). Northeast monsoon winds occur from November to March and southwest monsoon winds from June to September, with transition periods in April–May and September–October (Mohsin & Ambak, 1996). A large anticyclonic circulation (Fig. 2A) appears during the southwest monsoon, and a cyclonic circulation (Fig. 2B) occurs during the northeast monsoon (modified from Hu et al., 2000; Tang et al., 2004a). Four major (Pearl, Mekong, Han and Red Rivers) (Fig. 2B) and many small rivers discharge into the sea.

We sorted the data for four SCS regions (Fig. 3) influenced by similar hydrographic conditions: (A) North (southern China and northern Vietnam); (B) East (mainly west of the Philippines); (C) South (western Malaysia, Brunei, and Palawan Island); and (D) West (southern coast of Vietnam).

HAB data collection and analysis

Harmful algal bloom data were collected and compiled from various sources, including government statistics reports of China, Malaysia, Vietnam, Brunei, and the Philippines (96 websites), research journals (107 papers), conferences and other reports (80 reports), and newspapers. For the northern SCS, the collection did not include HABs occurring in Hong Kong, where the HAB outbreak is a regular occurrence and requires a separate study. For the western region, there were no HAB records prior to 1990. We analyzed the affected areas, seasonal frequency, and causative species of HABs, and changes for 1980–1990 versus 1991–2001.

Routine monitoring of HABs has been carried out in many countries; the number of monitoring stations and routine sampling frequency in the present study was collected from those departments of China, Malaysia, Vietnam, Brunei, and the Philippines that were in charge of routine monitoring on HABs (Fig. 1B).

Satellite data

QuickScat sea surface wind

Wind speed and direction over the ocean surface were retrieved from QuikScat measurements of backscattered power (Wentz et al., 2001). Monthly averaged QuickScat wind vector images were

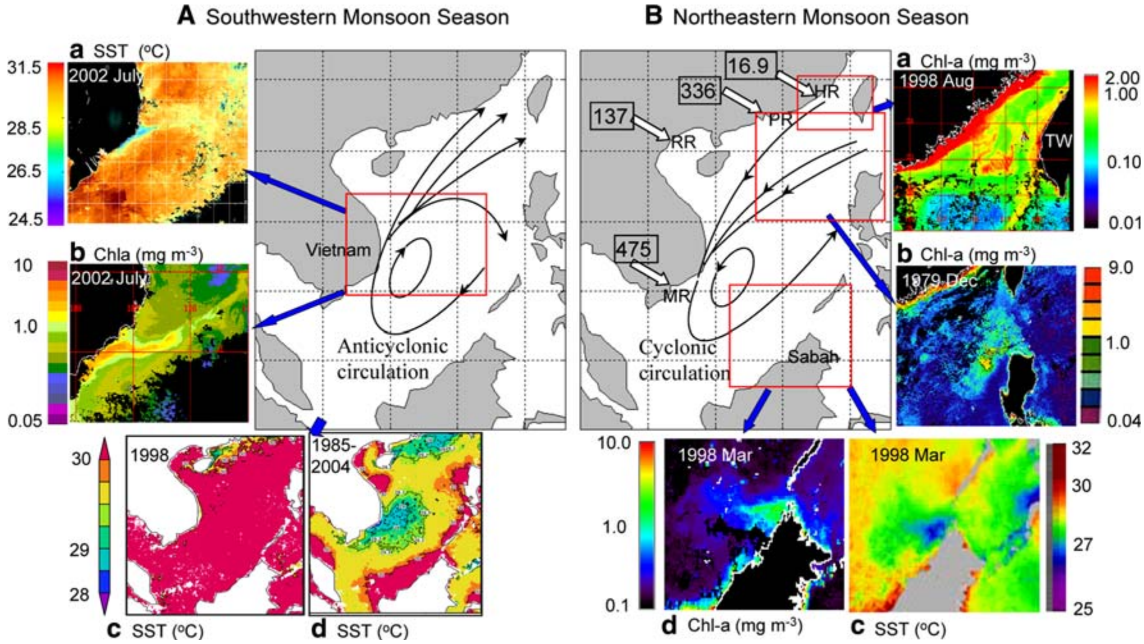

Fig. 2 Upper-layer mean circulation patterns in the SCS and satellite images of Chl *a* concentration and SST for phytoplankton bloom events (Hu et al., 2000). Four rivers are identified by white arrows: HR (Han River); RR (Red River); PR (Pearl River); MR (Mekong River). (**A**) Southwestern monsoon. a and b: satellite images showing upwelling and phytoplankton bloom in the coastal water of Vietnam (Tang et al., 2004a, b); c and d: SST images for summer season (June–August) of 1998 and 1995–2004 in the SCS (Zhao & Tang, 2006). (**B**) Northeastern monsoon. The numbers in squares show the annual river discharge (km^3). a: SeaWiFS images showing high-Chl *a* concentration in the Taiwan Bank Upwelling (Tang et al., 2002); b: CZCS Chl *a* image showing a phytoplankton bloom in Luzon Strait; c and d: Chl *a* and SST in an upwelling area near Sabah (Isoguchi & Kawamura, 2006)

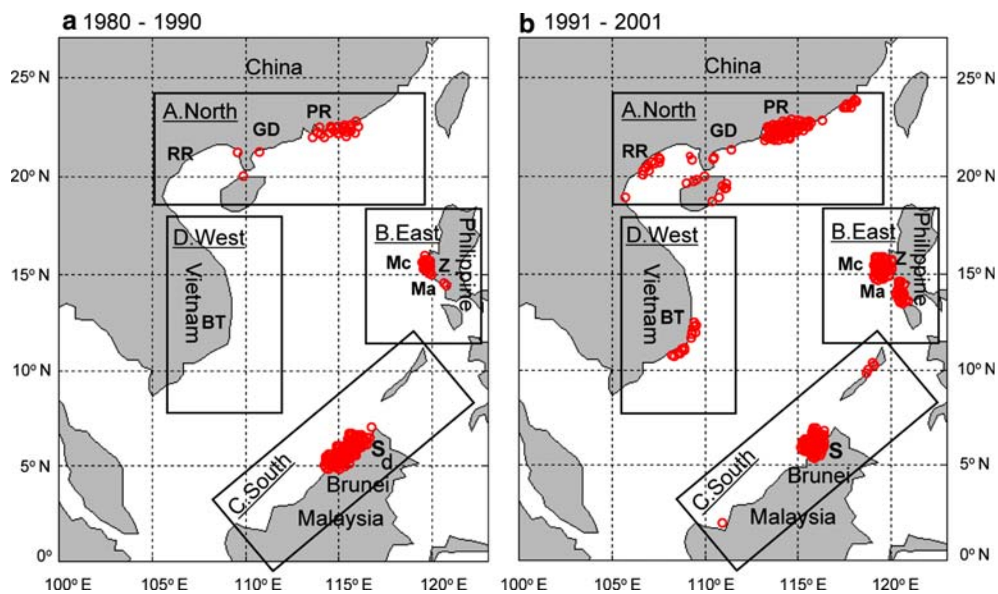

Fig. 3 (**a**) HAB distributions in the SCS from 1980 to 1990. (**b**) HAB distributions in the SCS from 1991 to 2001. Boxes show four study regions. Each red circle means one HAB occurrence. PR: Pearl River; GD: Guang Dong Province, RR: Red River Delta; BT: Binh Thuan Province; S: Sabah; Ma: Manila Bay; MC: Masinloc Bay

produced by Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team (http://www.ssmi.com/qscat/qscat_description.html).

AVHRR sea surface temperature (SST)

SST data from the Advanced Very-High Resolution Radiometer (AVHRR) Pathfinder Version 5 SST Project (spatial resolution 4 km/month-daytime), a re-analysis of the AVHRR data stream, were obtained from the Physical Oceanography Distributed Active Archive Center (PODAAC), the Jet Propulsion Laboratory (JPL), and NASA (http://www.podaac.jpl.nasa.gov/sst).

SeaWiFS-derived Chl a

SeaWiFS-derived Chl *a* images of 1×1 km^2 spatial resolution were processed through the SeaWiFS Data Analysis System (SeaDAS) using the Ocean Color 4-band algorithm (OC4,4) (O'Reilly, 1998). To investigate the spatial distribution of Chl *a*, we first processed images at 1×1 km^2 spatial resolution, and then made monthly average Chl *a* images at 4×4 km^2 (Tang et al., 2003b).

Monthly satellite images of winds, SST, and Chl *a* concentration for March, June, September, and December were processed for 2001 to present general conditions for the SCS, because satellite data coverage are relatively good for this year (Tang et al., 2004a, 2006a). Some other images were processed to analyze special HAB occurrences.

Results

Spatial distribution

The occurrence of HABs increased and the affected area spread substantially from 1980 to 2001 (Fig. 3). HABs occurred frequently off the Pearl River, Sabah, Masinloc, and in the Manila Bay from 1980 to 2001 (Fig. 3). Among the four regions the southern region (C) had the highest frequency, with 369 HABs observed (Fig. 4). The fewest HABs were observed in the western region (D in Fig. 4), but HABs were not officially reported in Vietnam prior to the early 1990s.

Occurrences of HABs during 1980–2003

In the northern region (A in Fig. 5), HABs occurred most frequently in 1990 (19), 1991 (24), and 1998 (18). In the eastern regions, HABs occurred almost every year. In the southern region, HABs also occurred almost every year, but most frequently from 1994 to 1998 (C in Fig. 5). A few HABs were observed in the western region, but with two peaks in 1999 (9 HABs) and 2002 (8 HABs) (D in Fig. 5). For the entire SCS area, HABs were frequent in 1991 (57), 1995 (55), and 1998 (67), and a high number occurred from 1994 to 1998 (>40 y^{-1}) (E in Fig. 5). About 206 HABs were observed during 1980–1990, and 499 during 1991–2003.

Seasonality

Harmful algal blooms have strong seasonal characteristics in the SCS area (Figs. 6, 7). In the northern region, the highest frequency (33) was in April. The highest frequency (25) is in June in the eastern regions and in July (8) in western regions. In the southern region, HABs occurred relatively evenly year-round (20–40 y^{-1}) (Fig. 6).

For the entire SCS, from 1980 to 2003, March to May had the highest number of HAB records (>70 month^{-1}) and September to November had the lowest (30–50 month^{-1}) (E in Fig. 8). Very few HABs were recorded in the western region during September–February (<3 month^{-1}) (Figs. 6, 7).

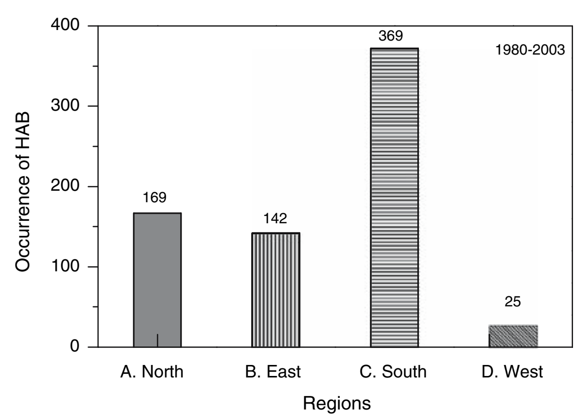

Fig. 4 The total numbers of HAB in the four regions of the SCS from 1980 to 2003

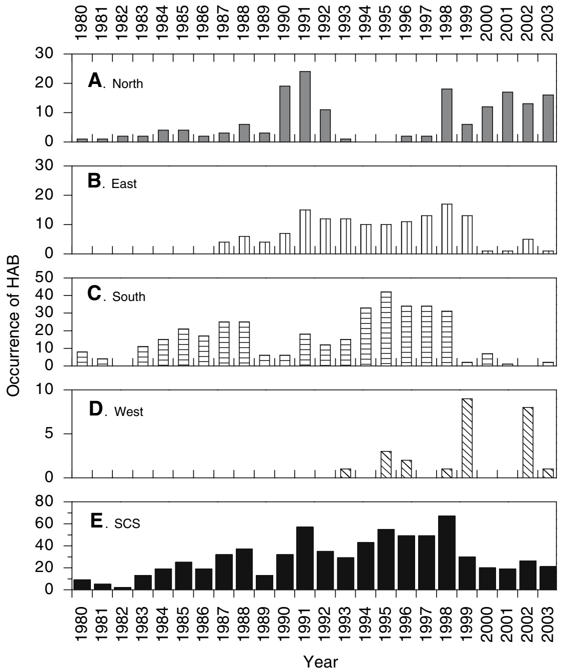

Fig. 5 Reports of HAB events in the SCS from 1980 to 2003

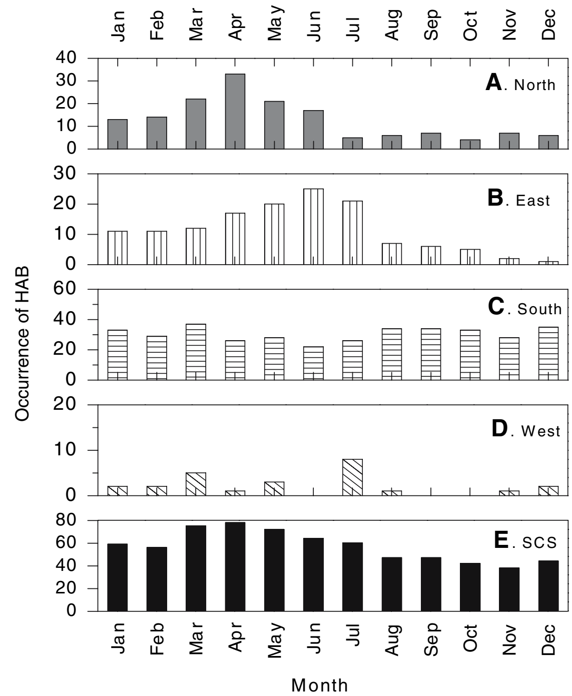

Fig. 6 Monthly distribution of HABs in the SCS from 1980 to 2003

Causative species of HAB

The dominant species were *Noctiluca scintillans* in the northern region and *Pyrodinium bahamense* in the eastern and southern regions (Table 1, Fig. 8). There were many different species in the northern and western regions, and relatively few in the southern and eastern regions (Table 1).

The dominant HAB species were dinoflagellates (Table 1). *N. scintillans* and *P. bahamense* were the principal HAB species during 1980–2003 (E in Fig. 8). From 1990, some previously unobserved HAB species were observed such as *Phaeocystis globosa, Scrippsiella trochoidea, Heterosigma akashiwo*, *Mesodinium rubrum*, and others (E in Fig. 8 and Table 1).

Environmental conditions

The reversal of tropical monsoon wind plays an important role in hydrological features and general circulation in the SCS (Shaw & Chao, 1994). Northeast winds prevail in March, and southwest winds prevail in June (Fig. 9A). In September the wind direction changes from southwest to northeast, and in December northeast winds prevail. Monsoon winds drive circulation in the SCS (Fig. 2).

Sea surface temperature (SST) was relatively low in March and December (18–29°C) and high in June and September (27–31°C). Chl *a* concentrations were higher along the coast than in the open sea (Fig. 9C), and the highest levels occurred near river mouth areas (R in Fig. 9C) and in some bays (Y in Fig. 9C).

There are four large rivers discharging nutrition into the SCS (Fig. 2B: numbers in four squares indicate annual discharges) that provide nutrients for phytoplankton to bloom. Regional upwelling occurs in the Taiwan Strait (a in Fig. 2B) (Tang et al., 2002) and along the coast of Binh Thuan province (Vietnam) (a and b in Fig. 2A) during southeast monsoon (Tang et al., 2004b), and in northwest of Philippines (Luzon Strait) (b in Fig. 2B) (Tang et al., 1999), in the west coast of Sabah (c and d in Fig. 2B) in northeast monsoon (Isoguchi & Kawamura, 2006). Upwelling brings nutrients from the bottom to the surface and to phytoplankton blooming.

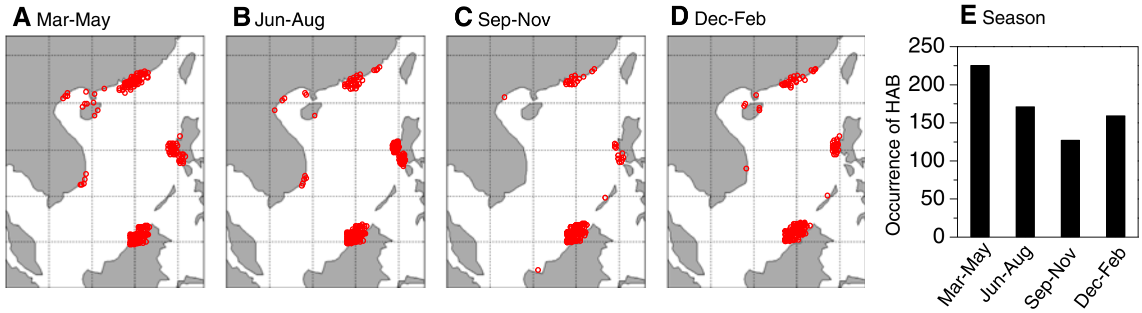

Fig. 7 HAB distributions in the SCS for different seasons from 1980 to 2003 (each circle is one HAB occurrence)

El Niño-Southern Oscillation (ENSO) affects the global ocean (Alexander et al., 2002) as well as the SCS. Southwest winds were relatively weak while water temperature was higher than normal in the western SCS in 1998 when there was a strong El Niño year (c and d in Fig. 2A) (Zhao & Tang, 2006).

Discussion

Eutrophication or nutrient enrichment

River discharges with high-inorganic nutrients can invoke coastal eutrophication (nutrition enrichment) (Zhu et al., 2003) and thus HABs (Hodgkiss & Ho, 1997; Hodgkiss & Lu, 2004; Wang et al., 2003). HABs also occur frequently in the bays of coastal water due to eutrophication and limited current flows (Lim et al., 2005; Corrales & Crisostomo, 1996).

In the northern region, most HABs occur in the waters near the Pearl River estuary (PR in Fig. 3) where waters are enriched by high-inorganic nutrients in freshwater runoff, sewage discharge, agricultural fertilizers, and nearby high-density coastal aquaculture (Qian & Liang, 1999). Manila Bay and Masinloc Bay (Ma and Mc in Fig. 3) in the eastern region are also affected frequently by HABs; these are the most important aquaculture districts in the Philippines. The western coast of Sabah is also an important aquaculture region (the aquaculture production was 160,000 t in 1994, increasing to 2,000,000 t in 1998) (Fishery Department, Sabah). Nutrient enrichment supports HABs and is characteristic of these regions (Azanza et al., 2005). In winter, strong winds and coastal currents may shift HABs from Sabah to Palawan (Azanza & Banula, 2005). For the western regions, HABs occur frequently in July–September along the coast of Binh Thuan Province of Vietnam, where eutrophication is not so serious but where there is strong regional upwelling of nutrients (Tang et al, 2004a, b) that has contributed to HABs.

Seasonal characteristics

In the northern region, the temperature was 16–28°C in March–May. During this season, the northeast monsoon changes to southwest monsoon and the weather gradually becomes warmer. It is also the beginning of the rainy season, with the wind velocity generally becoming weakened and the air pressure becoming lower (Qi et al, 2004). These conditions are ideal for phytoplankton growth and are denoted by occurrence of HABs occurring (A in Fig. 6).

Harmful algal blooms in the western region were most frequent in July (Fig. 6) along the coast of Vietnam (BT in Fig. 3), where there are no major rivers discharging and little coastal aquaculture. HABs in southeastern Vietnamese coastal waters in July 2002 (b in Fig. 2A) appeared offshore, coinciding with anticyclonic circulation leading to an upwelling plume (a in Fig. 2A). When strong southwest monsoon winds blow parallel to the coastline in July, Ekman transport induces strong upwelling (Tang et al., 2004a), which delivers inorganic nutrients and subsurface phytoplankton to the surface, causing phytoplankton blooms (Tang et al., 2004b). A comparison between Gulf of Thailand and SCS indicated that the angle of wind direction with the coastline was an important factor for phytoplankton blooms. Most phytoplankton

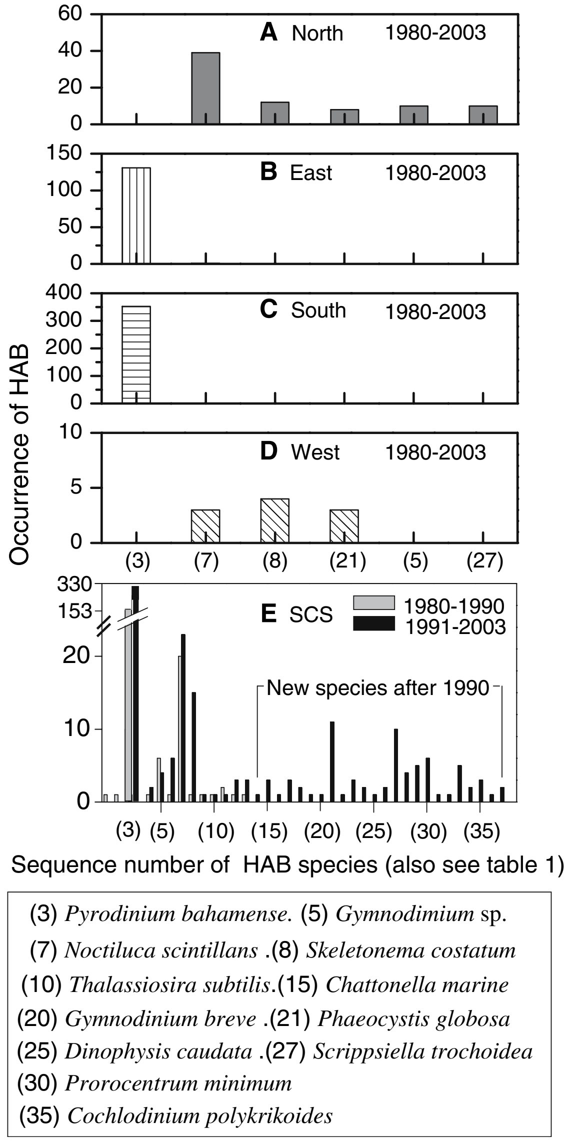

Fig. 8 Occurrences of six most numerous HAB species for four regions during 1980–2003 (**A**–**D**) and occurrences of all HAB species for entire SCS during 1980–1990 and 1991–2003 (**E**). See Table 1 for the species sequence numbers (*X*-axis)

blooms appear during the southwest monsoon season off the SCS coast of Vietnam, whereas blooms in the Gulf of Thailand are most frequent during the northeast monsoon season (Tang et al., 2006b).

HABs occurred year around in the southern region (C in Fig. 6), where the climate is tropical, and temperature are mostly high and invariant all year. In addition, mariculture contributed to eutrophication along the coast. In this region, *P. bahamense*, a species that grows well at high temperature has been observed throughout the whole year.

For the eastern region (B in Fig. 6), the major HAB species are the same as in the southern region (Table 2), but HABs frequently occur in June and July. The high temperature and heavy rainfall in these two months (http://www.worldweather.cn) may be responsible for the HAB occurrence.

Diversity of causative species

For the entire SCS, 37 species have been reported to cause HABs (Table 1), and among them dinoflagellates were responsible for about 90% of the events (Table 1, Fig. 8). *P. bahamense* was the most frequent HAB species, responsible for 153 blooms from 1980 to 1990 and 330 from 1991 to 2003 (E in Fig. 8).

In the southern and eastern regions, most dinoflagellate blooms are initiated from germination of cysts (Usup & Azanza, 1998), which are present in high density in sediment of Manila Bay and nearby regions (Yñiquez et al., 2000). *P. bahamense* blooms frequently occurred in June when there was high temperature (about 31°C) (http://www.worldweather.cn) in the eastern region (Fig. 6), coinciding with periods of southwest wind, suggesting that the strong winds may resuspend the cysts and initiate blooms. *P. bahamense* is a tropical species (Azanza & Taylor, 2001) which has a narrow range of temperature for reproduction. It only blooms at temperature over 26°C (Badylak & Phlips, 2004). Water temperatures in the eastern region are less than 29°C during the northeast wind period. In the south, *P. bahamense* cells are present in the northwest of Sabah (Azanza & Taylor, 2001) and can bloom all year-round.

Blooms of *Cochlodinium polykrikoides* have been found in both Sabah (January, 2005) and Palawan (March, 2005) coastal waters (Azanza & Banula, 2005). Under southwest wind conditions, coastal currents (Fig. 2B) may bring masses of phytoplankton from the coastal waters of Sabah northeastward to the Palawan coast (Azanza & Banula, 2005).

The optimal temperature for *N. scintillans* growth is 19.8–22°C (Ji, 2003), and blooms often occur when the northern region has a suitable temperature

Table 1 Frequencies of HAB species in four regions of the SCS from 1980 to 2003 ((–): absent; ''nd'': no data; *: new species after 1990). The sequence numbers of HAB species are same with Fig. 8

	HAB species	Sequence	North		East		South		West		SCS	
	Time period		1980–1990	1991–2003	1980–1990	1991–2003	1980–1990	1991–2003	1980–1990	1991–2003	1980–1990	1991–2003
Dinophyceae	*Pyrodinium bahamense*	(3)	–	–	21	110	132	220	nd	–	153	330
	Noctiluca scintillans	(7)	20	19	–	1	–	–	nd	3	20	23
	Gymnodimium sp.	(5)	6	4	–	1		–	nd	–	6	5
	**Scrippsiella trochoidea*	(27)	–	10	–		–	–	nd	–	0	10
	**Prorocentrum minimum*	(30)	–	–	–	2	–	–	nd	4	0	6
	**Ceratium furca*	(28)	0	2	–	–	–	–	nd	2	0	4
	**Gonyaulax polygramma*	(17)	–	3	–	–	–	–	nd	–	0	3
	**Cochlodinium polykrikoides*	(35)	–	–	–	2	–	1	nd	–	0	3
	**Gymnodinium mikimotoii*	(23)	–	3	–	–	–	–	nd	–	0	3
	**Gyrodinium instriatum*	(24)	–	2	–	–	–	–	nd	–	0	2
	**Alexandrium* sp.	(34)	–	–	–	1	–	1	nd	–	0	2
	**Gymnodinium breve*	(20)	–	–	–	1	–	–	nd	–	0	1
	**Gymnodinium sanguineum*	(32)	–	1	–	–	–	–	nd	–	0	1
	**Gymnodinium simplex*	(16)	–	1	–	–	–	–	nd	–	0	1
	**Dinophysis caudata*	(25)	–	–	–	–	–	–	nd	1	0	1
	Prorocentrum sigmoides	(1)	1	–	–	–	–	–	nd	–	1	–
Total			27	45	21	118	132	222		10	180	395
Bacillariophyceae	*Skeletonema costatum*	(8)	1	11	–	–	–	–	nd	4	1	15
	Pseudonitzchia pungens	(12)	1	3	–	–	–	–		–	1	3
	Rhizosolenia alata f. *gracillima*	(13)	1	3	–	–	–	–	nd	–	1	3
	Rhizosolenia styliformis	(11)	2	1	–	–	–	–	nd	–	2	1
	Leptocylindrus danicus	(4)	1	2	–	–	–	–	nd		1	2
	Chaetoceros affinis	(9)	1	1	–	–	–	–	nd	–	1	1
	**Pseudonitzchia delicatissima*	(18)	0	2	–	–	–	–	nd	–	0	2
	Thalassiosira subtilis	(10)	1	1	–	–	–	–	–	–	1	1
	**Thalassiosira rotula*	(14)	–	1	–	–	–	–	nd	–	0	1
	**Guinardia delicatula*	(31)	–	–	–	–	–	–	nd	1	0	1
	**Thalassionema nitzschioides*	(19)	–	1	–	–	–	–	nd	–	0	1
	Melosira sulcata	(2)	1	0	–	–	–	–	–	–	1	0
	**Asterionella japonica*	(22)	–	1	–	–	–	–	nd	–	0	1
Total			9	27	0	0	0	0	0	5	9	32

Table 1 continued

	HAB species	Sequence	North		East		South		West		SCS	
	Time period		1980–1990	1991–2003	1980–1990	1991–2003	1980–1990	1991–2003	1980–1990	1991–2003	1980–1990	1991–2003
Haptophyceae	**Phaeocystis globosa*	(21)	–	8	–	–	–	–	nd	3	0	11
Total			0	8	0	0	0	0	0	3	0	11
Cyanophyceae	*Trichodesmium erythraeum*	(6)	1	–	–	–	–	–	nd	5	1	5
	**Trichodesmium thiebautii*	(26)	–	–	–	–	–	–	nd	2	0	2
	**Microcystis* sp.	(37)	–	–	–	–	–	–	nd	2	0	2
	**Trichodesmium hildebrandtii*	(36)	–	–	–	–	–	–	nd	2	0	2
Total			1	0	0	0	0	0	0	9	1	9
Raphidophyceae	**Heterosigma akashiwo*	(33)	–	4	–	–	–	–	nd	1	0	5
	**Chattonella marine*	(15)	–	3	–	–	–	–	nd	–	0	3
Total			0	7	0	0	0	0	0	1	0	8
Kinetofragminophora	**Mesodinium rubrum*	(29)	–	5	–	–	–	–	nd	–	0	5
Total			0	5	0	0	0	0	0	0	0	5

(Table 1). Temperature varies from 16°C to 27°C in the northern region and nutrient concentrations increase during the spring (March–May) (Qi et al., 2004), which creates conditions suitable for phytoplankton blooms.

After 1990, 24 previously unobserved species have been recorded to cause HABs (Table 1, E in Fig. 8). *P. globosa* is the most frequent among these new species. *P. globosa* dominates phytoplankton communities in temperate and polar waters (Tang et al., 2001). It has high adaptation ability to temperature changes, and the most favorable temperature is 16°C (Qi et al., 2001). It can bloom in temperate and tropical waters and develop massive blooms in the nutrient-enriched areas (Schoemann et al., 2005). In the SCS it was noted in the northern and western regions only after 1990 (A and D in Fig. 8). In the western region, upwelling was likely to be the main reason for the HABs, providing high-nutrient levels but low temperatures for the growth of algae. For the northern region, *P. globosa* always occurred in winter in regions with enriched nutrient concentrations (Xu et al., 2003).

Previous studies have found the changes of dominant HAB causative species in the different periods in the East China Sea (Tang et al., 2006a, b). In the present study, some species, such as *Melosira sulcata* and *Prorocentrum sigmoides*, induced HABs prior to 1990, but have not induced HABs in recent years, and some other new causative species have been observed in recent years (Table 1). Those changes may be related to many environmental factors. The exact reasons remain to be investigated.

Diatom blooms are included in Table 1 because they were reported as harmful by historical studies, actually killing fish, shrimps, or oysters. For example, fish kills by the diatoms (*Skeletonema costatum*) in April 2003 (http://www.people.com.cn/GB/huanbao/57/20030501/983_235.html). In our database, diatom blooms account for less than 7% of HABs (Table 1).

HAB occurrences related with environmental conditions

The present results show HABs occurred frequently in the northern region in 1998 (A in Fig. 5). In this region, the average precipitation was approximately

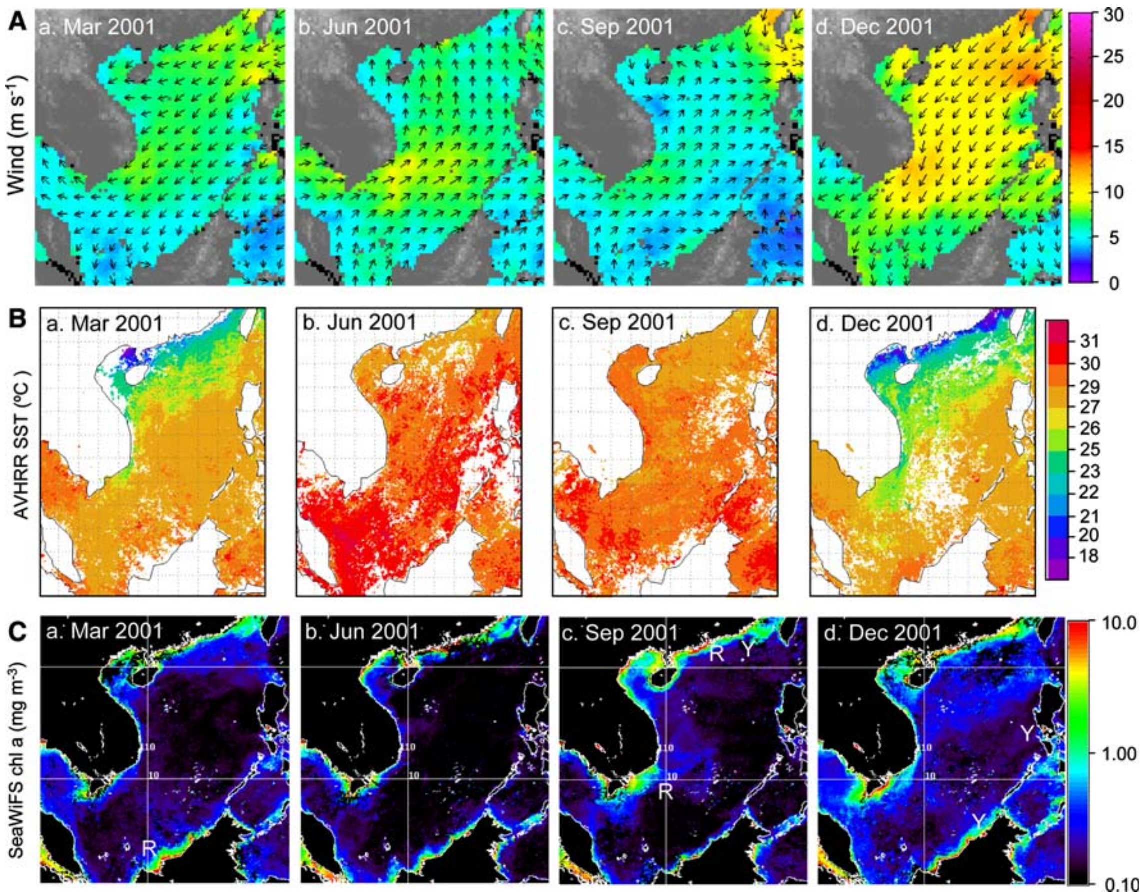

Fig. 9 Satellite images of SCS for March, June, September, and December 2001. (**A**) Monthly average wind; (**B**) Monthly average sea surface temperature; (**C**) Monthly average Chl *a*

56 mm in March, but it reached 257 mm in April of 1998 (http://www.lake.nascom.nasa.gov/tovas/). Heavy rainfalls may have reduced salinity from high river discharges and enriched coastal waters along the northern coast of the SCS. In the same year, the mariculture production was over 1.5 million tons in Guangdong province (http://www.cafs.ac.cn/). Intensive aquaculture causes self-pollution as a result of excessive feeding and fish feces, causing eutrophication of the aquaculture area, thus providing suitable environmental conditions for algae to grow and blooms to occur in the region.

In contrast, very few HABs were observed in the west (D in Fig. 5) in 1998, possibly related to abnormal oceanic conditions in that year. The year 1998 is the most intense El Niño year in the 20th century, resulting in anomalous high SST, weak wind and weak wind-driven ocean circulations (Tang et al., 2004a; Zhao & Tang, 2006; Xie et al., 2003). Under the influence of El Niño, southwest winds were weaker in the west, inducing a decline of coastal upwelling alongshore and lower Chl *a* concentrations in the western SCS (Tang et al., 2004a; Zhao & Tang, 2006). Since upwelling is one of the most important factors in algal blooms in the western region (a and b in Fig. 2) (Tang et al., 2004a, b), weakened upwelling may result in reduced phytoplankton blooms.

We also noticed that phytoplankton blooms occurred in the southern region of SCS, particularly in the northwest region of Sabah in 1998. For similar reasons, El Niño-related changes in the surface winds over the southeast of SCS invokes a strong wind jet in winter season (Isoguchi & Kawamura, 2006), which supports upwelling (c in Fig. 2B) and causes phytoplankton blooms (d in Fig. 2B).

Table 2 Characteristics of HABs in the SCS

	A, Northern SCS	B, Eastern SCS	C, Southern SCS	D, Western SCS
Highly frequent month	April	June	All year around	July
Highly frequent year	1991, 1998	1998, 1991	1994–1998	1999, 2002
Major species	*Noctiluca scintillans*	*Pyrodinium bahamense*	*Pyrodinium bahamense*	*Trichodesmium erythraeum*
Potential cause	Eutrophication/river discharge	Eutrophication	Eutrophication	Upwelling
Examples	March 1998, Mouth region of Pearl River	June 1998, Manila Bay	August 1995, Sabah	June 2002, Binh Thuan Province
Reference	Qi et al. (2004), Tang et al. (2003a)	Azanza & Taylor (2001)	Azanza & Taylor (2001)	Tang et al. (2004b)

The annual HAB occurrences have the highest frequency in 1991, 1995, and 1998 (E in Fig. 5), coincident with three El Niño events (Garcés-Vargas et al., 2005). Studies in the northeast Atlantic have shown that the frequency of HABs is related to regional climate change, in particular change in water temperature (Edwards and Johns, 2006). Further investigation is needed to a better understanding of the effects of El Niño on HABs.

It is evident that the monitoring intensity of HABs has constantly increased in recent years for the entire SCS region (Fig. 1B), but there is no consistent relation between the HAB occurrence and the monitoring frequency (R^2 = 0.0654, $P > 0.05$) (Fig. 10A, B). HAB occurrence decreases after 1998 (E in Fig. 6) though the frequency of monitoring continues to increase (Fig. 1b), and so the ratio (HAB occurrence/HAB monitoring frequency) decreases in recent years (Fig. 10B). The increase of monitoring frequency may contribute only a small part (Fig. 10A) to the increase in HAB reports.

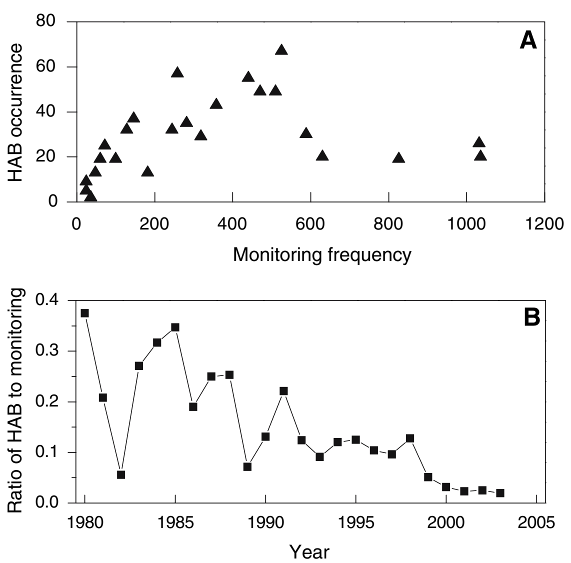

Fig. 10 (**A**) Relation between HAB occurrence and monitoring frequency during 1980–2003. (**B**) Ratio: Divide annual HAB occurrences by annual monitoring frequency

Summary

The present study shows regional, seasonal, and annual variations of HABs in the South China Sea. The causative algae varied among regions and periods. Key factors influencing HABs differ across the regions (Table 2), including wind, current, temperature (factors are not showed in Table 2).

Eutrophication appears to be the key factor for HABs in coastal and bay waters, such as the Pearl River estuary (A in Fig. 11), Manila Bay and the northwest coast of Sabah (B and C in Fig. 11).

Monsoon winds inducing regional upwelling may be one of the key reasons for HABs in some locations, such as coastal water along Vietnam in the southwest monsoon season (D in Fig. 11) and coastal water along Sabah in northeastern monsoon (Upwelling in Fig. 11). Meanwhile, strong wind can resuspend cysts above the sediment, potentially causing blooms in Manila Bay and west of Sabah.

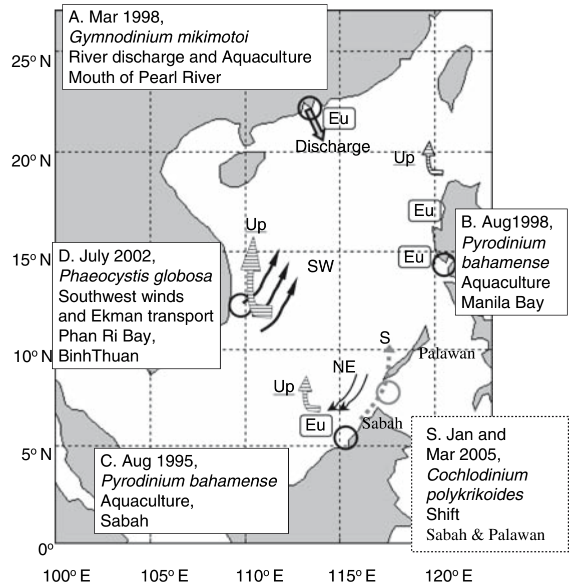

Fig. 11 Four examples of HABs (A, B, C, and D) with associated environmental factors in the SCS. Eu: Eutrophication; NE: Northeast wind; SW: Southwest wind; Up: Upwelling

Coastal currents may shift HAB masses between Sabah and Palawan in the south region.

Relatively high frequencies of HABs in the northern region and low frequencies in the western area in 1998 may be related to the specific environmental conditions associated with El Niño in the area.

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