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Distribution of chlorophyll and harmful algal blooms (HABs): A review on space based studies in the coastal environments of Chinese marginal seas

GuiFeng Wei [a], DanLing Tang [b,c,*], Sufen Wang [b]

[a] Research Center of Hydrobiology, Jinan University, Guangzhou 510632, China
[b] LED, South China Sea Institute of Oceanography, Guangzhou 510301, China
[c] Department of Environmental Science and Engineering, Fudan University, Shanghai 200433, China

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Abstract

Monitoring of spatial and temporal distribution of chlorophyll (Chl-a) concentrations in the aquatic milieu is always challenging and often interesting. However, the recent advancements in satellite digital data play a significant role in providing outstanding results for the marine environmental investigations. The present paper is aimed to review 'remote sensing research in Chinese seas' within the period of 24 years from 1978 to 2002. Owing to generalized distributional pattern, the Chl-a concentrations are recognized high towards northern Chinese seas than the southern. Moreover, the coastal waters, estuaries, and upwelling zones always exhibit relatively high Chl-a concentrations compared with offshore waters. On the basis of marine Chl-a estimates obtained from satellite and other field measured environmental parameters, we have further discussed on the applications of satellite remote sensing in the fields of harmful algal blooms (HABs), primary production and physical oceanographic currents of the regional seas. Concerned with studies of HABs, satellite remote sensing proved more advantageous than any other conventional methods for large-scale applications. Probably, it may be the only source of authentic information responsible for the evaluation of new research methodologies to detect HABs. At present, studies using remote sensing methods are mostly confined to observe algal bloom occurrences, hence, it is essential to coordinate the mechanism of marine ecological and oceanographic dynamic processes of HABs using satellite remote sensing data with *in situ* measurements of marine environmental parameters. The satellite remote sensing on marine environment and HABs is believed to have a great improvement with popular application of technology.

Keywords: Remote sensing; Chlorophyll; HABs; Chinese marginal seas; Marine environment

1. Introduction

China encompasses with four marginal seas namely the Bohai Sea, Yellow sea, East China Sea, and South China Sea situated on the northwestern region of Pacific Ocean. Three major waterways namely Yellow River, Yangtze River and the Pearl River flow generally eastwards into the Bohai Sea, East China Sea, and South China Sea, respectively (Fig. 1). China has encountered a fast economic growth since 1980s, especially in coastal areas through its production, import and exports. Anthropogenic activities confessed with rapid development of agriculture and industries along with population have put a great influence on these coastal waters and the marine environment. Marine chlorophyll concentrations have mounted high in many of the areas e.g., in Daya Bay of Guangdong Province, it was noticeably increased in the last two decades (Qiu, 2001). At the same time, the occurrence of harmful algal

* Corresponding author. Present address: LED, South China Sea Institute of Oceanography, Guangzhou 510301, China. Tel./fax: +86 20 89023203.
E-mail addresses: lingzistdl@126.com, lingzis@scsio.ac.cn (D. Tang).
URL: http://lingzis.51.net/ (D. Tang).

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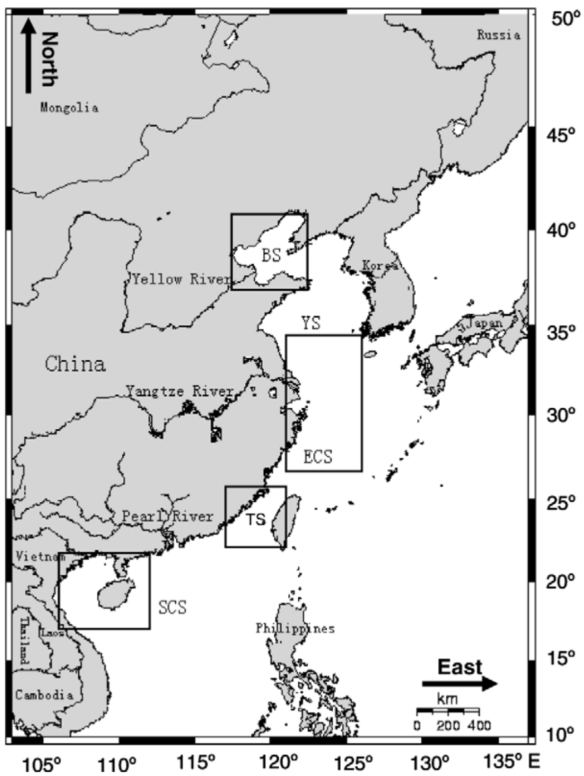

Fig. 1. The geographical location of Chinese marginal seas. BS: Bohai Sea; YS: Yellow Sea; ECS: East China Sea; SCS: South China Sea; TS: Taiwan Strait.

blooms (HABs) also had shown such characteristics of increasing frequency, expanding range, long-lasting period, and severe consequences.

The radiances received by satellite sensors above the ocean generally comes from the scattering of atmospheric moister and aerosols, reflectance of sea surface and ocean color factors (including pigment, suspended material and yellow material etc.), and the reflectance of seabed in case of shallow waters. Those reflecting radiances from pigment, suspended material, and yellow materials are the so called water leaving radiances, of which 5% being the target for ocean color satellite sensors out of total radiance received. In ocean body (case I water), the water leaving radiance is mainly due to chlorophyll reflectance while in coastal water body (case II water), lots of sand and other suspended materials besides ample of phytoplankton are responsible. Especially in estuarine areas, the water leaving radiance mostly comes from the combined distribution of chlorophyll, suspended sand, yellow material, and the like.

Chlorophyll has its specific absorption and reflecting spectrum. The information of chlorophyll concentration in seawaters could be retrieved with the help of ocean color satellite images based on their spectral characteristics. Retrieval of chlorophyll concentration in the oceans with remote sensing is much easier than in coastal waters because of its mature arithmetic of chlorophyll concentrations from remote sensing. Significant studies have been carried out on spectral characteristics of water bodies in Chinese marginal seas, forming a scientific basis for the application of remote sensing technology in coastal waters (Li et al., 2002; Yue et al., 1999; Wu et al., 1998; Ren and Zhao, 2002; Zhang et al., 1992; Fu et al., 1997). Earlier, Chinese researchers have used foreign satellite data to study Chinese marine environments since the first Chinese ocean color satellite (HY-1) was launched only during May 2002. Satellites that provide data on chlorophyll concentration and other marine environmental parameters are listed in Table 1.

2. Chlorophyll and marine primary production in Chinese marginal seas

2.1. Marine chlorophyll

Dynamic changes in spatial and temporal distribution of chlorophyll concentrations in wide range sea areas could be monitored with ocean color satellite remote sensing. Tang

Table 1
Satellites being used to study the ocean color and coastal environments in China

Satellite	Launched by	Sensor	Function period	Factor monitored	Application
Nimbus-7	USA	CZCS	1978 Jun–1986 Dec	Ocean color	Chlorophyll concentrations in Chinese marginal seas (Tang et al., 1998), the upwelling in Taiwan Strait (Tang et al., 2004d)
ADEOS-1	Japan	OCTS	1996 Aug–1997 July	Ocean color and SST	High chlorophyll concentration zones on the north of South China Sea (Tang and Kawamura, 2002a; Tang et al., 2004c)
SeaStar	USA	SeaWiFS	1997 Aug–current	Ocean color	Chlorophyll concentrations on the surface layer of South China Sea (Tang et al., 2003a, 2004c), Upwelling in Taiwan Strait (Tang et al., 2002b, 2004d)
ROCSAT	Taiwan–China	OCI	1999 Jan–current	Ocean color	Upwelling in Taiwan Strait (Tang et al., 2004d), chlorophyll concentrations in South China Sea (Tang et al., 2004c)
FY-1B	China	VHRSR	1990 Sep–current	Ocean color	HABs in Bohai Sea, Yangtze River and Pearl River estuaries during 1999 and 2000 (Cong et al., 2001)
NOAA series	USA	AVHRR	Since 1970	SST	HABs in Pearl River estuary and Hong Kong waters (Tang and Ni, 1996; Tang et al., 2003b)
Landsat series	USA	TM	Since 1972	Marine monitoring	HABs in Bohai Sea (Hu et al., 1991)
HY-1	China	COCTS	2002 May–current	Ocean color	Distribution of chlorophyll concentration, SST, suspended material, and the occurrence for HAB (NSOAS)

et al. (1998) emphasized the spatial–temporal distribution of chlorophyll (pigment) concentrations in Chinese marginal seas through analyzing CZCS data from 1978 to 1986. Their results have clearly indicated that the distribution of marine chlorophyll has followed a generalized distributional pattern. Concerned with spatial distribution, the chlorophyll concentrations in northern seas (Bohai and Yellow Seas) usually stand higher than the southern (South China Sea) (Tang et al., 1998). The concentration values were found rather high (>1 mg m^{-3}) in a 50 km zone along the coast and slowly declined in the seaward direction. In general, the chlorophyll concentrations are also significant in estuaries and the areas outside the estuaries formed Bays (e.g. Yangtze River estuary) (Fig. 2). In upwelling zones of Zhoushan sea area in Zhejiang Province and Taiwan Strait, the chlorophyll concentrations are also remarkable (Tang et al., 1998) (Fig. 2).

The temporal distribution of chlorophyll varied with different seas. In Bohai and Yellow Seas (northern), the sea surface temperature (SST) and chlorophyll concentrations are ranged between 0–28 °C and 0.5–3.5 mg m^{-3}, while, chlorophyll reached crest during the period, Spring-Summer and Autumn-Winter in a year (Tang et al., 2004a). SST of East China Sea is observed to be in the range of 7–28 °C with two peaks of chlorophyll (1.2–1.3 mg m^{-3}) during Spring and Autumn. But in the South China Sea, SST varied between 15–29 °C, yet chlorophyll concentration is relatively less (0.1–0.4 mg m^{-3}), and the monthly variations are not as evident as northern seas (Tang et al., 2004a). The Bohai Sea, Yellow Sea and East China Sea are shallow in nature when compared with the South China Sea. The inputs of Yellow and Yangtze Rivers have made the waters highly turbid and the turbidity is more during the winter due to exchange of surface and bottom waters and also SST declines rapidly in the north of China. Yoko et al. (2001) found that chlorophyll concentrations obtained from the CZCS and OCTS remote sensing data are coinciding well with *in situ* measurements made in East China Sea for all seasons except in winter, for which the estimated values are much higher than field observations. They have concluded that water turbidity in winter would greatly enhance the error between remotely sensed data and field-measured data. Based on the analysis of CZCS and AVHRR data, Ning et al. (1998) discovered that spatial distribution of chlorophyll concentration had a good relationship with surface water temperature in East China Sea, and turned down from north to south with the rise of water temperature.

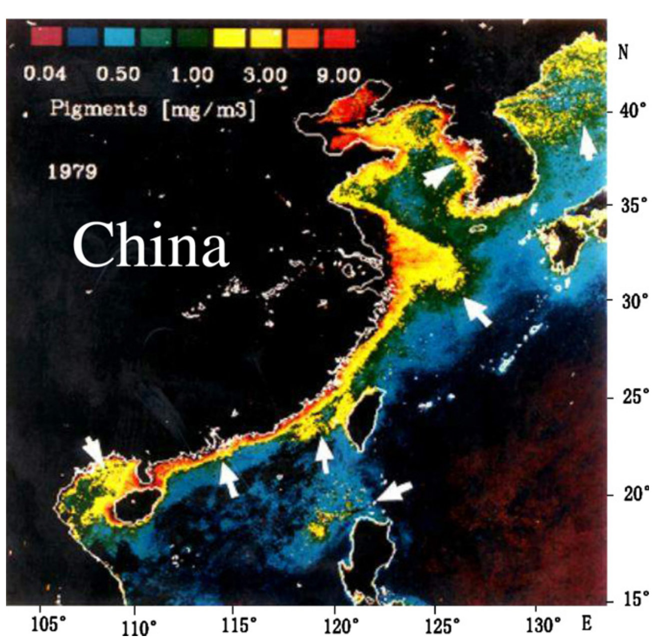

Fig. 2. Spatial distribution of pigment concentrations derived from CZCS in Chinese seas (From Tang et al., 1998).

Differing from northern seas, the South China Sea has lower chlorophyll concentrations except near the coastal waters. For instance, the concentrations are remarkably high in the Gulf of Tonkon, Zhanjiang peninsula, Qiongzhou Strait and at some coastal waters of Hainan Island (Chen et al., 2001a, Tang et al., 1998, 2003a). In contrast, a high chlorophyll concentration zone on the north of South China Sea was observed from OCTS remote sensing image of Asian sea waters during November 1996 (Tang and Kawamura, 2002a). The chlorophyll concentrations retrieved from SeaWiFS data are well matched with field observations even though, the turbidity of the water usually makes overestimates in estuaries. Considering both chlorophyll concentrations retrieved from SeaWiFS data and some marine environmental field measured parameters, Tang et al. (2003a) found that seasonal variation of chlorophyll a and SST in South China Sea were understandable. In most part of the South China Sea, the chlorophyll concentrations are low in summer and high during the winter along with phytoplanktonic blooms on several occasions. Fig. 3 shows a rather high chlorophyll concentration in the Gulf of Tonkin in autumn (Tang et al., 2003a).

Spatial and temporal distributions of chlorophyll concentrations are closely related with river discharges, upwelling, tides, and currents etc., (Chen et al., 2001a; Hu et al., 2003; Tang et al., 1998, 2004c). The high concentrations usually occur in waters with abundant supply of nutrients like estuaries and upwelling areas. In estuaries, the upstream runoff brings a lot of terrestrial nutrients into the sea facilitating growth of phytoplankton, which ultimately results for high chlorophyll concentrations (Hu et al., 2003). Pan et al. (2000) claimed high chlorophyll concentrations near Zhoushan sea area while examining SeaWiFS images (8 October, 1997) acquired for Yangtze River estuary. Zhoushan sea area of Zhejiang Province is well known for its famous fishing zone in China with a considerable fresh water mix and upwelling that allows a great deal of nutrients into this waters favoring for the growth of phytoplankton and chlorophyll (as shown in Fig. 4). The southwest part of Luzon Strait, located between Philippine Sea and the South China Sea, always shows increased chlorophyll concentrations during winter establishing a close

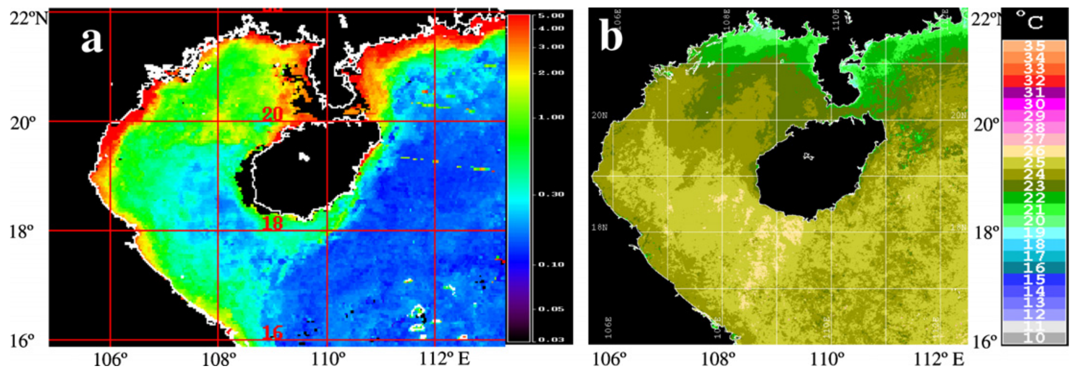

Fig. 3. Distributions of chlorophyll and SST at the Gulf of Tonkin, South China Sea. (a) SeaWiFS Chl. a image in Oct 2000, (b) NOAA SST image in Nov 2000 (From Tang et al., 2003a).

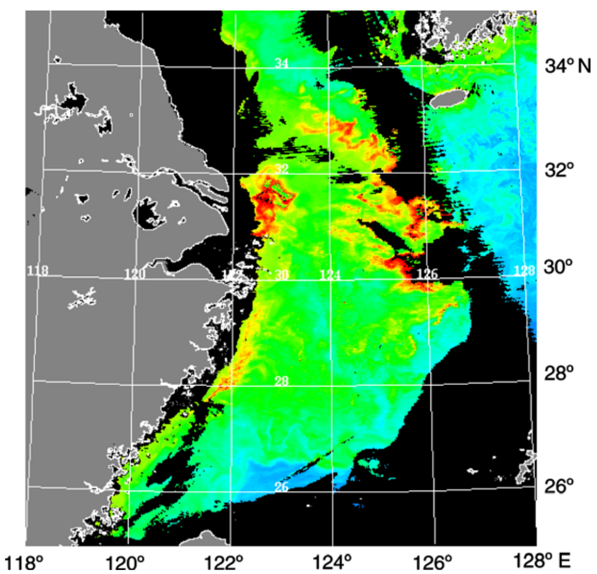

Fig. 4. MODIS image showing Chl. a distribution pattern for the Yangtze River Estuary area in April 2003.

relationship with winter-occurred upwelling in this area (Tang et al., 1999). Every year, southeast monsoon brings upwelling in the waters near Vietnam from July to September, ensuing high chlorophyll concentrations (Dien et al., 2003; Tang et al., 2004b,c).

2.2. Marine primary productivity

Marine primary productivity is very important in marine ecosystem and hence, it is imperative to figure out the spatial and temporal distribution of marine primary productivity in wider areas. For the study of marine primary productivity, satellite remote sensing is a powerful tool to obtain distributional patterns on a large scale. Since phytoplankton is the most prominent component of productivity, the marine primary productivity could be calculated using chlorophyll concentrations estimated from remote sensing data with the help of available arithmetics. Many researchers have developed numerous arithmetics intended to calculate the primary productivity from chlorophyll data in the sea areas of China (Li and Shao, 1998; Fei et al., 1997; Shang and Hong, 2001a; Wu, 2000). However, these arithmetics are much varied from one another and many of them are still needs to be improved. Fishing zones in the sea are usually traced out with the help of primary productivity values and for example, the upwelling zone in Taiwan Strait is considered as a big fish catch area (Tang et al., 2002b).

Only a few studies have been completed so far on the distribution of marine primary productivity using remote sensing data. Li et al. (2003) combined both SeaWiFS data and field-oriented observations to calculate monthly chlorophyll concentrations of 1998 in the East China Sea, and further discussed spatial–temporal distribution of monthly primary productivity. In East China Sea, the primary productivity is high near the coastal areas and declined towards offshore. The temporal distribution also had two peaks showing one is in spring and another in autumn, concurring with the results of Tang et al. (2004a).

3. Oceanic environmental studies

Distribution of chlorophyll is primarily related to the ocean currents and therefore, satellite ocean color study can help us to investigate ocean currents through analyzing the spatial pattern of ocean color distribution.

Differentiation of upwelling zones using a chlorophyll concentration image is found to be very useful method. Usually, the chlorophyll concentration and SST in upwelling zones are distinctly different from adjacent waters on remote sensing images and so, the position and boundary of some big upwelling zones could be easily identified on the images of ocean color and SST remote sensing. Five big upwelling zones in Taiwan Strait are evidently seen from the spatial distributions of retrieved chlorophyll concentration and SST from SeaWiFS and AVHRR images (Tang et al., 2004d). Both SST and chlorophyll concentrations in upwelling zones are apparently higher than adjacent waters (Fig. 5).

The SeaWiFS images of February and March 1998 showed that chlorophyll concentrations in the western

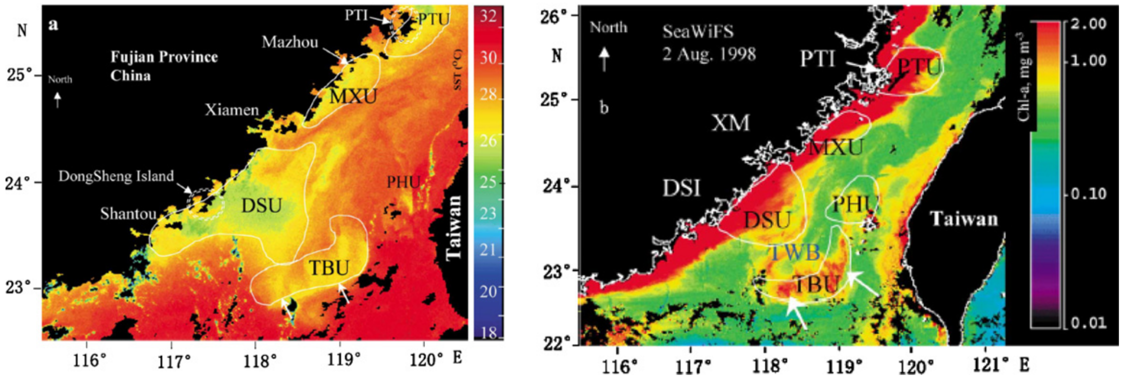

Fig. 5. The upwelling zones in the Taiwan Strait (TS in Fig. 1) in August 1998. (a) SST (°C) and, (b) chlorophyll concentration (mg m^{-3}) (From Tang et al., 2002b).

Taiwan Strait were higher than that of east. Historical data indicates that runoff from both Fujian and Zhejiang provinces brings a lot of nutrients into Taiwan Strait, and the invasion of Kuroshio branch current from south to north are the two major causes for such a kind of chlorophyll concentration distributions (Shang et al., 2001b). Shang et al. (2001c) have analyzed the ecological effects of Kuroshio Current incursion for the winter of 1998 based on SST, chlorophyll concentration, water temperature, salinity, and the field observations made on chlorophyll concentrations. Also, the current flow velocity can be calculated with the variation of chlorophyll concentrations in the current in a given period. The average velocity of the surface current in Taiwan Strait was estimated as 12 km d^{-1} (August, '97), while analyzing the chlorophyll concentrations of SeaWiFS for two days (Pan et al., 2000).

Chlorophyll concentrations usually stand high in the mixing zones between two water masses. Based on this phenomenon, Liu and Su (1989) divided the Yellow Sea into eight water masses by analyzing the chlorophyll concentrations estimated from CZCS data combined with simultaneous field-measured variables such as water temperature, salinity and transparency etc.

4. HABs monitored by satellite remote sensing

In Chinese coastal waters, harmful algae blooms (HABs) have caused tremendous environmental and economic losses for decades (Guan and Zhen, 2003). Marine HABs being monitored by satellite remote sensing is an expanding application of remote sensing-retrieved chlorophyll concentration (Chaturvedi et al., 1998; Stumpf et al., 2003), and is also a hotspot in the marine environmental studies (Yang and Lin, 1997; Huang et al., 2002; Pan et al., 2000). Yet, most of studies on HABs using remote sensing technicals in China are just to observe the occurrence of HABs only. It was felt that further studies on the dynamic process and mechanism of HABs in relation to other marine environmental factors such as SST, wind, current etc. should be carried out.

4.1. HABs monitoring with non-ocean color satellites

Sea surface temperature usually changes with the occurrence of algae blooms and so it is quite feasible to monitor large scale HABs with the help of SST satellite remote sensing data. Many HABs monitoring in Chinese seas were done with the help of NOAA series, Landsat series, and other non-ocean color satellites. NOAA/Tiros satellites play an important role in monitoring of HABs. SST monitored by AVHRR remote sensor carried on NOAA series satellites has been used for HABs monitoring in East China Sea (Huang et al., 2002). The development period and boundary of an HAB could be estimated via combined analysis of SST variations and marine environmental field observation. For example, Pan et al. (2000) observed *Noctiluca scintillans* bloom in Liaodong Bay during July 1991 and late September 1989 using Landsat data. Cong et al. (2001) monitored HABs in Bohai Sea, Yangtze River and Pearl River estuaries with the help of NOAA-14 and FY-1C satellite data and found that was of great assistance.

4.2. HABs monitoring with ocean color satellite

If any algae bloom area is large enough and lasts for a considerable period, the high chlorophyll concentration zone could be easily identified from ocean color remote sensing images and therefore, the status of HAB occurrences would easily traced out by analyzing the variations of ocean color factors and SST.

In 1998, frequent occurrences of HABs had resulted in serious economic and environmental losses in Chinese seas. Tang et al. (2003b) observed a path of 20–30 m algal bloom in the Pearl River estuary during November 1998, combining both field observation and SeaWiFS analysis. High chlorophyll concentrations were detected during the formation of HAB and this bloom appeared at the mixing zone of fresh water characterized by low temperature and salinity while, seawater with high temperature and salinity values. A *Phaeocystis* cf. *globosa* bloom occurred on the west of South China Sea during June–July, 2002. Tang et al. (2004b) have

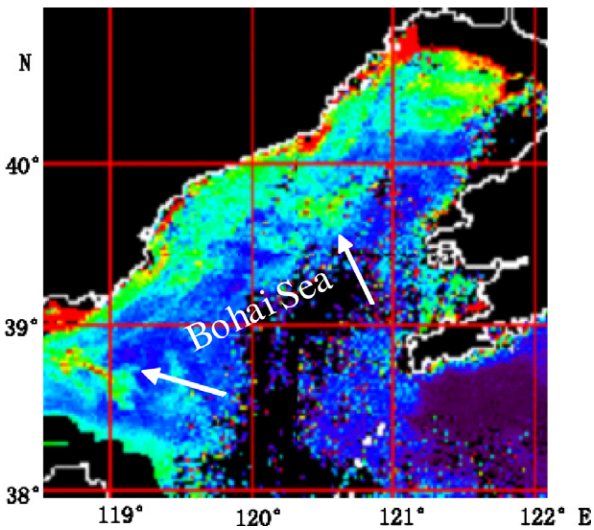

Fig. 6. SeaWiFS derived ocean color image showing HAB related features in the Bohai Sea (BS in Fig. 1) in September 1998. (From Tang et al., 2006).

analyzed the marine dynamic processes of this HAB on the basis of remote sensing images of marine chlorophyll, SST and wind velocity combined with *in situ* measured data.

Sequential satellite remote sensing images are highly helpful in studying the movement of HAB and its marine dynamic processes. Tang et al. (2006) observed the movement of HAB in Bohai Sea through the analysis of SeaWiFS and AVHRR images. They emphasized on the impacts of wind, wave and currents on the movement of HAB and stated that terrestrial nutrient inputs, water temperature, and current characteristics are also responsible for HAB movements (Fig. 6).

Satellite remote sensing has advantages in detection and tracing the process of algae blooms, and it could be well applicable for HABs monitoring and forecasting on large scales. At present, there are some limitations in satellite applications to study HABs as it is difficult to detect small HAB cases. Moreover, much of these works in this field are still at primitive level and there is a hope for greater perspectives in the studies of HABs and their dynamic processes in China. HABs monitored with remote sensing in Chinese seas are listed in Table 2.

5. Summary

No doubt that satellite remote sensing has become an effective tool in the assessment of natural resources from land to the ocean providing timely and cost effective means to obtain reliable data over inaccessible areas like high seas where, chlorophyll and HABs naturally occurs. It is always advantageous to study these variables both technically as well as conventionally to make authoritative conclusions. The distribution of chlorophyll concentrations in Chinese

Table 2
Major research works on HABs using remote sensing in Chinese seas

Time	Area	Satellite/sensor	HAB species	Reference
1989	Bohai Sea	Landsat/TM	*Gymnodrium* sp.	Hu et al. (1991)
1991 July	Liaodong Bay in Bohai Sea	NOAA/AVHRR	*Noctiluca scintillans*	Gong et al. (2000)
1995 Aug	Xingcheng, suizhong sea area in Bohai Sea			
1995 Apr	Coastal sea area of Zhejiang Province	NOAA/AVHRR	*Skeletonema costatum* *Noctiluca scintillans*	Lu et al. (2000)
1997 Aug			*Gonyaulax polygramma* *Prorocentrum* sp.	
1996 Aug	Zhejiang province sea area	SeaStar/SeaWiFS	*Gymnodinium* sp. *Noctiluca scintillans*	Huang et al. (1998)
1997 July	Zhejiang province sea area		 *Chrysocapsa* sp.	
1997 Nov	Guangdong province sea area			
1997 Nov	Coastal sea area of Xiamen city, Fujian province	SeaStar/SeaWiFS	*Mirocystis* sp.	Chen et al. (2001b)
1997 July	Bohai Sea	NOAA/AVHRR	*Ceratium furca*	Pan et al. (2000)
1998 Sep	Bohai Sea	SeaStar/SeaWiFS NOAA/AVHRR	*Ceratium furca*	Tang et al. (2006)
1998 Nov	Pearl River estuary	SeaStar/SeaWiFS NOAA/AVHRR QuikScat		Tang et al. (2003b)
1998	Bohai Sea	NOAA-14 /AVHRR	*Ceratium furca*	Zhao (2003)
1999–2000	Bohai Sea, Yangtze River Estuary, Pearl River Estuary	NOAA-14/AVHRR FY-1C	*Gymnodrium* sp. *Noctiluca scintillans* *Prorocentrum triestinum* *Skeletonema costatum* *Peridinium* sp. *Gyrodinium* sp.	Cong et al. (2001)
2002 Jun–July	Western of the South China Sea	SeaStar/SeaWiFS NOAA/AVHRR QuikScat	*Phaeocystis* cf. *globosa*	Tang et al. (2004b)

marginal seas showed high ranges in the northern seas, coastal waters, estuaries, and upwelling zones. It was proved that the study of occurrence and dynamics of harmful algae blooms, marine primary productivity, and oceanic environments is much easier with the help of chlorophyll concentration data retrieved from ocean color satellites. Nowadays in China, the main research method in marine environmental investigations is field observation and there is a great perspective for monitoring of HABs and marine chlorophyll concentrations with satellite remote sensing. Most of HABs monitoring studies using remote sensing are just at primitive stages and it is essential to study the HABs formation and ocean dynamics mixed with biology, remote sensing, and oceanographic aspects etc.

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