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Low nutrient and high chlorophyll *a* coastal upwelling system – A case study in the southern Taiwan Strait

Jun Hu [a, c], Wenlu Lan [a], Bangqin Huang [a, *], Kuo-Ping Chiang [b], Huasheng Hong [a]

[a] *Key Laboratory of Coastal and Wetland Ecosystems, Ministry of Education, Fujian Provincial Key Laboratory of Coastal Ecology and Environmental Studies, Xiamen University, Xiamen 361005, China*
[b] *Institute of Marine Environmental Chemistry and Ecology, National Taiwan Ocean University, Keelung 202-24, China*
[c] *Qingpu District Environmental Monitoring Station of Shanghai, Shanghai 201799, China*

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ABSTRACT

Using the field data during four summer cruises of 2005, 2006, 2008 and 2013, an interesting phenomenon of low nutrient and high Chl.*a* (LNHC) was observed in the coastal upwelling system off Dongshan in the southern Taiwan Strait. The results indicated that the upwelling region was dominated by cold (<25 °C) and saline (>33.9 psu) upwelled water, and the concentration of nitrate (<1 μM) and phosphate (<0.1 μM) was very low, while with high Chl.*a* content (mean 1.98–3.56 μg L^{-1}, maximum 8.3 μg L^{-1}) during the stronger summer upwelling cruise of 2005, 2006 and 2008. The upwelled water originated from the 50–100 m layer off Shanwei with a low concentration of nitrate (<7.5 $\mu mol \cdot L^{-1}$) and phosphate (<0.5 $\mu mol \cdot L^{-1}$), which was transported to Shantou-Dongshan by the northeastward bottom current. During the time that the upwelled water moved the long-distance (150–300 km) from Shanwei to Shantou-Dongshan and was transported through the euphotic zone alongshore, the phytoplankton grew rapidly due to the favorable temperature, N/P ratio and illumination, and consumed most of the nutrients in the upwelled water. These unique physical, chemical and biological processes are the main reasons for the formation of the low nutrients/high chlorophyll *a* in this coastal upwelling system in the southern Taiwan Strait.

1. Introduction

Nutrient availability is one of the key factors which can strongly influence primary production in the euphotic zone of the pelagic ecosystem. Upwelling can play an important role in nutrient transport in the ocean and has a significant impact on fishery production (Rykaczewski and Checkley, 2008). Generally, coastal upwelling is recognized as bringing nutrient-rich deep water up to the euphotic zone, thereby enhancing phytoplankton growth resulting in a high standing stock of phytoplankton, and so displaying the phenomenon of high nutrients and high chlorophyll *a* (Chl.*a*). Examples are the Peru upwelling (Dugdale and Wilkerson, 1986; Mann and Lazier, 1996; Silva et al., 2009), the California upwelling system (Haury and Shulenberger, 1998; Pennington & Chavez, 2000), the Bengula upwelling (Probyn, 1985; Giraudeau and Bailey, 1995) and the Oregon upwelling (e.g. Dickson and Wheeler, 1995; Geen et al., 2000). However, the fact that increased algal growth is not an immediate result of the enhanced nutrient supply causes a lag period between the upwelling and Chl.*a* accumulation (Habeebrehman et al., 2008). Therefore we usually find a high phytoplankton standing stock at the margin, or downstream, of upwelling, where the nutrients are depleted due to the high phytoplankton uptake (MacIsaac et al., 1985; Wilkerson et al., 2006). This causes the relationship between nutrients and phytoplankton distribution to be more complex in upwelling regions.

The southern Taiwan Strait (also known as northern South China Sea, SCS), is a shallow shelf in the west Pacific Ocean, characterized by seasonal upwelling due to the southwest monsoon (Tang et al., 2002, 2004; Shang et al., 2004). Several upwelling zones in the southern Taiwan Strait are noted for their high fisheries production, and these upwelling zones have been well studied during field investigation, through remote sensing, and by modeling during the past two decades (e.g. Hong et al., 1991; Hu et al., 2001; 2003; Tang et al., 2002). The coastal upwelling off Dongshan on the coast of

* Corresponding author. Key Laboratory of Coastal and Wetland Ecosystems, Ministry of Education, Xiamen University, Xiamen 361005, China.
E-mail address: bqhuang@xmu.edu.cn (B. Huang).

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Mainland China (here called the Dongshan upwelling or DSU) is the largest and strongest, and sometimes extends offshore (Tang et al., 2002). This upwelling is principally forced by the prevailing southwest monsoon and the ascending northeastward-flowing bottom current (Hu et al., 2003). Gan et al., (2009a) noted that the cold upwelled water off Dongshan is transported along the coast from Shanwei rather than climbing over the Taiwan Bank (see Fig. 1a). Offshore of Taiwan bank, there is another cold, high nutrient water mass, but it cannot cross the bank and so the two water mass are separated (Jiang et al., 2011). And the model study indicated local wind is the main mechanism for Dongshan upwelling, but without local winds, the cold water still exists off Dongshan Island, while reducing the area considerably (Jiang et al., 2011). In addition, several previous investigations indicate that the strength of this upwelling presents interannual variability (Hu et al., 2001; Tang et al., 2004), and that a delayed ENSO effect is likely to be a major contributing mechanism (Hong et al., 2009). Shang et al., (2004) also provide the short-term variability of chlorophyll associated with coastal upwelling events and indicate that phytoplankton growth lagged behind the upwelling activities by about 2 days.

These studies provide a preliminary understanding for the DSU and its physical, chemical and biological features. However, the dynamics between nutrients and phytoplankton in the DSU remain unclear. In southern Taiwan Strait, the mechanisms driving DSU is more complex than for most of the typical coastal upwelling, e.g., the Canary upwelling, the Benguela upwelling, the Californian upwelling and the Peru upwelling, which are caused by the Ekman

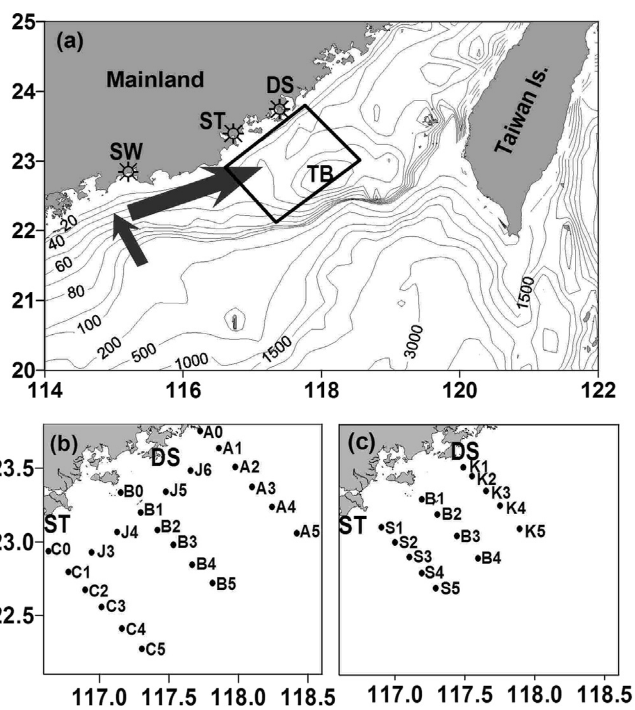

Fig. 1. Study area (a) and sampling stations (b,c) in the southern Taiwan Strait during the summer cruises of 2005, 2006, 2008 and 2013. (a) Study area is the solid lined rectangular area; the arrow perpendicular to the coast indicates the path of the deep water upwelled to the coastal region off Shanwei; and the arrow parallel to the coast shows the transportation path of the upwelled water along the coast from off Shanwei to off Shantou-Dongshan. DS, Dongshan; ST, Shantou; SW, Shanwei; TB, Taiwan Bank. (b) Sampling stations during the summer cruises of 2005, 2006 and 2013; Stns. A0 and C0 are not sampled in the summer cruise of 2005, Stns. A0, B0, C0, J3, J4, J5, J6 are not sampled in the summer cruise of 2013. (c) Sampling stations during the summer cruise of 2008.

Transport driven by the equator-ward trade wind stress plus Coriolis effect. Consequently, the nutrients, chlorophyll *a* feature in this upwelling might be great different to the typical coastal upwelling. Here we report a low nutrient and high Chl.*a* in the coastal upwelling system in the southern Taiwan Strait, and the purpose of present study was to report such a unique phenomenon and analyze its formation based on physical, chemical and biological processes in the study area.

2. Data and methods

The R/V Yanping 2 was used to collect samples during the summer cruises of 2005, 2006, 2013 (Fig. 1b) and 2008 (Fig. 1c). Field investigation of physical, chemical and biological parameters was carried out during July 10th to July 14th, 2005, June 20th to June 24th, 2006, July 4th to July 7th, 2013, and June 27th to June 28th, with a smaller spatial coverage in 2008. Alongshore transects (A1-B1-C1 for 2005, 2006 and 2013, and K1–B1–S1 for 2008) were used to analyze spatial variations of physical, chemical and biological parameters during the transportation of the upwelled coastal water.

The Quick Scatterometer (QuikSCAT) wind data (Fig. 2) used here were obtained from the NASA Goddard Space Flight Center. The spatial resolution was 0.25° by 0.25° for QuikSCAT winds. The data were averaged by day in the rectangle with Stns. C1, A1, A5 and C5 as the vertex (Fig. 1)a, b.

Hydrographic measurements and water samples were taken using a CTD (Seabird SEB 19) profiler equipped with a 12 bottle (10L, Go-Flo) Rosette sampler. The downward photosynthetically active irradiance (PAR, 400–700 nm) at the water surface, and the water column was measured using a biospherical QSP 2300 underwater sensor. Water subsamples for nutrient analysis were collected in 100 ml polypropylene bottles and nutrient analysis was performed aboard using standard spectrophotometric methods. Nitrate concentration was determined by the pink azo dye method (Pai et al., 1990a). Phosphate and silicate concentrations were measured by the molybdenum blue method and the silicomolybdenum blue method, respectively (Pai et al., 1990b). The detection limits of nitrate and phosphate were 0.5 and 0.1 $\mu mol \cdot L^{-1}$, respectively. Chl.*a* was determined using fluorescence analysis, with the volume of the seawater sample being 300–500 mL, depending on the Chl.*a* concentration, and *in vitro* measurements were conducted using a Shimadzu fluorospectrometer (RF-5301PC) with the excitation and emission wavelengths set at 430 and 670 nm (Parsons et al., 1984).

3. Results

3.1. Quick scatterometer wind data

One month recoards wind intensity and direction in the study area examined around the times of the summer cruises of 2005, 2006 and 2008 (Fig. 2). During the summer of 2005 (Fig. 2a), the southwest monsoon had been blowing at 2–6 m/s for at least 13 consecutive days (10th-23rd June), then shifted to a southeast wind for 7 days and switched back to SSW immediately before the shipboard field investigation began. During the cruise time (6th July-14th July) the wind turned to southwest monsoon. During the summer of 2006 (Fig. 2b), strong southwest or northward winds blew from June 1st to June 17th, and after 4 days weak northeast or east wind, it shifted to southeast during the cruise time. During the summer of 2008 (Fig. 2c), the southwest wind dominated through this period including the cruise time (4th-7th July). During the cruise of 2013, the southeast wind dominated in the study area with lower speeds (Fig. 2d). In a word, the upwelling favorable