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Phytoplankton patchiness during spring intermonsoon in western coast of South China Sea

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ABSTRACT

Jet-like phytoplankton blooms usually occur off the southwestern coast of the South China Sea (SCS) caused by strong winds during summer monsoons. However a jet-like phytoplankton patch was observed in the western SCS in the spring intermonsoon of 2010 in both field and remote sensing data. The present study investigated the biological processes associated with this spring phytoplankton patchiness. The data showed that chlorophyll *a* concentrations increased in the surface water, extending out to the SCS, and the depth of the subsurface chlorophyll maximum uplifted from 75 m to 50 m depth; low dissolved oxygen, low pH and nutrient enrichment (nitrate+nitrite and soluble reactive phosphate) were observed in the subsurface water (50 to ~200 m depth). Data analysis showed that variations in chlorophyll *a*, nutrients and temperature in the water column were related to wind-stress curl: the spatial distribution pattern and vertical structure of the phytoplankton patchiness were controlled by vertical flux of nutrients caused by curl-driven upwelling through Ekman pumping. There was a high correlation between chlorophyll *a* concentration and wind-stress curl where the influence of nutrient influx from the coast was limited. This study shows the importance of wind-stress curl in providing nutrients to support phytoplankton growth during the spring intermonsoon along the western coast of SCS. It may help to better understand the role of wind in marine biological processes.

1. Introduction

Over most of the South China Sea (SCS), the phytoplankton biomass is low and controlled by monsoons (Ning et al., 2004). The climate of the SCS is part of the Asian monsoon system, where northeast monsoons occur in winter and southwest monsoons occur in summer (Liu et al., 2002). In the southwestern coastal region of the SCS, phytoplankton blooms, including harmful algal blooms (HABs), frequently occur in summer when southwest monsoons are parallel to the Vietnamese coast (Tang et al., 2004a, 2004b). Long-term observations indicate that these phytoplankton blooms are consistent phenomena appearing almost every summer (Tang et al., 2004a, 2005). In the upper layer of the open ocean, the supply of new nutrient is one of the primary factors controlling the growth of phytoplankton (McGillicuddy et al., 2003), and physical processes control nutrient flux into the euphotic zone and hence play a profound role in the phytoplankton growth and their temporal and spatial distribution (Cloern, 1996). Monsoon-induced coastal upwelling is one of the most important processes in the physical oceanography of the SCS and can deliver ample new nutrients to sustain the phytoplankton growth (Tang et al., 2002; Botsford et al., 2006). The persistent alongshore southwest monsoon forces Ekman transport and the resultant coastal upwelling delivers nutrients to surface waters and sustains high phytoplankton biomass (Tang et al., 2004a; Dippner et al., 2007). Xie et al. (2003) found that an anticyclonic eddy develops from the Vietnam coast to the open SCS in July and August, advecting coastal water in the form of coastal filaments. The distribution of coastal filament displays large interannual variability associated with changes in the SCS ocean circulation. Phytoplankton patchiness is associated with the coastal filament during this period. The resultant anticyclonic eddy may have impacts on the spatial distribution of phytoplankton biomass during the summer monsoon season (Tang et al., 2004a). The summer blooms of the haptophyte genus *Phaeocystis* are often observed in the coastal upwelling region off the coastal Vietnam during southwest monsoon (Tang et al., 2004b; Hai et al., 2010). The phytoplankton blooms subsequently disappear when the southwest monsoon ends.

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In this region the intermonsoon is a transition period between summer and winter monsoons; the spring intermonsoon is from March to June (Voss et al., 2006). During the intermonsoon, the wind direction is variable and patterns tend to be very chaotic (Corrigan et al., 2006). Consequently wind stress during intermonsoon seasons does not usually induce persistent coastal upwelling. In the absence of southwesterly winds, the anticyclonic ocean circulation is weakest in the spring intermonsoon in the SCS (Hwang and Chen, 2000). Oligotrophic conditions prevail during most of the spring intermonsoon period. Based on field measurements, Voss et al. (2006) found that nitrogen fixation rates and other hydro-chemical variables during the spring intermonsoon of 2004 were 10 times lower than in the summer monsoon. In May, 2003, a phytoplankton bloom was reported during this oligotrophic period (Lin et al., 2010). Many studies have investigated primary productivity and the coupling of biological–physical processes in monsoon seasons in the SCS, but little attention has been focused on the dynamic features of phytoplankton during intermonsoon.

In the present work, a jet-like phytoplankton patchiness was observed in the western coastal area of the SCS during the spring intermonsoon in 2010. A key question was can this phytoplankton patchiness occur without alongshore winds during intermonsoon season? Can the chaotic winds during this period contribute to the spring phytoplankton patchiness? We combined in situ observations together with analysis of remote sensing data to elucidate the phytoplankton patchiness and related dynamic processes. The objective of this work was to identify how winds during spring intermonsoon regulate the phytoplankton patchiness on spatial distribution and vertical structure in the upper ocean.

2. Data and methods

2.1. Study area and in situ observations

The study area comprises the eastern Vietnamese coastal water and adjacent western SCS (Fig. 1A and B). In situ observations were made between May 7 and 16, 2010 at 15 sampling stations (Fig. 1B) along the ship's track. The stations were more than 1000 m in depth. Seawater temperature profiles were obtained at each station using a Sea-Bird SBE9 Conductivity–Temperature–Depth (CTD). Seawater samples were collected with Niskin bottles triggered at various depths (surface, 25 m, 50 m, 75 m, 100 m, 150 m, and 200 m). Seawater samples for dissolved oxygen analysis were carefully taken in calibrated dry glass bottles from the Niskin bottles. Dissolved oxygen concentrations were measured using automated precision Winkler titration using a Metrohm 716 DMS Titrino (Oudot et al., 1988; Pomeroy et al., 1994). The seawater pH were measured immediately after samplig using a Mettler Toledo pH meter. The in situ pH values were corrected for depth and pressure. Seawater samples for chlorophyll *a* concentration analysis were filtered onto 25 mm Whatman glass fiber filters (GF/F) and then quickly frozen in dark until analysis in laboratory. Chlorophyll *a* was extracted in ice-cold 90% v/v acetone and measured using a Turner Designs TD-700 fluorometer with 436 nm excitation filter and 680 nm emission filter. Concentrations of nitrate + nitrite (NO_x) and soluble reactive phosphate (SRP) were analyzed on a flow injection analyzer (FIA Lachat QC8500, Lachat Instruments, USA) using the standard pink azo dye and phosphorus molybdenum blue method, respectively (Strickland and Parsons, 1972).

2.2. Remote sensing data and analysis

Remote sensing data of sea surface chlorophyll *a* concentration, the normalized water-leaving radiance at wave-length 443 nm (*nLw* (443)) and 555 nm (*nLw* (555)), with 1 km × 1 km spatial resolution, were derived from MODerate resolution Imaging Spectroradiometer (MODIS) onboard Aqua, launched in 1999. A strong absorption of phytoplankton is at *nLw* (443) (Shi and Wang, 2007). The *nLw* (555) denotes suspended sediment and hence the influence of coastal water (Zheng and Tang, 2007). We compared *nLw* (443) and *nLw* (555) with sea surface chlorophyll *a* concentration to determine the influence of coastal water on the formation of the phytoplankton bloom. Raw satellite data were obtained from the NASA OceanColor Website. To investigate the temporal variation, we composited 8-day averaged chlorophyll *a* images.

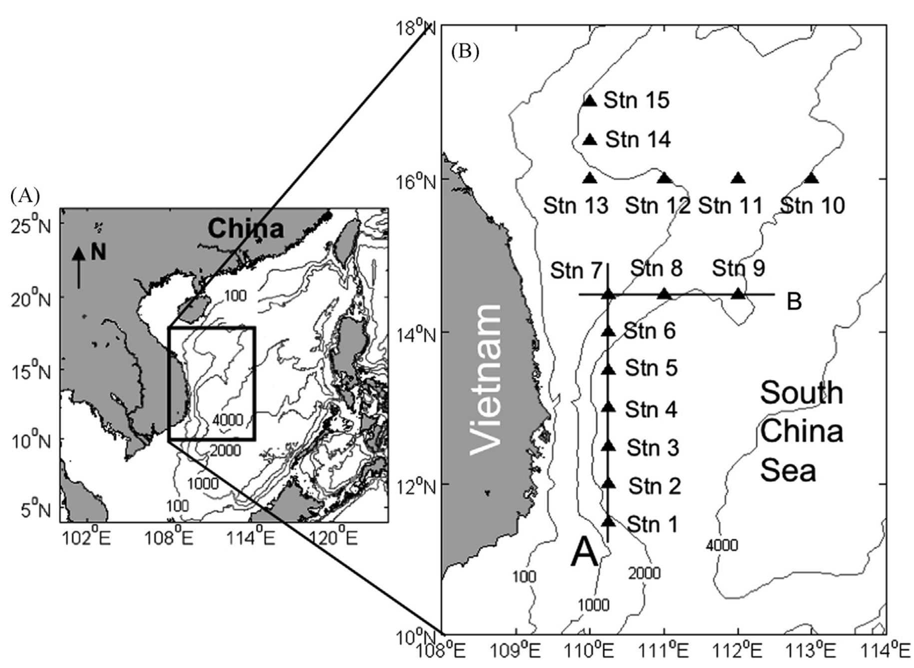

Fig. 1. (A) The geographic location and bathymetry of the study region in the western South China Sea. (B) Locations of sampling stations and transects A and B in the western South China Sea between May 7 and May 16, 2010.