Hydrobiologia **511:** 1–15, 2004.

Monthly variation of pigment concentrations and seasonal winds in China's marginal seas

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Received 27 February 2001; in revised form 7 April 2003; accepted 5 May 2003

Key words: satellite remote sensing, CZCS, pigment concentration, OCTS, wind, sea surface temperature, monthly variation, China Sea

Abstract

China's marginal seas extend from temperate, subtropical to tropical zones, which encounter different monsoons. This study investigates the monthly variation of phytoplankton pigment concentrations (PC) from 1978 to 1986, and analyzes seasonal winds with sea surface temperatures (SST) among the Bohai Sea, the Yellow Sea, the East China Sea and the northern South China Sea. Nimbus satellite Coastal Zone Color Scanner (CZCS)-derived PC images were averaged into monthly fields for the entire area; we then emphasize the period of one year from November 1979 to October 1980, when CZCS data availability was relatively good. Monthly variability of PC has been compared among three regions (the outlets of the Yellow River, the Yangtze River and the Pearl River). The results revealed well-defined seasonality of PC, wind and SST from north to south in China's marginal seas. In the northern area (Bohai Sea and Yellow Sea), variability in SST (0–28 °C) and PC (0.5–3.5 mg m^{-3}) was high with two peaks of PC appeared in spring–summer and in fall–winter in each year. In the East China Sea, two peaks of PC (1.2 mg m^{-3} in March and 1.3 mg m^{-3} in November) were in evidence, where SST variations were ranged 7–28 °C in one year. However, in the southern area (northern South China Sea), variation in SST (15–29 °C) and PC (0.1–0.4 mg m^{-3}) was relatively low; the monthly variation of PC was not so high compared with north area. OCTS derived ocean color data obtained from April 1997 conformed the spatial pattern of Chl-*a* and colored dissolved organic matter (CDOM), and showed high CDOM and total suspended material (TSS) in the coast waters in the north part of China's marginal seas. Seasonal variation of PC may be related to the reversed monsoon; and spatial variation of PC may be influenced by river discharge, upwelling and coastal currents. High PC areas match good fishing grounds in terms of season and location in the study waters.

Introduction

Rapid industrialization of China since 1980 has placed very heavy burdens on the coastal environment. The magnitude of the problem will increase in the coming decades as river water runs into the coastal zone, carrying organic and inorganic wastes from inland development, and as the fast-growing coastal aquaculture industry extends its eutrophicating effects (Qian, 1994). A thorough examination of the seasonal and geographic variations of pigment concentrations (PC) during 1979–1986 in the continental margin regions off China can provide relevant information for oceanic environment. It may also help to determine eutrophicating and anthropogenic impact by comparison of patterns from earlier years with recent years. This study examines the monthly variability of PC in the continental shelf region of China by examining Nimbus satellite Coastal Zone Color Scanner (CZCS) and ADEOS's Ocean Color and Temperature Sensor (OCTS) derived ocean color images. The monthly variation has been displayed with an emphasis during November 1979 to October 1980 and then compared with NOAA's AVHRR sea surface temperature and QuikBird's SeaWinds data. Our aim is to determine the monthly variation of PC in the continental region of China, with particularly attention to the shelves off mouths of the Yellow, Yangtze, and Pearl Rivers where are good fishing grounds.

Chlorophyll *a* (Chl-*a*) distributions have been studied in separated regions of China seas. Fei et al. (1988) reported that there were two peaks of Chl-*a* in one year in Bohai Sea, with a high peak in March (1.95 mg m^{-3}) and a low peak in September (1.4 mg m^{-3}). Two peaks of Chl-*a* were again reported (Zhang et al., 1985) in Dongshan Bay (Fig. 1) in the southern East China Sea in each year, with one peak in the autumn (3.81 mg m^{-3} in September) and the other in the winter (4.59 1.95 mg m^{-3} in January and February). Ning et al. (1988) reported that in the adjacent East China Sea, small-cell phytoplankton dominated in winter whereas the presence of sharp maxima related to diatom populations was found in summer. Chl-*a* in the Taiwan Strait also had two peaks (Fujian Institute of Oceanology, 1988), with the higher one in October (2.51 mg m^{-3}) and the lower one in April. All of these previous studies were conducted by ship surveys and therefore had limited spatial and temporal coverage. The Chinese State Oceanic Administration had sponsored the publication of 'Marine Atlas of Bohai Sea, Yellow Sea and East China Sea' (Chen & Niu, 1991), which summarized all oceanic surveys in China seas up to 1987. The atlas displayed seasonally horizontal (surface, 10 m, 20 m, 35 m, 50 m, 75 m and 100 m) Chl-*a* distributions from Bohai Sea to Shantou (Fig. 1). However, there have been no large-scale, monthly variation studies of the pigment concentration covering the entire area of China's marginal seas from satellite. Remotes sensing study is also lacking for the comparison of wind and water temperature profiles among all China's seas.

Satellite ocean color data have been successfully used to study the seasonality of phytoplankton pigments in many oceans of the world (Müller-Karger et al., 1989; Strub et al., 1990; Thomas & Strub, 1990; Kester & Fox, 1993; Tang et al., 2003). With satellites (CZCS and AVHRR) and in situ observations, Ning et al. (1998) studied physicobiology in the East China Sea. They reported that variation of physicobioloical features shifted systematically from each subarea to the next, as exemplified by the temperature increases and the pigment decrease from northwest to southeast. They pointed out that it was difficult to define the explicitly extent of phytoplankton biomass by the circulation within the East China Sea. By examining annual composite CZCS images, Tang et al. (1998) reported annually variations of PCs on the continental shelf of China. PCs were higher ($>$2.0 mg m^{-3}) over the inner shelf along China and in the Yellow Sea and decreased seawards and southeastwards (offshore) with a minimum value ($<$0.5 mg/m^{-3}) in the Philippine Sea. CZCS images also revealed winter phytoplankton blooms southwest of the Luzon Strait in the South China Sea (Tang et al., 1999). Their results indicated that the spatial variation of PC is related to river discharge, upwelling, and ocean current.

China's marginal seas lie between 15–42° N and 105–134° E in the western Pacific Ocean (Fig. 1). It includes the Bohai, the Yellow Sea, the East China, and the north part of the South China Sea, extending from temperate, subtropical to tropical zones. Such a latitudinal pattern with reserved monsoon may also play an important role in the marine ecology, particularly on fish migration and fisheries recruitment. Our questions are: what is the monthly/seasonal variation of PC in China's marginal seas? What is the spatial variation of PC among these four seas from north part (Bohai) to south part (South China Sea) of China? How does monsoon affect distribution of PC and SST? The present study utilizes the historical CZCS archive (1978–1986) to examine phytoplankton PCs, and their relation to wind and SST in this region. The PC patterns of geographic and monthly variations gathered from November 1979 to October 1980 are the earliest available satellite data for comparison with later ocean color data. In doing so, long-term changes in coastal water quality might be projected with an improved knowledge of the historical phytoplankton biomass in this region.

Materials and methods

CZCS data processing

Nimbus CZCS data were collected from November 1978 to June 1986. All available individual two-minute scenes covering the study area were screened with the BROWSE facility developed by the National Aeronautics and Space Administration (NASA) at the

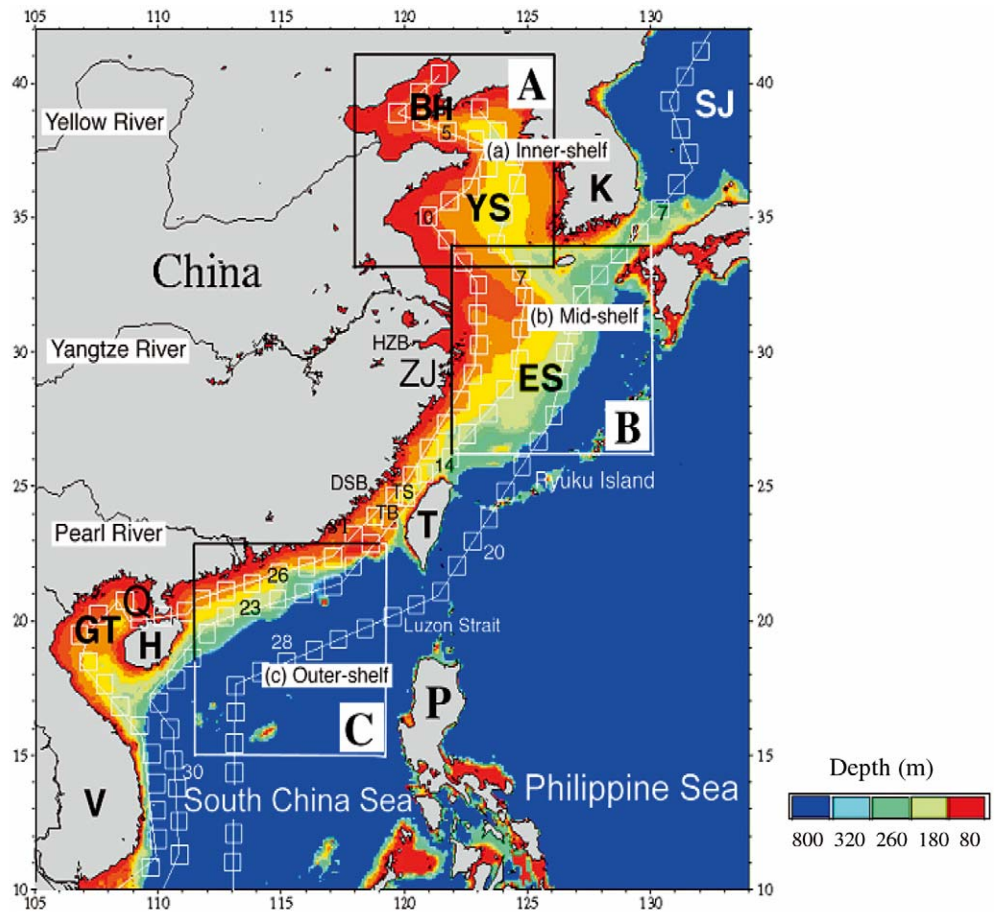

Figure 1. Bathymetric chart of the study area with three sub-region (Box A, B and C), and three transects (a: inner shelf; b: mid-shelf and c: outer shelf) for CZCS data sampling. BH: Bohai Sea, DSB: Dongshan Bay, ES: East China Sea, GT: Gulf of Tonkin, H: Hainan Island, HZ- Hangzhou, K: Korea, LS: Luzon Strait, P: Philippines, Q: Qiongzhou, QTJ: Qiantangjiang, SJ: Sea of Japan, ST: Shantou, T-Taiwan, TB: Taiwan Bank, TS: Taiwan Strait, V: Vietnam, YS: Yellow Sea, Z: Zhejiang.

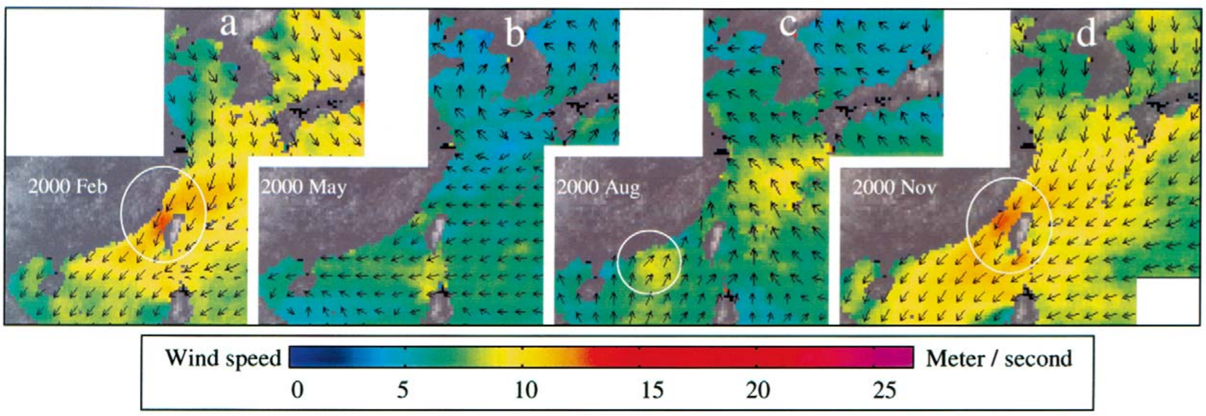

Figure 7. Monthly averaged wind images derived from QuikScat. Color bar indicates wind speed, and arrows show wind directions. Land regions are colored gray. Areas where QuikScat data are not available are black.

Goddard Space Flight Center. All valid CZCS data covering more than 5% of the study area were selected, and all available 2-min scenes of the study area for each month/year were analyzed (Tang et al., 1998).

The images had a spatial resolution of 4×4 km^2 as processed by NASA. Standard atmospheric and bio-optical algorithms were used (Gordon et al., 1983) to correct for aerosols, cloud cover, and sun glint. PC (chlorophyll plus phaeopigments and dissolved organic material) was derived from ratios of blue (443 nm) or blue-green (520 nm) water-leaving radiance to green radiance (550 nm). Areas with no data, land, clouds, or areas with high reflectance due to influence of the bottom or sun glint were eliminated by masking. Coastal zones with high concentrations of sediment, particularly nearshore regions of river plumes, are classified as land and/or clouds by simple thresholds set in the NASA-approved algorithms on CZCS bands 1, 3, and 6. In relatively clear oceanic waters, the accuracy of the CZCS product is expected to be of the order of 30–40% of the concentration of pigments (Gordon et al., 1983). All images were remapped to an area encompassing the region (15–42° N and 105–134° E) using a cylindrical equidistant projection before generating the averaged images. The final spatial resolution of each image was approximately 6×6 km^2 per pixel (Tang et al., 1998). Monthly averaged images were computed based on the arithmetic average of cloud-free pixels using in-house software developed with IDL (Interactive Data Language from Research System Inc.).

Three large regions of 780 km $\times$ 780 km (130 pixels $\times$ 130 pixels) were chosen to cover the three river outlet regions, namely the outlets of the Yellow River, the Yangtze River, and the Pearl River (Fig. 1, Box A, B and C). The average values of PCs of maximum possible 16 900 pixels in each box were computed to derive a regional monthly mean value. The 16 900 pixels, stated as the number of samples per box, will vary depending on the amount of cloud and land in the box. If there is no data, we do not include them in calculating the average values.

Three sampling transects (inner shelf, mid-shelf, and outer shelf) were also selected along the Chinese coast from the northern Bohai Bay to the southern Gulf of Tonkin (Fig. 1). Each transect was composed of a series of stations (small boxes in Fig. 1), and each station covered 25 $\times$ 25 pixels. The location of each transect was based on the depth of the water and the distance offshore to illustrate the variation in pigment values from north to south as well as from inshore to offshore. There were 40 stations in the inner shelf transect, which was about 50 km off the coast with a depth around 40–60 m (except on the west coast of the Yellow Sea, which is very shallow). The mid-shelf transect was about 250 km off the coast and had 33 stations. Depth along this mid-shelf is about 180 m (except in the East Coast of Vietnam, which is very deep). The outer shelf transect had 37 stations. Depths along this transect were greater than 300 m (except in the Sea of Japan and the eastern parts of the East China Sea) and it was about 500 km off the coast. The average PC of the 625 pixels at each station was computed for each monthly mean.

Some limitations exist with the CZCS data set because of the substantial temporal gaps in the series of images. This is caused by the lack of scheduled operation of the CZCS sensor at various times combined with cloud coverage (Feldman et al., 1989; Tang et al., 1998). A total of 2139 scenes were obtained over our area of interest during the CZCS mission (1978 to 1986), and we generated 71 monthly averaged images from the series. CZCS data coverage and availability varied from month to month for our study area. Image coverage was fairly good during the period from November 1979 to December 1980, with 629 scenes (29.4% of total) for those 13 months. The largest number of scenes obtained for one month was 97, for May 1980, followed by 77 scenes for June and 67 scenes for November of the same year.

OCTS ocean color data

Japanese ADEOS's Ocean Color and Temperature Sensor (OCTS) derived ocean color images were processed through SeaDas (MSL 1) (Baith et al., 2001), adopting the in-water algorithm developed by Kishino et al. (1998) as part of the ongoing Asian I-Lac Project (Tang & Kawamura, 2002). We processed monthly averaged OCTS Chl-*a*, Colored Dissolved Organic Matter (CDOM) and Total Suspended Material (TSS) images with 4 $\times$ 4 km^2 for April 1997.

Wind speed and direction

The microwave scatterometer SeaWinds was launched on the QuikBird satellite in June 1999. QuikScat is essentially a radar device that transmits radar pulses down to the Earth's surface and then measures the power that is scattered back to the instrument. Wind speed and direction over the ocean surface are retrieved from measurements of the QuikScat backscattered power (Wentz et al., 2001). Monthly averaged QuikScat wind vector images were produced by Remote Sensing Systems and sponsored by the NASA Ocean Vector Winds Science Team (NASA 2001). The earliest monthly wind data we could obtain is for 2000.

Water temperature

Sea surface temperature (SST) data were obtained from the series of NOAA (National Oceanographic and Atmospheric Administration) satellites collecting data with Advanced Very High Resolution Radiometer (AVHRR), collected from July 1983 to December 1986 with resolutions of 4 $\times$ 4 km^2. Weekly mean SST were calculated for the three regions – the outlets of the Yellow River, the Yangtze River, and the Pearl River (Fig. 1, Box A, B and C) – using in-house software developed with IDL at the Remote Sensing Laboratory of the University of South Florida.

Results

Monthly variation of pigment concentrations

Winter (November–January)
In November 1979 (Fig. 2a), high PC (about 2 mg m^{-3}) appeared in the Bohai Sea (area [1] in Fig. 2a; hereafter the area is noted only as a number), in the northern Sea of Japan [2], and southern coastal Japan [3]. PCs were high in all coastal waters of China, especially in the East China Sea [4], the Taiwan Strait [5], and the Gulf of Tonkin [6]. Because of high suspended sediment concentrations, coastal areas of the Yellow Sea [7] and the outlet of the Yangtze River [8] were masked black. PC was low ($<$ 0.5 mg m^{-3}) around the Philippines. In December 1979 (Fig. 2b), PC was higher in the Sea of Japan compared with November, particularly in the north [1]. A remarkably large plume of high PC ($>$1.0 mg m^{-3}) [4] extended southeastward nearly 500 km from the Yangtze River. This plume merged with high pigment waters from the coast of Yellow Sea [7]. Some of this discoloration is likely due to CDOM and also suspended sediment in addition to phytoplankton, as is seen in other river plumes. A very obvious and large area (300 km $\times$ 450 km) of high PC ($>$1.0 mg m^{-3}) appeared in southwestern Luzon Strait [5]. Another patch ($>$1.0 mg m^{-3}) occurred northeast off Taiwan [6]. PC was very low ($<$0.2 mg m^{-3}) in the Philippine Sea. In January 1980 (Fig. 2c), PC reached a very high level in the Yellow Sea, particularly in the southwestern part [1], where it reached 3 mg m^{-3}.

Spring (February–April)
In February and March 1980 (Fig. 2d, e), PC was very high in the Bohai Sea [1]. In April 1980 (Fig. 2f), PC was high in the Bohai [1] ($>$5 mg m^{-3}), the Yellow Sea, the Sea of Japan [2] and the waters off southern Japan. The high values in the Bohai Sea could be the result of discharge of CDOM, as well as high concentrations of algae off the Yellow River mouth. Pigments concentrations were also high in the Japan Sea [2]. An arc-shaped feature [3] of high PC was observed about 600 km off the center of the Yangtze plume, along the edge of the continental shelf of the East China Sea, connecting with the Korea Strait [4]. The concentration stayed high near the coast in the Bohai Sea [1] and in plume off the Yangtze River [5]. Again, the nearshore core of the plume of the Yangtze was masked black because of high sediment concentrations, but high values due to the combined effect of CDOM and phytoplankton dominated the offshore portions of the plume.

Summer (May–July)
CZCS coverage was very good in May 1980 (Fig. 2g). High PC ($>$5 mg m^{-3}) was seen in the center of the Bohai Sea [2], as in April. The Yangtze plume [1] was much smaller and sparser than in previous months. The arc-shaped feature of high pigment off the plume of the Yangtze was still present [3]. Uneven high PCs (long patches of yellow color) appeared in the Sea of Japan [4]. In June 1980 (Fig. 2h), PCs were relatively low. There were two eddy-like features [1 and 2] traced by pigments south and offshore of the Ryukyu Islands. The plume off the Yangtze River appears to have two edges [3 and 4]. The upper edge [3] merged with high pigment from the coast of the Yellow Sea [5], the down edge [4] came from the Yangtze River and was big. In July 1980 (Fig. 2i), PCs in the Bohai Sea [1] and in the Sea of Japan [2] decreased further. The plume off the Yangtze River [3] had a very high PC, but it did not extend as far as it had in previous months. There was an area with high PCs 150 km off the Zhejiang province [4] (Fig. 2i).

Fall (August–October)
In August 1980 (Fig. 2j), the PC was generally much reduced. PC was high in the Bohai Sea [1]. The plume [2] off the Yangtze River was small. An individual CZCS image of 25 August 1984 clearly showed this

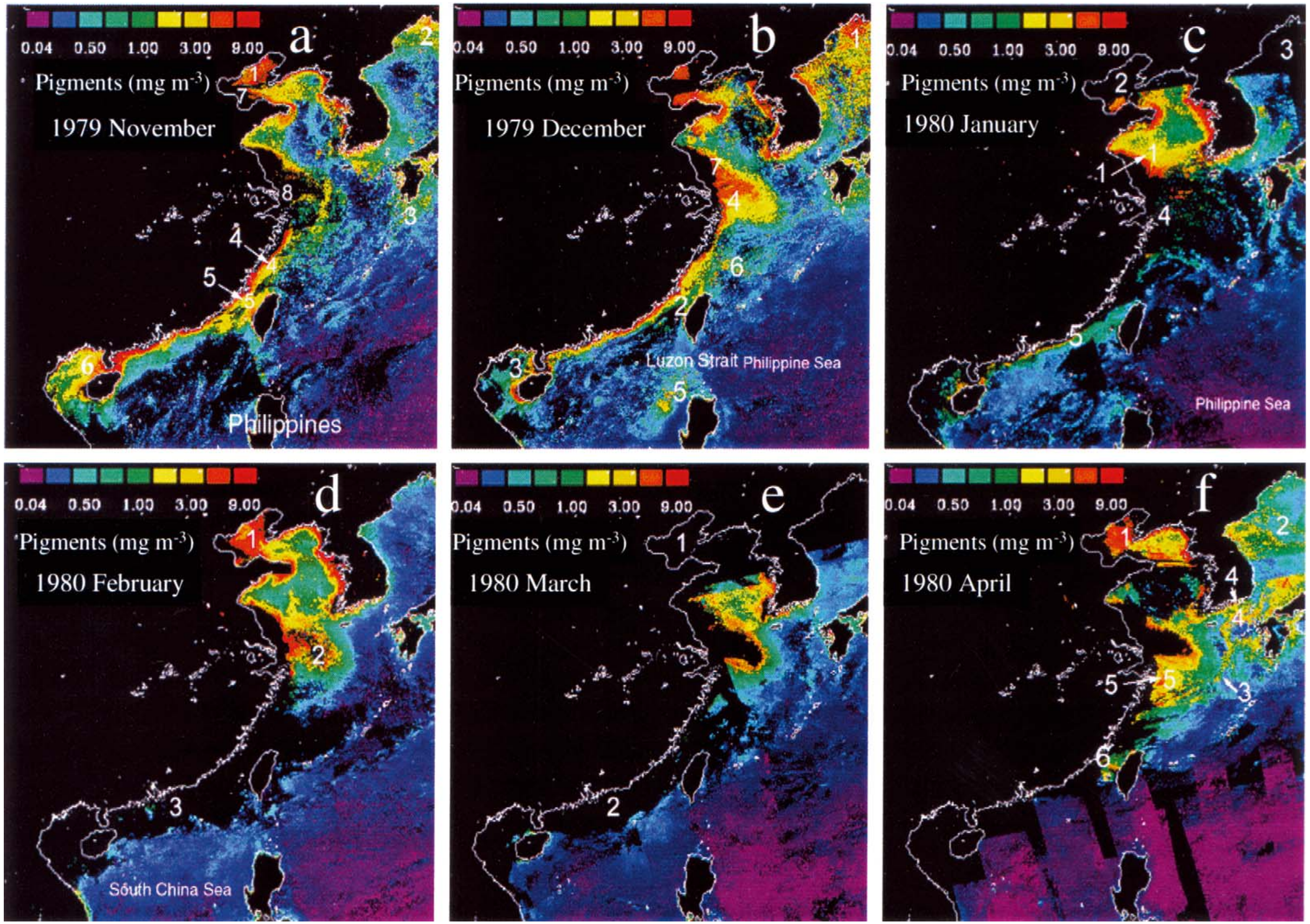

Figure 2. (a–l) CZCS monthly averaged images from November 1979 to November 1980. The small image in Figure 2j is an individual scene of CZCS pigment concentration of 25 August 1984, showing the pigment plume (two tongues) off the Yangzte River. The coastline was marked with white; land, clouds and missing data were marked with black. Color bars indicate pigment concentration (mg m^{-3}). H: Hainan Island.

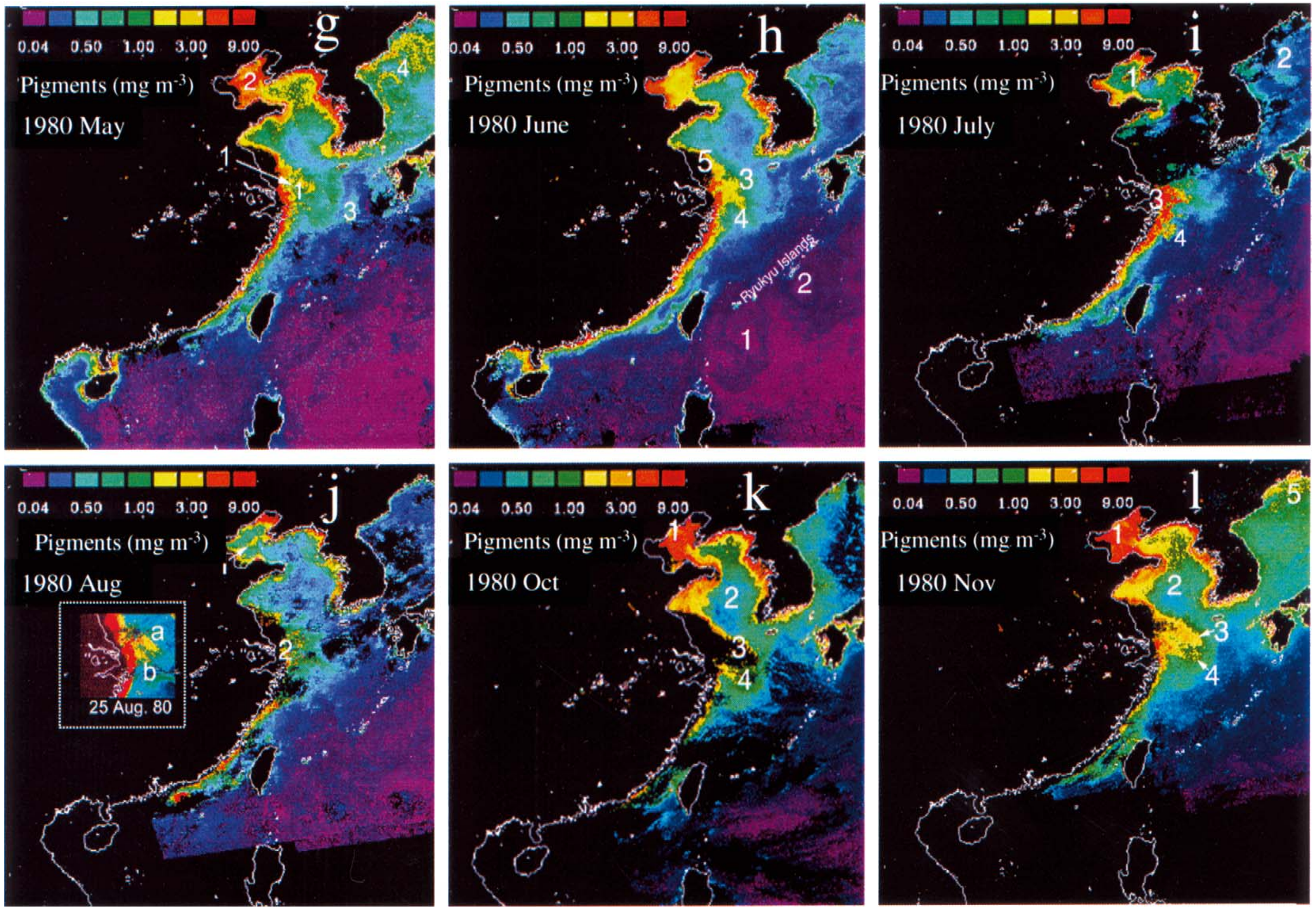

Figure 2. (Continued).

pigment plume with two edges (a and b in small box image of Fig. 2j). There was no data available in September. In October (Fig. 2k) and November (Fig. 2l) 1980, PC increased, particularly in the Bohai Sea [1] and the Yellow Sea [2]. The plume off the Yangtze again diverged into two edges: the northern edge [3] merged with high pigment on the coast of the Yellow River and was bigger than the southern edge [4], which came from the Yangtze River. PC increased in the Japan Sea in November [5]. This pattern was similar to that in November 1979.

Seasonal and geographic variations of pigment concentrations

Along three (inner, mid, and outer shelves) transects: The monthly mean PCs in the three transects (inner, mid-, and outer shelves) along the Chinese coast are shown in Figure 3. The inner shelf (Fig. 3a) is the area with highest pigment variability from month to month. Highest PCs appeared in the Bohai Sea (st. 1–5) from October to March and were lower during May to July. In the Yellow Sea (st. 6–11), PCs were lower in summer than in spring and fall. The second peak of PC was to the north of the mouth of the Yangtze River (st. 11–16). The high pigment center moved from north (Hangzhou Bay, st. 11) (A in Fig. 3a) in December 1978 to south (the mouth of the Qiantangjiang River, st. 16) (B in Fig. 3 a) in July 1979. The high pigment center moved north (Hangzhou Bay, st. 11) (C in Fig. 3a) in December 1980, and then moved south (D in Fig. 3a) in July 1980. The same zigzag pattern can be identified in other years, even though the image coverage was not very good. The third peak was in the Taiwan Strait (st. 19–23), and the fourth was in Qiongzhou Strait (st. 30–35). PC in the Qiongzhou Strait was higher than in the Taiwan Strait.

The pattern of variability in PCs in the mid-shelf (Fig. 3b) was similar to that of the inner shelf. The concentrations were highest (1.4 mg m^{-3}) in the Yellow Sea and in the northern East China Sea (st. 1–12) in 1981. In the northern area, PCs were high in spring 1981. A second peak was found over the Taiwan Bank (st. 15–17). These data suggest that there was a spring bloom in this region. Over the outer shelf (Fig. 3c), PCs are relatively low (0.5 mg m^{-3}). High PCs ($>$2.0 mg m^{-3}) appeared between South Korea and Japan (stations 5–11), especially during the periods from March 1981 to March 1982 and from October 1984 to May 1985. Two peaks occurred each year, one lasting from March to May and the other from October to January. These patterns match well with ship data collected from June 1991 to February 1993 across the outer shelf transect in the Japan Strait (Harashima, 1995).

Figure 3 shows clearly how coverage differs among locations along the three transects. The outer shelf has the best coverage among the three transects, and the mid-shelf is better than that of inner shelf. This is because there was less cloud coverage and less masking due to bottom or sediment reflection further out to sea. Generally, image coverage was particularly good from October 1979 to March 1981 and it was better in the north (Bohai and Yellow Sea) than in the south (South China Sea). Image coverage was also good in the East China Sea even for the inner shelf during October 1979 to March 1981. The data collected from November 1979 to November 1980 was therefore used to examine monthly variation over an annual cycle. By considering data coverage, distance offshore, and depth of water, we selected the mid-shore transect to represent the pigment variation along the continental shelf of China.

Among three regions (Outlet of Yellow, Yangtze, and Pearl river)

Figure 4 shows monthly average pigment values from 1978 to 1986 in three regions (Bohai and Yellow Sea, East China Sea, and Northern South China Sea). In the northern area off the Yellow River mouth (Box A in Fig. 1), there were peaks of PC in the spring of 1979, 1980, 1981) (Fig. 4, Box A). One peak was very high (6.5 mg m^{-3}) in 1981, particularly around April. In the East China Sea off the Yangtze River (Box B in Fig. 1), the peak occurred in April of 1979, 1980, and 1981, February of 1982, and March of 1983 (Fig. 4, Box B). In the north of the South China Sea (Box C in Fig. 1), the seasonality was quite apparent, though the range of PC variation was small (Fig. 4, Box C).

In general, variation of PC was higher in the northern area (Bohai Sea) than in the southern area (South China Sea). PCs were very high (3.1 mg m^{-3}) in the northern South China Sea in February 1983 (Fig. 4, Box C), this may due to biased data availability. After checking monthly PC images, we found that the image in February 1983 covered only a bloom southwest of the Luzon Strait and the other places in Box C were under clouds. This winter phytoplankton bloom was reported in a separate paper (Tanget al., 1999).

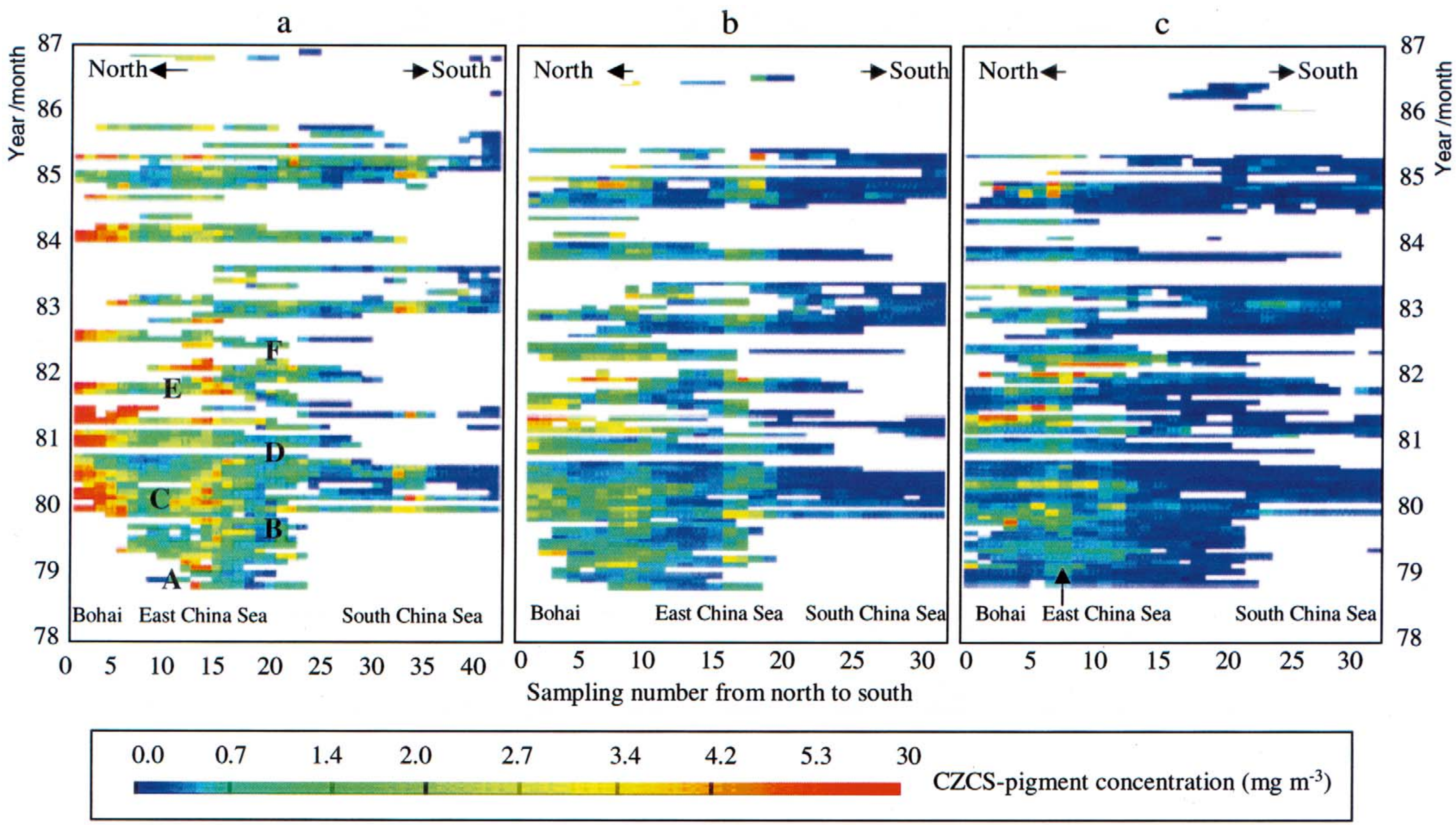

Figure 3. Monthly variation of pigment concentrations (PCs) along three transects (a: inner shelf; b: mid-shelf; and c: outer shelf) from July 1978 to June 1986 (Y-axis). The X-axis indicates the sequential number of sampling stations in three transects from north (Bohai) to south (north of South China Sea) as shown in Figure 1. The Y-axis represents month-year from July 1978 to June 1986 (bottom to top, scale 1–12 in each year representing January–December) and the colors indicate PCs. Blanks indicate that no data are available at the station for the corresponding months.

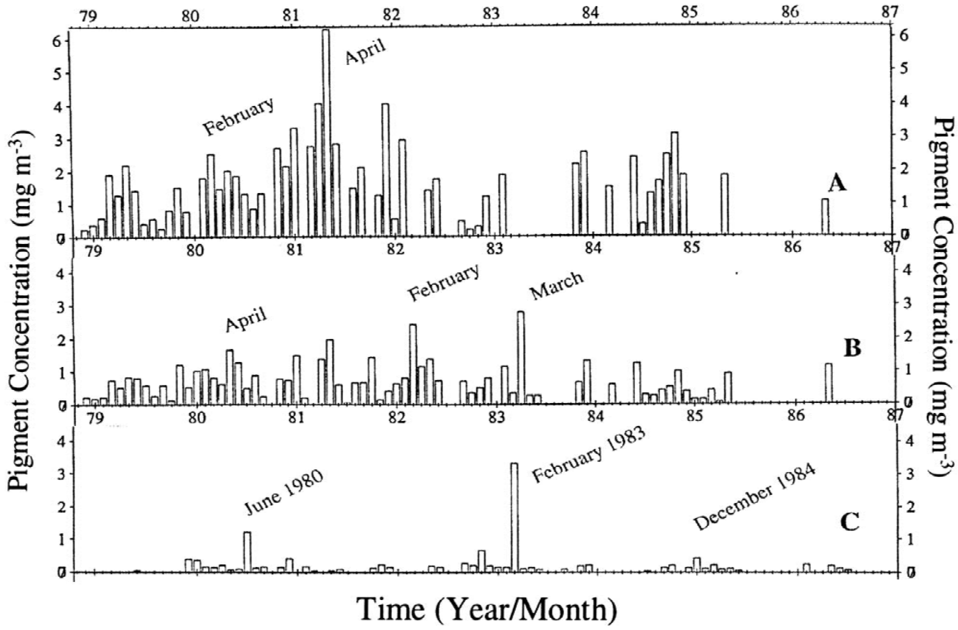

Figure 4. Monthly variation of PCs in three regions during the CZCS mission. (A) Bohai Sea and Yellow Sea (Box A in Fig. 1); (B) East China Sea (Box B in Fig. 1); (C) North of South China Sea (Box C in Fig. 1). X-axis: time (Year-month); Y-axis: Pigment concentrations (mg m^{-3}).

Combined monthly average PC during1978 to 1986

A combined monthly average PC along the whole continental shelf of China (the mid-shelf transect in Fig. 1) from November 1978 to July 1986 is shown in Figure 5A. Number of sampling data is indicated by figure 5B. The three latitudinally different regions (Fig. 1) showed different seasonally varied PC patterns. In the Yellow Sea (st. 1–7 of mid transect in Fig. 1), we observed two peaks in the year (Fig. 5, line a): the first and higher peak occurred in late winter and early spring (February and March) and the second peak was in November. In the East China Sea (st. 8–17 of mid transect in Fig. 1), a peak was seen in March and a second peak in November (Fig. 5, line b), but PCs were lower than in the Yellow Sea. Compared with the Bohai Sea, the Yellow Sea, and the East China Sea, PCs in the South China Sea (st. 18–25 of mid transect in Fig. 1) were relatively low (0.1–0.5 mg m^{-3}). There was a seasonal cycle with one peak in November–January and a secondary peak in August (Fig. 5, line c) in the South China Sea.

OCTS derived ocean color images

We used Japanese ADEOS satellite to compare and verify our findings from Nimbus CZCS. OCTS image show the similar spatial pattern of Chl-*a* and CDOM in April 1997 (Fig. 6a). Both Chl-*a* and CDOM concentrations are the highest in Bohai, and the lowest in the South China Sea. High TSS has been found in the coast of Bohai and Yellow Sea, and off the Yangtze River. It has been noticed that TSS pattern is different from Chl-*a* pattern. Chl-*a* is high in the north Yellow Sea (circle 1 in Fig. 6a), southeast Hangzhou Bay (circle 2 in Fig. 6a), and west of Taiwan (circle 3 in Fig. 6a) whereas TSS is lower in these three regions (circles 1–3 in Fig. 6c).

Weather and water conditions

Monthly wind pattern in 2000 is shown in Figure 7. In winter (Fig. 7a), northwesterly wind was observed in the Bohai and Yellow Sea. The wind was then gradually parallel to the coast. It got stronger and changed as north wind in the East China Sea and the Taiwan Strait. It again changed as northeastern wind in the northern South China Sea. In spring, wind was getting weaker and southern in the Boghai and Yellow Sea. The wind was then changed as easterly wind in the East China Sea toward coastal areas (Fig. 7b). In summer, the wind almost reversed in comparison with winter season: southeastern wind in the Bohai and northern Yellow Sea, and southwestern strong wind

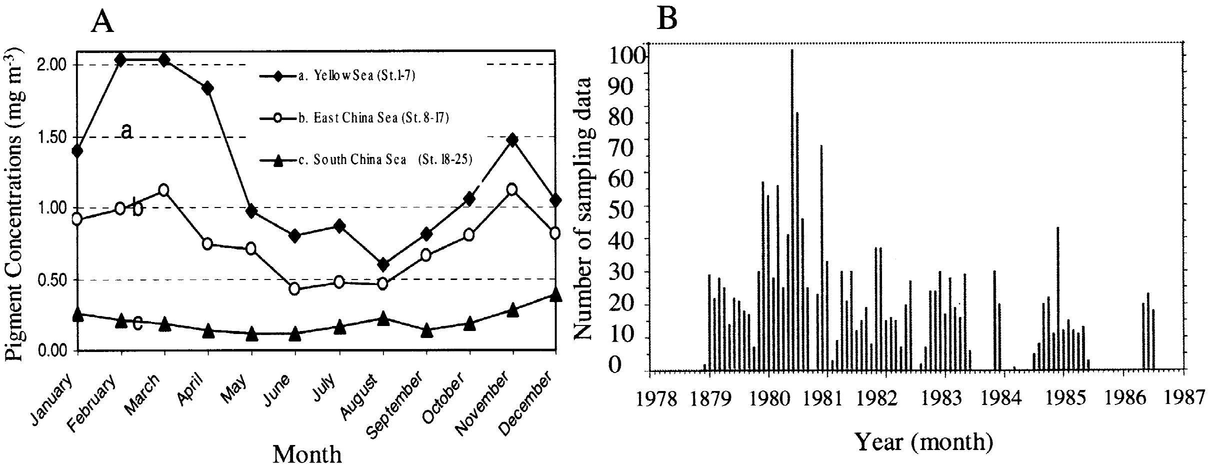

Figure 5. (A) Combined monthly average PC of three regions along the mid-transect from November 1979 to July 1986. a: Yellow Sea (St.1–7 of mid-shelf in Fig. 1); b: East China Sea (St. 8–17); c: South China Sea (St. 18–25). (B) Number of CZCS data (a total of 2139) for each month over the period of the CZCS mission.

in the South China Sea (circle in Fig. 7c). The wind in late fall gradually become similar with winter (Fig. 7d), strong northeast wind was observed in the Taiwan bank and northern South China Sea. In general, wind is stronger during fall-winter (Fig. 7 a, d) than that of spring-summer (Fig. 7 b, c) in the China seas. And the Taiwan Strait seems had strong winds during the fall–winter season.

Figure 8 displayed the weekly mean SST in three regions from July 1983 to December 1987. In the northern area (the Bohai and Yellow Sea, Box A in Fig. 1), the seasonal variations of SST were large and varied from 0 to 28 °C (Fig. 8A). In the East China Sea (Box B in Fig.1), the SST averaged about 21 °C and ranged from 7 to 28 °C (Fig. 8B). In the southern area (north of the South China Sea, Box C in Fig. 1), the SST was high and its seasonal variation was small, varying from 21 to 29 °C (Fig. 8C).

Discussion

Remote sensing of ocean pigments

The State Oceanographic Administration (SOA) had summarized Chinese oceanic surveys for the publication of 'Marine Atlas of Bohai Sea, Yellow Sea and East China Sea' (Chen & Niu, 1991). The atlas displayed seasonally horizontal Chl-*a* distribution from the Bohai Sea to Shantou (Fig. 1) based upon survey data before 1987. Coincidentally, our satellite remote sensing studies of yearly (Tang et al., 1998) and this monthly variations were also depending mainly upon period during 1978–1986 from CZCS data on pigment concentration covering the entire area of China's marginal seas. We can therefore compare our satellite imageries with oceanic survey maps and then interpret with updated satellite on wind and water temperature profiles among all China's seas.

The CZCS-derived PCs might be biased where CDOM concentrations could not be differentiated from phytoplankton PCs, as happens in river plumes (Fig. 2). Therefore, the high pigment values might be in part an artifact of CDOM present in the discharge from the Yangtze River. Suspended sediment from the Yangtze River may also affect the CZCS reading and should be interpret with caution for absolute concentrations. This is verified and matched by OCTS measurements showing high TSS in the river mouths (Fig. 6). The building of the Three Gorges Dam project in the Yangzte River is underway. Effects of this project on the coastal ecology because of regulated man-made river water runoffs may affect dramatically on the recruitments of fishes and shellfishes. The impact can be evaluated with relative concentrations by the comparison of CZCS data of both monthly and annual (Tang et al., 1998) studies with future ocean color data (i.e. SeaWiFS and EOS-PM's MODIS) to quantify the project's impact on the delivery of nutrients to the fisheries recruitment (e.g. Tang et al., 2002).

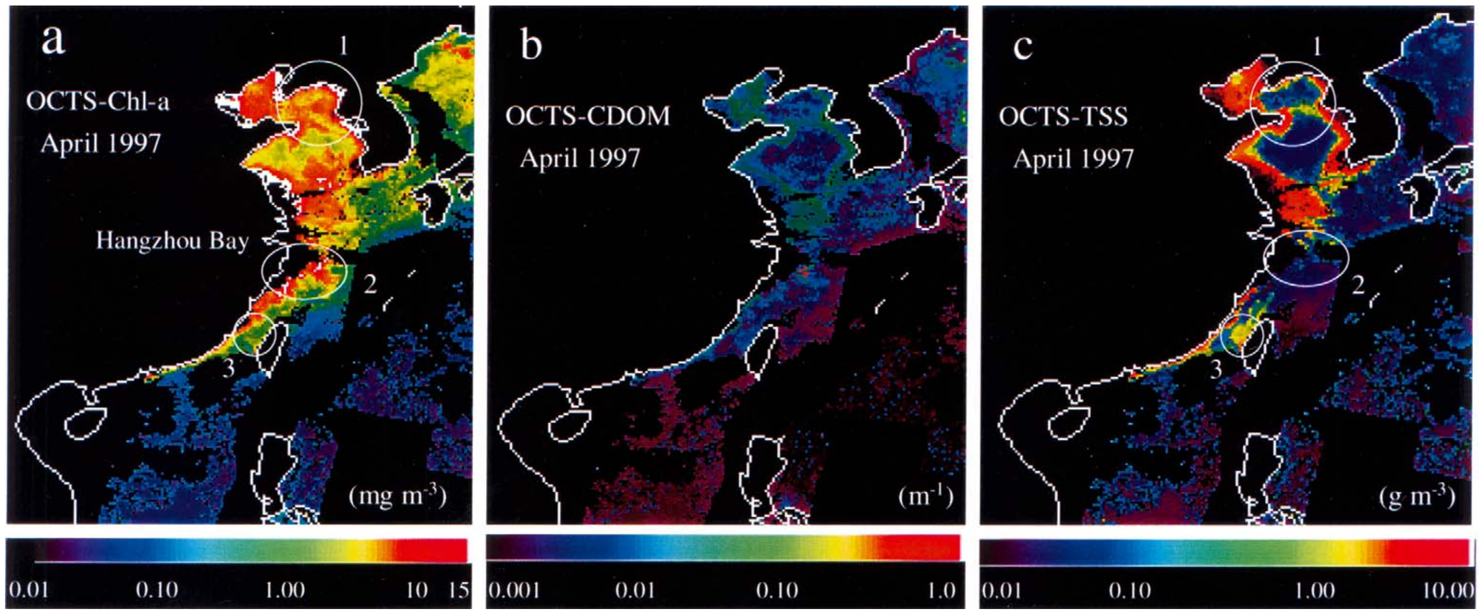

Figure 6. Monthly averaged OCTS derived Chl-*a*, colored dissolved organic matter (CDOM) and total suspended material (TSS) obtained in April 1997.

Seasonal variation of PC and reversed monsoon

From ship survey data in the Bohai Sea, Fei et al. (1988) reported two peaks of Chl-*a* in one year, the higher one was in March (1.95 mg m^{-3}) and a lower peak was in September (1.4 mg m^{-3}). In comparison with hydrographic data, they suggested that the peaks were related to light, water temperature, water transparency, nutrients and zooplankton. In late spring, when phytoplankton grow well, zooplankton can also grow well since they graze upon phytoplankton. Consequently, PC increased in early spring and decreased in summer. PC increased in fall again because of light, water temperature, water transparency and nutrients. Chai (1986) measured *in situ* chl-*a* in the southern Yellow Sea and also found higher concentrations in the spring.

The seasonality of PC and SST among all China's marginal seas has been again demonstrated in this study from satellite remote sensing data during the same period. We have clearly displayed a much higher variation in the northern area and a less variation in the southern waters (Figs. 3, 4 and 5a). These matched with Thomas and Strub (1990) study in the California Current frontal zone (30–38° N) and showed that a strong seasonality was present in the region north of 32° N but virtually absent in water to the south. When analyzing the annual pattern of PC in the continental Shelf of China, Tang et al. (1998) noticed that the annual mean of PC was proportionally related to the range of seasonal variation of water temperature. It has been further confirmed by the present study.

The seasonal variation of SST was related to the summer/winter monsoon. In the northern area, the variation of SST ranged from 0 to 28 °C whereas in the southern area it ranged from 20 to 29 °C (Fig. 8). The SST was low (about 16 °C) along the coast during the northeast monsoon season and the SST increased in summer with a strong southwest monsoon (Fig. 7). The changes of water temperature were related to strong monsoon. Relatively strong northern wind during fall-winter may bring nutrients from Yangtze River discharges along the coastal water of East China Sea and the north South China Sea (Fig. 7) as evidenced in Figure 2a–l. High PC in the Gulf of Tonkin in winter (Fig. 2a) consisted with SeaWiFS and in situ measurements obtained in 2000 (Tang et al., 2003). That was associated with water advection westward toward the center of the gulf from the Hainan Island coastal area drawn by Ekman drift during strong northeast monsoon (Fig. 7d).

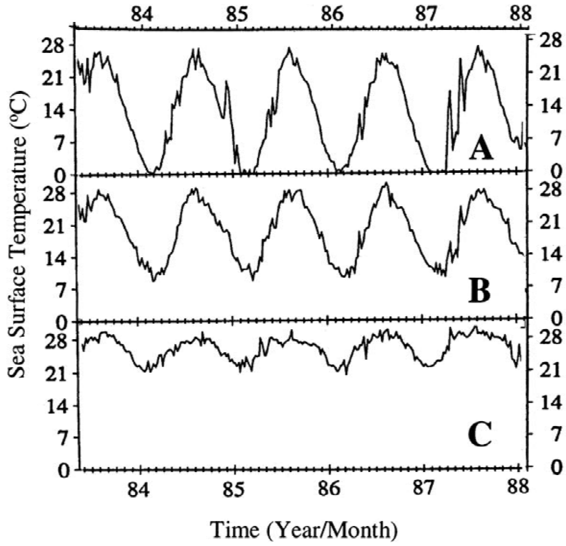

Figure 8. Weekly mean sea surface temperature (SST) in three regions during July 1983 to December 1978, showing seasonal variation of water temperature in China's Marginal Seas. (A) Bohai Sea and Yellow Sea (Box A in Fig. 1); (B) East China Sea (Box B in Fig. 1); (C) North of South China Sea (Box C in Fig. 1). X-axis: time (Year-month); Y-axis: Sea surface temperature (°C).

Fei (1990) reported high content of chl-*a* in the waters off the Yangtze River. Tang et al. (1998) examined the annual variations of PC and reported a large, consistent pigment plume east of the Yangtze River. Ning et al. (1998) indicated that the high PC and plume tongues are clearly corresponding to the climatologically average river discharge pattern over all years of the CZCS mission, as displayed in Tang et al. (1998). The occurrence of the high concentrations of chl-*a* in estuaries can be summarized from the river water runoffs, sea bottom topography, monsoon wind direction, and ocean currents. Generally, there was high correlation between the high concentration of chl-*a* and the high-nutrient environment. The present study revealed the monthly changes of the plume: it had two edges in November, with the northern edge related to high pigment from the coast of the Yellow Sea, and the southern edge more related to the Yangtze River discharge. The plume was small in winter and large in summer that might be due to largest discharge from the Yangtze River in summer over year. Generally speaking, the Yangtze River plume goes southward along the coast in winter and flows northeastward during the flooding period when the runoff is great as reported by Hu & Li (1993).

High PCs areas coincident with fishing grounds

River water runoffs carries organic and inorganic nutrients to the sea and estuaries have very high productivity, rate as high as 20 times as the open sea (Iversen, 1996). Prevailing wind patterns may also induce nutrient upwelling and high productivity in different coastal areas at different times of the year (Kester & Fox, 1993). These high PC areas usually have extremely high biological productivity and therefore are good fishing grounds. From the spatial and seasonal patterns of PC observed in this study, we can compare with fisheries concentrations, as in Atlas of the living resources of the seas (Gulland, 1971; FAO, 1972; Chinese Natural Resources Editorial Board, 1995; FACOA, 1995) and also locate seasonal fishing grounds in various seasons (Chen & Niu, 1991). For example, we observed high PCs almost whole year in the Bohai Sea, where is a very good fishing ground as displayed from the horizontal distribution and concentration of total zooplankton biomass (Chen & Niu, 1991). Our data show high PCs appeared 150 km off the Zhejiang Province (Fig. 1) in July 1980 (Fig. 2i). Chai (1986) reported high chl-*a* in the same place in June 1981; it is located between the Dasa fishery ground and the Chanzan Ko fishery ground. In February 1983, PCs have been found high (3.1 mg m^{-3}) in the northern South China Sea (Box C in Fig. 1 and Fig. 7C). This winter phytoplankton plume occurred during the winter of 1979, 1983, 1985 and 1986, and this area might be a good fishing ground (Tang et al., 1999). Other high Chl-*a* areas have been observed in the Taiwan Strait, where several famous fishing ground are (Hong et al., 1991; Tang et al., 2002). Therefore, the publication of these temporal and geographic SST and PC patterns may invite more fisheries biologists and oceanographers to examine most of the pelagic fisheries along the Chinese coasts in detail and will help us for a better sustainable management of coastal fisheries sources.

Conclusions

This study reveals seasonal /monthly variability of pigment concentrations (PC), SST and wind conditions in China's marginal seas. In general, seasonal variations of PC and SST were relatively higher in the northern area than in the southern area. The differences pattern of PC among the Boihai Sea, the Yellow Sea East, the East China Sea, and the northern South China Sea may be affected by the reversed monsoon cycle as evidenced by seasonal wind data and SST; the spatial variation of PC distribution in the coast waters is related to river discharges and coastal currents. The large phytoplankton plume off the Yangtze River has a significant seasonal variation; it may be related to seasonal river water discharges, the direction of monsoon and currents. Locations of high PCs in offshore waters are coincident with good fishing grounds.

Acknowledgements

Original data analysis was conducted by D.L. Tang at University of South Florida. The authors are very grateful to Prof. Joe Baker, Commissioner for the Environment in Australia, Dr Antony Liu of NASA, Dr Dana Kester and Dr James Yoder of Rhode Island University, Dr Z. J. Liu of University of South Florida, and two anonymous reviewers for their valuable comments and suggestions. A part of this study was presented at International Marine Science Conference-Assessment and Monitoring of Marine Systems, Trengganu, Malaysia, in 1997, and at International Workshop on Remote Sensing of Marine Environment in the Northwest Pacific Region in 2000. This project was partly supported by National Science Council 92-2313-B-019-046 to Ni I.-H, and also by funding from the U.S. National Aeronautics and Space Administration (NASA) to Frank Müller-Karger at the University of South Florida.

References

Baith, K., R. Lindsay, G. Fu & C. R. McClain, 2001. SeaDAS: Data Analysis System Developed for Ocean Color Satellite Sensors, Eos 82: 202.

Chai, X. Y., 1986. Distribution of chlorophyll-*a* and estimation of primary productivity. J. Shandong College of Oceanol. 16: 1–25 (in Chinese).

Chen, G. Z. & Y. Y. Niu, 1991. Marine Atlas of Bohai Sea, Yellow Sea and East China Sea, In Chen, Niu et al. (eds), China Ocean Press, Beijing. 272 pp.

Chinese Natural Resources Editorial Board, 1995. Chinese Natural Resources – Fisheries. Chinese Environmental Science Press, Beijing. 379 pp. (in Chinese).

FACOA, 1995. Taiwan Agriculture encyclopedia – Fishery edition. In Lee, J. L. et al. (eds), Fisheries Administration, Council of Agriculture, Taiwan.

FAO, 1972. Atlas of the living resources of the seas, prepared by the FAO Department of Fisheries, Rome.

Fei, Z. L., X. H. Mao, M. Y. Zhu, B. Lee, B. H. Lee, Y. H. Guan, X. S. Zhang & R. H. Liu, 1988. Study on primary productivity in Bohai. Acta Oceanologica Sinica, 10: 481–489 (in Chinese).

Fei, Z. L., 1990. Preliminary analysis on the formation mechanism of high content of chlorophyll-*a* in the waters of the East China Sea continental shelf edge. Collection of Research Reports on Kuroshio: 114–125 (in Chinese).

Feldman, G., N. During, C. Ng, W. Esaias, C. McClain, J. Elrod, N. Maynard, D. Endres, R. Evans, J. Brown, S. Walsh, M. Carle & G. Podesta, 1989. Ocean color: availability of the global data set. EOS, 70: 634.

Fuijing Institute of Oceanology, 1988. Distribution of chlorophyll-*a* and estimation of primary productivity. Report of investigations in the northern and middle of Taiwan Strait, Scientific Publishing Hushing. China: 244–259 (in Chinese).

Gordon, H. R., K. D. K. Clark, J. W. Brown, O. B. Brown, R. H. Evans & W. W. Broenkow, 1983. Phytoplankton pigment concentrations in the Middle Atlantic Bight: comparison of ship determination and CZCS estimates. Appl. Opt. 22: 20–35.

Gulland, J. A. 1971. The fish resources of the ocean. FAO, Fishing News Ltd. 255 pp.

Harashima, A., 1995. Collected data of high temporal-spatial resolution marine biogeochemical monitoring by Japan-Korea Ferry. CGER-D007(CD)-95. Center for Global Environmental Research, National Institute for Environmental Studies, Environment Agency of Japan.

Hong, H. S., S. Y. Qiu, W. Q. Ruan & G. C. Hong, 1991. Minnan-Taiwan Bank Fishing Ground Upwelling Ecosystem Study. In Hong H. S., S. Y. Qiu, W. Q. Ruan & G. C. Hong (eds), Minnan-Taiwan Bank Fishing Ground Upwelling Ecosystem Study. Science Publishing House, Beijing, China: 1–18 (in Chinese).

Hu, D. X. & Y. X. Li, 1993. Study of Ocean Circulation. In Tseng, C. K., H. O. Zhou & B. C. Li (eds), Marine Science Study and Its Prospect in China. Qingdao Publishing House, China: 129–150 (in Chinese).

Iversen, E. S., 1996. Living Marine Resources – Their Utilization and management. Chapman & Hall, New York. 403 pp.

Kester, D. R. & M. F. Fox, 1993. Chemical and biological remote sensing of the South China Sea: satellite and *in situ* observations. In Fang, M. & A. Liu (eds), Proceeding of Environment'93-Symposium on Remote Sensing in Environmental Research and Global Change, The Commercial Press. Hong Kong: 60–72.

Kishino, M., T. Ishimaru, K. Furuya, T. Oishi & K. Kawasaki, 1998. In-water algorithms for ADEOS/OCTS. J. Oceanogr. 54: 431–436.

Müller-Karger, F. E., C. R. McClain, T. R. Fisher, W. E. Esaias & R. Varela, 1989. Pigment distribution in the Caribbean Sea: Observations from space. Prog. Oceanogr. 23: 23–64.

NASA, 2001. Available at: http://www.ssmi.com/qscat/qscat_description.html.

Ning, X., D. Vaulot, Z Liu & Z. Liu, 1988. Standing stock and production of phytoplankton in the estuary of the Changjinh (Yangtse River) and the adjacent East China Sea. Mar. Ecol. Prog. Ser. 49: 141–150.

Ning, X., Z. Liu, Y. Cai, M. Fang & F. Chai, 1998. Physicobiological oceanographic remote sensing of the East China Sea: Satellite and in situ observations. J. Geophys. Res. 103: 21623–21635.

Qian, Z. L., 1994. The development of the Chinese fisheries and man power in aquaculture. Chinese Aquaculture Pub. Beijing, China. 212 p.

Strub, P. T., C. James, C. A. Thomas & M. R. Abbott, 1990. Seasonal and non-seasonal variability of satellite-derived surface pigment concentration in the California Current. J. Geophys. Res. 95: 11501–11530.

Tang, D. L., H. Kawamura, M. A. Lee & T. V. Dien, 2003. Seasonal and spatial distribution of chlorophyll *a* concentrations and water conditions in the Gulf of Tonkin, South China Sea. Remote Sensing of Environment 85: 476–483.

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

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

Tang, D. L. & H. Kawamura, 2002. Ocean color monitoring of coastal environments in the Asian waters. J. Korea Soc. Oceanogr. 37: 154–159.

Tang, D. L., D. R. Kester, I-H. Ni, H. Kawamura & H. S, Hong, 2002. Upwelling in the Taiwan Strait during the summer monsoon detected by satellite and shipboard measurements. Remote Sensing of Environ. 83: 457–471.

Thomas, A. C. & P. T. Strub, 1990. Seasonal and interannual variability of pigment concentrations across a California Current frontal zone.1 J. Geophys. Res. 95: 13023–13042.

Wentz, F. J., D. K. Smith, C. A. Mears & C. L. Gentemann, 2001. Advanced Algorithms for QuikScat and SeaWinds/AMSR. In IGARSS'01 Proceedings 2001. NASA, U.S.A.

Zhang, F., Y. Yang, L. Y. Wu & S. H. Gao, 1985. Distribution and Characteristics of Chlorophyll *a* concentration in Dongshan Bay. Tropic Oceanology (in Chinese).