Continental Shelf Research 31 (2011) S37–S47

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

The coupling of temporal and spatial variations of chlorophyll a concentration and the East Asian monsoons in the southern Taiwan Strait

Huasheng Hong [a], Xin Liu [a], Kuo-Ping Chiang [b], Bangqin Huang [a,*], Caiyun Zhang [a], Jun Hu [a], Yonghong Li [a]

[a] State Key Laboratory of Marine Environmental Science, Fujian Key Laboratory of Coastal Ecology and Environmental Studies, Xiamen University, 361005 Xiamen, Fujian
[b] Institute of Environmental Biology and Fishery Science, National Taiwan Ocean University, Keelung 202-24, Taiwan

ARTICLE INFO

Article history:
Accepted 26 January 2011
Available online 12 February 2011

Keywords:
Seasonal variations
Chl *a*
Upwelling
Physical–biological coupling
Taiwan Strait

ABSTRACT

The impact of monsoon on the temporal and spatial variations of phytoplankton standing stock (Chl *a*) in the southern Taiwan Strait was studied based on long-term satellite data (1997–2008) and field observations (during 1987–1988 and 2006–2007). During the NorthEast (NE) monsoon, the high Chl *a* was induced by vertical mixing, the Zhejiang–Fujian Coastal Current and upwelling. However, for most of the area, the vertical mixing was the dominant process that enhanced phytoplankton growth. During the SouthWest (SW) monsoon, two low temperature and high Chl *a* areas were observed: one near the Dongshan Island and the other in the southeast edge of the Taiwan Bank. Both of them were identified as the upwelling areas a half century ago. The Dongshan upwelling is mainly caused by the cold waters, which is derived from the famous "East Guangdong upwelling" induced by the SW monsoon. And the latter upwelling is mainly induced by a shallowing of the topography and the Kuroshio intrusion. In the last decades, most of the studies suggested that the Chl *a* during the SW monsoon is higher than that during the NE monsoon, due to the upwelling and cold temperature, respectively. However, some recent studies made contrary conclusion. Using the satellite seasonal climatological Chl *a* data (SeaWiFS and MODIS), we acquired more extensive and long-term records and found a significant difference in the temporal variation patterns of Chl *a* concentrations in the three sub-areas of southern Taiwan Strait. In the coastal area, two Chl *a* peaks were observed, which were due to upwelling during the SW monsoon and Zhejiang–Fujian Coastal Current during the NE monsoon. On the Taiwan Bank, the high Chl *a* occurred throughout the year due to the topographical upwelling all year round. For the shelf break area, a higher Chl *a* was observed during the NE monsoon, which was induced by vertical mixing. For the whole study area, a significant coupling occurred between Chl *a* and wind speed ($r^2=0.23$, $p<0.05$) during the NE monsoon, while it was very weak during the SW monsoon. On the other hand, the mean surface Chl *a* was significantly higher in the NE monsoon (0.69 mg m^{-3}) than in the SW monsoon (0.53 mg m^{-3}). All these results demonstrated that the temporal and spatial variations of phytoplankton standing stock were affected by the East Asia monsoon system in the southern Taiwan Strait.

1. Introduction

The Taiwan Strait is an important channel between the East China Sea and South China Sea, with complex hydrodynamics as shown in Fig. 1. The South China Sea Warm Current extends northeastwards along the continental shelf (Hu et al., 2000). The Kuroshio intrudes into the northern South China Sea year-round though the Luzon Strait (Shaw, 1989, 1991; Jan et al., 1998; Hu et al., 2000). On the near shore side, the Zhejiang–Fujian Coastal Current, characterized by low temperature and nutrient-rich water has significant impacts on the southern Taiwan Strait during the NorthEast (NE) monsoon period (Jan et al., 1998, 2006; Lee et al., 2005).

Similar to the situation in the Arabian Sea, the climate and marine ecosystem of the southern Taiwan Strait is affected by the East Asia Monsoon, with a strong NE monsoon prevails over the Taiwan Strait from October to April, and a weak southwest (SW) monsoon prevails from June to August (Chen et al., 2006). The SW monsoon induces some active upwelling events in the southern Taiwan Strait. The Dongshan upwelling, near Dongshan Island, is the largest and strongest one in the Taiwan Strait which is principally induced by the Ekman transport during the SW

* Corresponding author: Tel.: +86 592 2187783; fax: +86 592 2180655.
E-mail address: bqhuang@xmu.edu.cn (B. Huang).

0278-4343/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.csr.2011.02.004

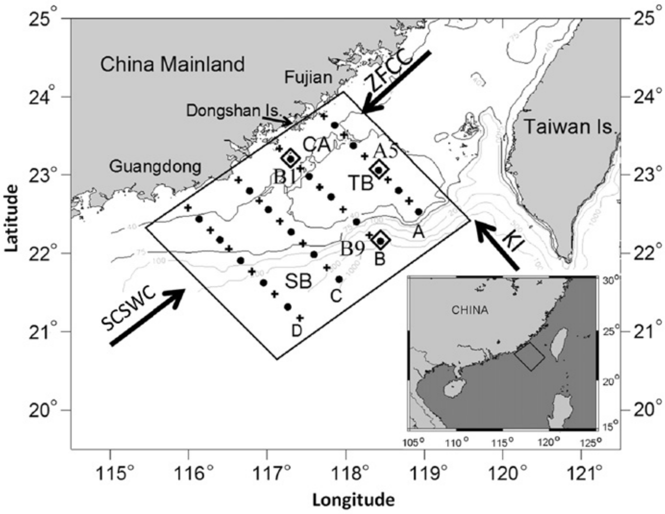

Fig. 1. Sampling stations in the southern Taiwan Strait. Hydrographic stations (+) and physical, chemical and biological stations (●). The three sub-areas were TB, the Taiwan Bank area, was defined as water with depth less than 40 m. CA, the coastal area, was defined as the area with depths less than 75 m but excluding the Taiwan Bank area, and SB, the shelf break area, involved depths greater than 75 m. Three representative stations B1, A5 and B9 are marked as ⋄. ZFCC: Zhejiang–Fujian Coastal Current, KI: Kuroshio Intrusion, SCSWC: South China Sea Warm Current.

monsoon (Tang et al. 2002; Hu et al., 2003). The Taiwan Bank upwelling, in the southern edge of the Taiwan Bank with its banana-like shape, occurs year-round with varying strength and scale. Wind stress, tides, bottom topography and the Kuroshio intrusion are four important influential factors in the formation of this upwelling (Hu et al., 2003). Tang et al. (2002) indicated that these upwelled areas, with its 2–3 °C lower temperature than the non-upwelling area, are consistent with the appearance of a high Chl *a* area during the SW monsoon period. Furthermore, Hu (2009) reveals that diatom dominates the phytoplankton community in coastal upwelling area with 72% in term of total Chl *a*. At the shelf break area, cyanobacteria and prochlorophytes are the main contributors for total Chl *a* (up to 82%). Hu et al. (2003) review the upwelling system in the Taiwan Strait, and indicate that the upwelling is very complicated in this area, especially the Taiwan Bank upwelling. They note that the upwelling is a multi-cell structure in the southern Taiwan Strait, and there are at least three independent upwelling water masses with different physical and chemical characteristics.

Seasonal variation features of Chl *a* in the southern Taiwan Strait have been studied for decades, however, it remains unclear as there are conflicting reports on underlying processes (Hong et al., 1991; Zhang et al., 1997; Wan et al., 2007 and references therein). Most of the studies suggest that the Chl *a* during the SW monsoon is higher than that during the NE monsoon. The results show that the peak of Chl *a* in summer (SW monsoon) is due to nutrient input by upwelling. In the winter (NW monsoon), they suggest that although the Zhejiang–Fujian Coastal Current can provide rich nutrients for phytoplankton growth, low temperature and high turbidity may be limiting factors of phytoplankton growth, especially, in the coastal and estuary areas (Zhang et al., 1997, 2002; Naik and Chen, 2008). However, some studies exhibit the contrary results (Hong et al., 1997; Zhang, 2006b; Wang et al., 2002; Kang, 2009). Due to the influence of the South China Sea and Kuroshio, the phenomenon that temperature limits phytoplankton growth in wintertime cannot happen in the most areas of southern Taiwan Strait (Zhang, 2006b; Kang, 2009). In addition, they suggest that there are different seasonal variation patterns of Chl *a* in the southern Taiwan Strait, compared to the northern Strait. The size-fractioned phytoplankton biomass and productivity are also different between the northern and the southern Taiwan Strait. Nanophytoplankton (3–20 μm) dominated the phytoplankton community in the northern Taiwan Strait while picophytoplankton (0.2–3 μm) dominated in the southern Taiwan Strait (Huang et al., 1999). All these results demonstrate that the phytoplankton community is significantly influenced by biogeochemical processes in the southern Taiwan Strait and the mechanism is totally different between NE monsoon and SW monsoon (Huang et al., 1999; Naik and Chen, 2008).

As monsoon-driven area, the relationship between phytoplankton and temporal monsoon variations in the Arabian Sea has been a subject of interest, and has made significant progress (Schott and McCreary, 2001, and references therein). However, it remains unresolved issue in the southern Taiwan Strait. First, the unstable upwelling event causes the phytoplankton standing stocks to exhibit high temporal and spatial variations in the coastal area during the SW monsoon, and during the NE monsoon, both the nutrient-rich Zhejiang–Fujian Coastal Current water and the vertical mixing can support the high phytoplankton biomass, but low temperature and high turbidity may also limit phytoplankton growth. In addition, few field data were available on the ecological impact of coastal currents and vertical mixing in the wintertime. There may not be a simple description of the temporal variations of Chl *a* based on a couple of cruises in the southern Taiwan Strait (Hong et al., 1991, 1997; Wang et al., 2002; Zheng et al., 2002; Naik and Chen, 2008; Kang, 2009). Second, since the hydrodynamics is complex in the southern Taiwan Strait, the nutrient inputs are different with the different areas (e.g. coast, shelf and Taiwan Bank). Third, few studies have been done on the coupling among phytoplankton standing stock, wind, upwelling, coastal current and vertical mixing in this area, and the relationship between wind speeds and Chl *a* is unclear. Therefore, based on long-term satellite data and field observations in the southern Taiwan Strait, the present study investigates the temporal and spatial variations of Chl *a* and illustrates the different control processes in the three sub-areas of the southern Taiwan Strait.

2. Materials and methods

The study area was in the southern Taiwan Strait as shown in Fig. 1. Four field survey cruises were carried out during December 1987, July 1988, August 2006 and February 2007. A total of 40 sampling stations were located along four cross-shelf transects. Temperature and salinity were recorded with a reversing thermometer and a salinometer during the cruises in 1987–1988 and with a Sea-Bird Conductivity–Temperature–Depth recorder (CTD) during the cruises in 2006–2007. Discrete seawater samples were collected and analyzed for nutrients and Chl *a*. Nutrient analysis was performed on board ship using standard manual spectrophotometric methods (Parsons et al., 1984; Pai et al., 1990a, 1990b), and the detection limits of nitrate, phosphate and silicate were 0.5, 0.1 and 0.5 μmol L^{-1}, respectively. Chl *a* was determined by spectrophotometric analysis during 1987–1988 (Jeffrey and Humphrey, 1975) and fluorescence analysis during 2006–2007 (Parsons et al., 1984). The Chl *a* samples were prepared by filtering 150–300 mL seawater through polycarbonate filter (0.45 μm in pore size), and then the filter was stored at −20 °C until analysis.

The monthly mean wind data were retrieved from Quik Scatterometer (QuikSCAT) observations from August, 1999 to July, 2008. The spatial resolution was 0.25° by 0.25° for QuikSCAT winds. The monthly mean Sea Surface Temperature (SST) data in the southern Taiwan Strait were derived from NOAA AVHRR Pathfinder SST products from January, 1985 to December, 2006, with a spatial resolution of 4 by 4 km. The surface Chl *a* was