THE SPATIAL DISTRIBUTION OF CHLOROPHYLL-*a* AND ITS RESPONSES TO OCEANOGRAPHIC ENVIRONMENTS IN THE SOUTH CHINA SEA

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This study investigates the spatial distribution of Chlorophyll *a* (Chl-*a*) in the summer season for the South China Sea (SCS) using satellite measurements and discusses the mechanisms of spatial variation of phytoplankton. Results show that Chl-*a* concentrations are higher in the west than in the east of the SCS. Chl-*a* concentrations in the west central basin, southeast of Vietnam and a jet like band east of Phan Ri Bay are evidently higher than in the rest of the SCS. Their spatial characteristics are related to upwelling derived from Ekman pumping, Ekman transport induced by southwest monsoon winds, and the strong offshore current east of Vietnam.

1. Introduction

The South China Sea (SCS) is the largest marginal sea, in the western Pacific Ocean covering 3.5 million km^2 from the equator to 23°N and from 99°E to 121°E, with an average depth of 2000 m (Fig. 1). The monsoons always play an important role in the dynamics of upper circulations of SCS throughout the year,[1,2] as it is dominated by strong northeasterly monsoon during winter (December–February) and southwesterly monsoon in summer (June–August).[3] The seasonally reversing monsoons arouse considerable changes in general oceanic circulations and hydrological features,[4,5] whilst southwesterly winds and the orientation of the coastline provide favorable conditions for wind-induced upwelling along the SCS west coast.[1,4] In addition, a strong offshore current northeast of Vietnam,[1,4,6] may also exert important influence on the growth of phytoplankton, especially the chlorophyll-*a* (Chl-*a*) close related to primary productivity in the northern SCS, and possibly over the whole SCS, by bringing nutrients from sublayer waters.

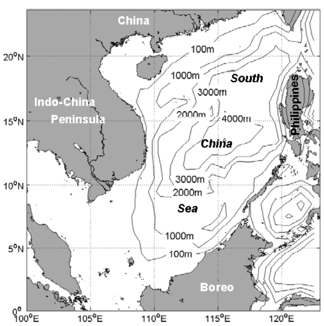

Fig. 1. Bathymetric and geographic map of the SCS. PRB: Phan Ri Bay.

Tang[7–9] studied spatio-temporal variability of regional chlorophyll and primary productivities in the SCS continental shelf, the Gulf of Tonkin and inshore Vietnamese coastal waters, and analyzed water conditions during the corresponding period based on *in situ* measurements and satellite data. Shang[10] and Tang[11] analyzed the distribution of Chl-*a* in upwelling zones. Hung *et al.*,[12] Lee Chen *et al.*,[13] and Agawin *et al.*[14] discussed the relation between biomass of phytoplankton and nutrient conditions. Chen *et al.*[15] investigated elementarily seasonal and spatial characteristics of chlorophyll concentrations of the SCS.

Tang *et al.*[9] observed high-chlorophyll concentrations in a jet-shape on the northeastern region of Phan Ri Bay (PRB) with sustaining nutrients-rich transport through the offshore current during almost the whole summer. Tang *et al.*[16] also observed harmful algal blooms (HABs) during July caused by upwelling. We carried out cruise studies for the northwest SCS in 2000 and 2005. The comparison studies[8,16,17] between satellite (SeaWiFS and Modisa) derived Chl-*a* data and *in situ* measurements show that satellite data are useful for verifying Chl-*a* concentration in this area.

The studies on spatial and temporal dissimilarities of Chl-*a* concentrations mingled with other environmental factors for this region are highly concerned with developing a better understanding of physical and biological processes along with existing bio-geochemical cycles. The present study focuses on the spatial distribution of Chl-*a* concentration during summer season for the entire SCS for a 5-year period and discusses its responses to environmental conditions linked with factors of sea surface temperature (SST), sea surface wind stress (SSWS), Ekman pumping and upwelling. Satellite data obtained from 1998 to 2003 have been analyzed to investigate interesting phenomena and related mechanisms.

2. Data and Analysis

The SCS is a marginal sea located in the west Pacific Ocean, lying in the tropical monsoon zone between the equator and the tropic of Cancer (Fig. 1). Our study focuses mainly on the western SCS with wide continental shelf in the south and north, and comparatively narrow continental shelf in the mid-west of the study area near Phan Ri Bay (PRB in Fig. 1), where the depth reaches 4000 m at its narrowest width of 2 km.

The Chl-*a* data acquired from SeaWiFS Version 4 has been used to derive the Chl-*a* estimates. Monthly Standard Mapped Image (SMI) Products (Level 3) (spatial resolution, $9 \times 9\,\text{km}^2$) were procured from the Distributed Active Archive Center (DAAC) of Goddard Space Flight Center (GSFC), NASA (http://oceancolor.gsfc.nasa.gov/cgi/level3.pl) The summer Chl-*a* image averaged for June–August from 1998 to 2003 were produced with the help of Matlab Version 6.5 and Grid Analysis and Display System (GrADS) Version 1.8 software from monthly data sets.

The SST data derived from Advanced Very-High Resolution Radiometer (AVHRR) of Ocean Pathfinder channel-5 (spatial resolution 4 km/month-daytime) was provided by Physical Oceanography Distributed Active Archive Center (PO.DAAC), Jet Propulsion Laboratory (JPL), NASA (http://podaac.jpl.nasa.gov/sst). The seasonal average SST images were generated by the means similar to SeaWiFS Chl-*a* data processing using Matlab and GrADS to show the spatial variations of SST during summer.

The wind stress data entitled, Tropical Indian Winds from 1970 to 2004 are obtained from the Center for Ocean-atmospheric studies of Florida State University (http://www.coaps.fsu.edu). The data is pseudo-stressed based on surface marine observations (TD-1129) for the years after 1980 produced by the National Climatic Data Center (NCDC) and for the years 1970–1979 they are based on the COADS CMR5 individual ship observations with a resolution of 1° grid, expressed in (m/s).[2]

3. Results

3.1. *Spatial distribution of Chl-a*

A relatively high concentration of Chl-*a* ($>0.13\,\text{mg/m}^3$) is observed offshore of southeast Vietnam (oval area marked in Fig. 2(A)) compared with other locations, while the Chl-a in areas east of the SCS, north of Borneo and southwest of Luzon Island, display lower concentrations ($<0.1\,\text{mg/m}^3$). Figure 2(A) also shows an extreme high band of Chl-*a* parallel to the

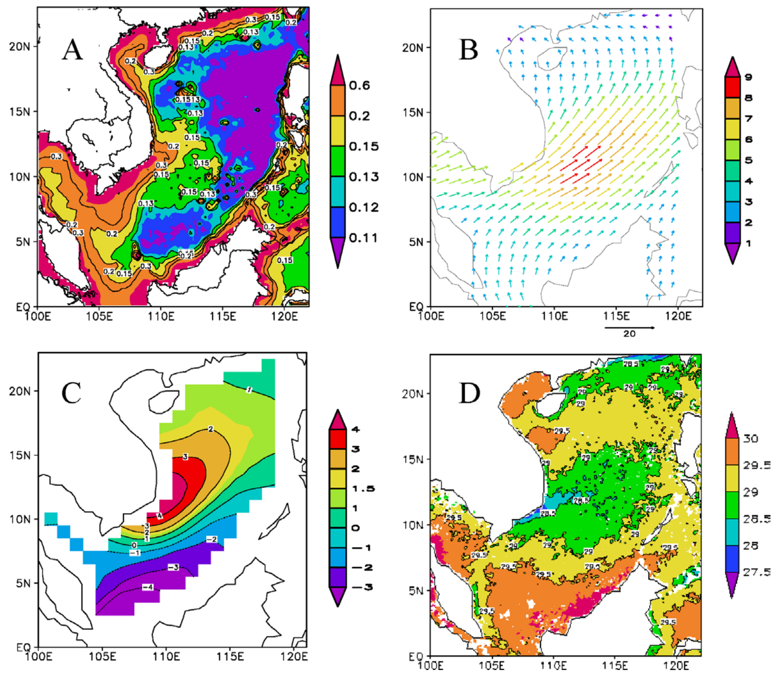

Fig. 2. (A) SeaWiFS-derived Chl-a (mg m^{-3}) images in summer for the SCS averaged for June–August from 1998 to 2003. (B) FSU SWS vectors and their magnitude (contours in 10^{-2} Nm^{-2}) for June–August from 1970 to 2003. (C) Summer Ekman Pumping velocity (upward positive in 10^{-6} m/s) derived from wind stress and averaged for June–August from 1970 to 2003 in the SCS. (D) Summer SST Image (in °C) averaged for June–August from 1998 to 2003 in the SCS.

coastline within a range of 200 km from the Mekong estuary to PRB. Furthermore, Fig. 2(A) also indicates a high Chl-a jet on the east side of PRB intruding as far as 116°E, and merging with the high chlorophyll bond parallel to the coastline.

3.2. *Spatial variability of prevailing winds and Ekman pumping velocity*

During summer, southwesterly winds are persistent in the SCS. Figure 2(B) displays the spatial distribution of wind stress for June–August. At about 11°N off Vietnam, the wind stress reaches maximum (approximately 0.09 Nm^{-2}), which is almost twice that of the ambient intensity. The southeast coast of Vietnam is oriented southwest to northeast, roughly parallel to the southwesterly winds. The axis of this wind seems to divide the SCS into two parts, with Ekman upwelling and downwelling in the north and south areas, respectively (Fig. 2(B)). The Ekman Pumping image (Fig. 2(C)) displays a strong upwelling tendency in the west basin southeast of Vietnam.

3.3. *Spatial variability of SST*

Figure 2(D) indicates that high temperatures prevail in most of the SCS (>29.5°C), while in the western SCS, low temperatures are obvious, in the shape of ellipse with a short radius of approximately 300 km to the southeast of Vietnam in the western SCS. This location matches roughly with the area of high positive Ekman pumping velocity, and especially a clearly defined lower jet-shape SST (<28.5°C) to northeast PRB.

4. Discussion

4.1. *Key factors limiting the growth of phytoplankton*

Generally, the availability of nutrients and light radiation are the key factors limiting the growth of phytoplankton. However, in the SCS light may not be a key factor because it is located in the tropics, whereas the accessibility of nutrients may perhaps be the determining factor.[8,18] The hydrological conditions in the study area are complex, varying with space and time, and the interaction between these factors must have had a considerable influence on the transport and distribution of nutrients in the study region, ultimately affecting the growth of phytoplankton. Hence, we place an emphasis on discussing important hydrological features influencing the distribution of Chl-*a* concentration in this study.

4.2. *The distribution of Chl-a and oceanic conditions*

In the southeastern offshore part of Vietnam, where high Chl-*a* concentration appears (oval-shape in Fig. 2(A)), intense Ekman Pumping upwelling (Fig. 2(C)) induced by positive SSWS (Fig. 2(B)) eddies will transport cold water from the sub-surface to surface layer, lowering SST (Fig. 2(D)) and increasing Chl-*a* concentration (Fig. 2(A)). The concept of Ekman Pumping velocity is seldom introduced in similar previous research. Our results (Fig. 2(A) and 2(B)) also show that high Chl-*a* concentration matches positive Ekman Pumping velocity and low SST (Fig. 2(D)) in terms of intensity, shape and location. The result may mean that the region of high Chl-*a* concentration is primarily induced by upwelled water with rich nutrients through Ekman pumping.

In the nearshore area to southeast Vietnam, the strong southwesterly wind stress (Fig. 2(B)) parallel to the coastline induces strong offshore Ekman transport, leading to coastal upwelling with low SST. In this region, well-defined coastal upwelling can be also identified in the SST image (Fig. 2(D)). By the intense Ekman upwelling associated with the strong influence of southwesterly winds, the upwelling east of Vietnam in the southwestern SCS may lead to conspicuous localized cooling of the area. The findings of Tang *et al.*[9,16] and Xie *et al.*[6] also revealed similar conditions in the same area under investigations. High Chl-*a* concentration may be a response to the upwelling in the coastal area. The band of high Chl-*a* concentration over the near-shore region in south Vietnam (south of PRB, in Fig. 1) coincides with the region of strong wind (Fig. 2(B)), with the band of low SST parallel to the coastline (Fig. 2(D)). Overall, by the mechanism of coastal upwelling in the near-shore area, offshore Ekman pumping transports cold water from the bottom to the surface and from the coast to offshore and thereby could induce the continuous supply of nutrients, low temperature and high Chl-*a* concentration.

In addition, in nearshore regions, another important factor for the sustenance of high Chl-*a* is attributed to the advantageous position of being close to the discharge waters of the Mekong River, which brings nutrients from upstream. Earlier investigations[19] revealed that there is a strong northeastward coastal current during the southwest monsoon, originating from shallow water in the southwest part of the SCS and the maximum runoff from the Mekong river along the Vietnamese coast (available: http://www.na.unep.net). This current turns into the northeast basin of the SCS near 11°N, forming an offshore jet in the northeast direction.[5] As a consequence, these conditions may also support a wide band of Chl-*a* in the coastal waters southeast of Vietnam and lead to a high Chl-*a* jet protruding into northeastern basin near PRB, as shown in Fig. 2(A).

5. Conclusions

This study revealed a high Chl-*a* concentrations in the western SCS during summer, also showing a larger spatial variation in the west than in the east owing to differences in oceanic conditions, especially the wind stress and Ekman pumping velocity. The high Chl-*a* concentration and the Chl-*a* jet in the western SCS are related to upwelling induced by southwesterly monsoon winds. A high coastal Chl-*a* band is sustained due to coastal upwelling derived from Ekman offshore transport of strong winds with lower temperature, while the high Chl-*a* in the western SCS basin is related to upwelling induced by wind stress.

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