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

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A B S T R A C T

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 μmol·L^{-1}) and phosphate (<0.5 μmol·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

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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 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.

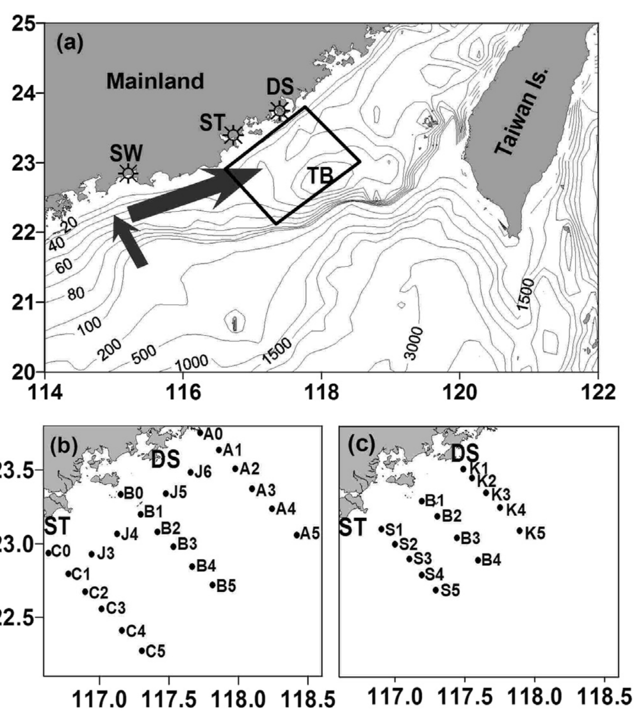

Fig. 1. Study area (a) and sampling stations (b,c) in the southern Taiwan Strait during the summer cruises of 2005, 2006, 2008 and 2013. (a) Study area is the solid lined rectangular area; the arrow perpendicular to the coast indicates the path of the deep water upwelled to the coastal region off Shanwei; 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.

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

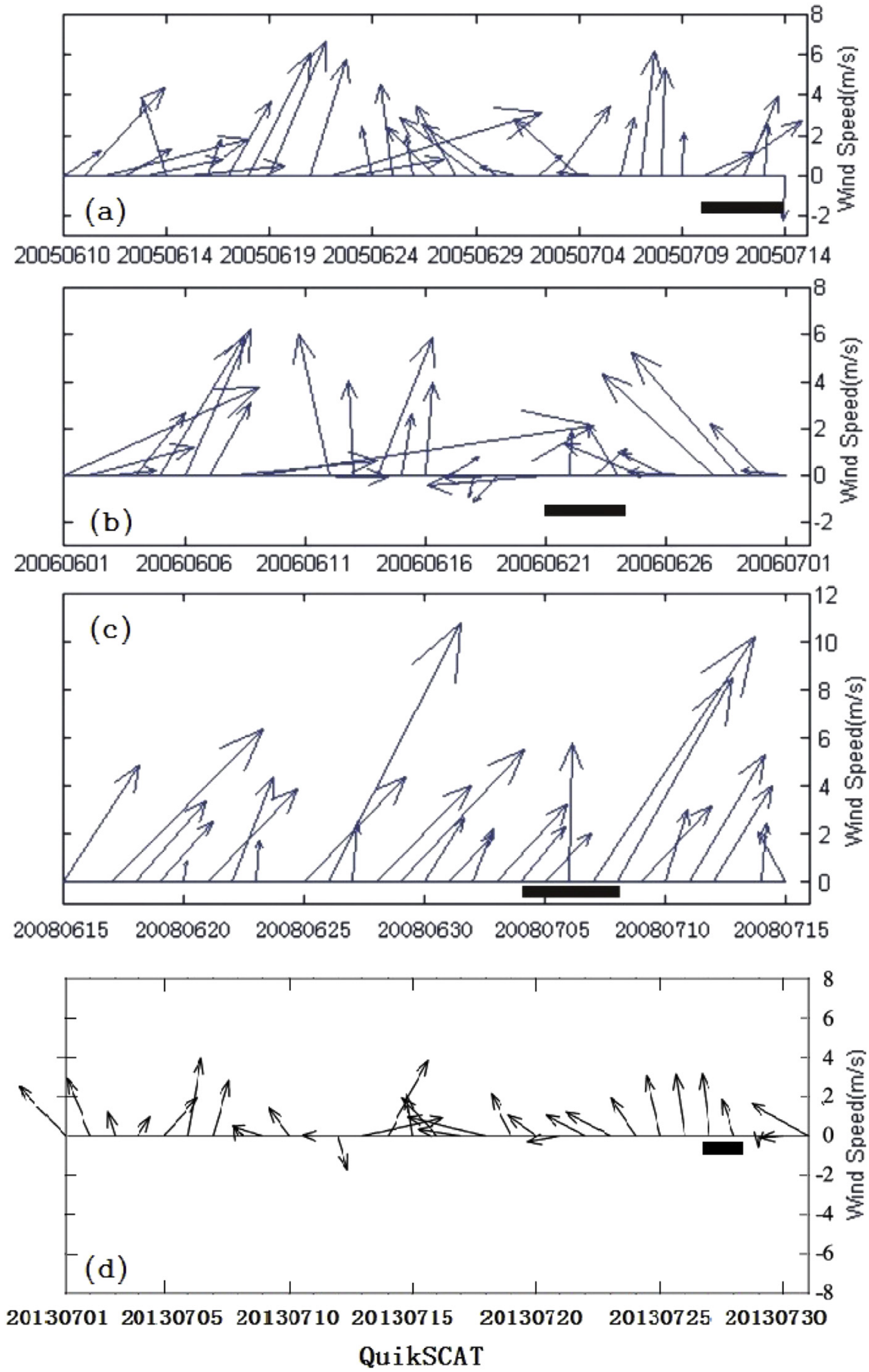

Fig. 2. Stick diagram of daily mean wind velocity in the coastal area off Dongshan Data were obtained from the NASA Goddard Space Flight Center: from June 10th – July 15th for 2005 (a); June 1st – July 1st for 2006 (b); 15th June – 15th July for 2008 (c).July 1st – August for 2013 (d). * The solid lines show the cruise times during 2005, 2006, 2008 and 2013.

southwest monsoon in the coastal region of the southern Taiwan Strait presented significant interannual variations during these four summer cruises.

3.2. Physical structure

Horizontal distribution of temperature and salinity of the surface water (at the 5 m layer) and the alongshore transects are shown in Figs. 3 and 4. The cold (<25 °C) and saline (>33.9 psu) upwelled water reached the surface (5 m layer) at Stns. B1 and A1 during 2005 (Fig. 3a, e) and 2006 (Fig. 3b, f), and the upwelled water occupied the surface of alongshore transect (K1–B1–S1) during 2008 (Fig. 3c, g). Warm (>28.5 °C) and low salinity (<31 psu) water, which was the Pearl River plume, was always on the southwest or south of the study area during the summer cruises of 2005, 2006 and 2008. During the summer of 2013, the low temperature and high salinity water also can be observed, but the temperature was higher while salinity was lower, leading to a

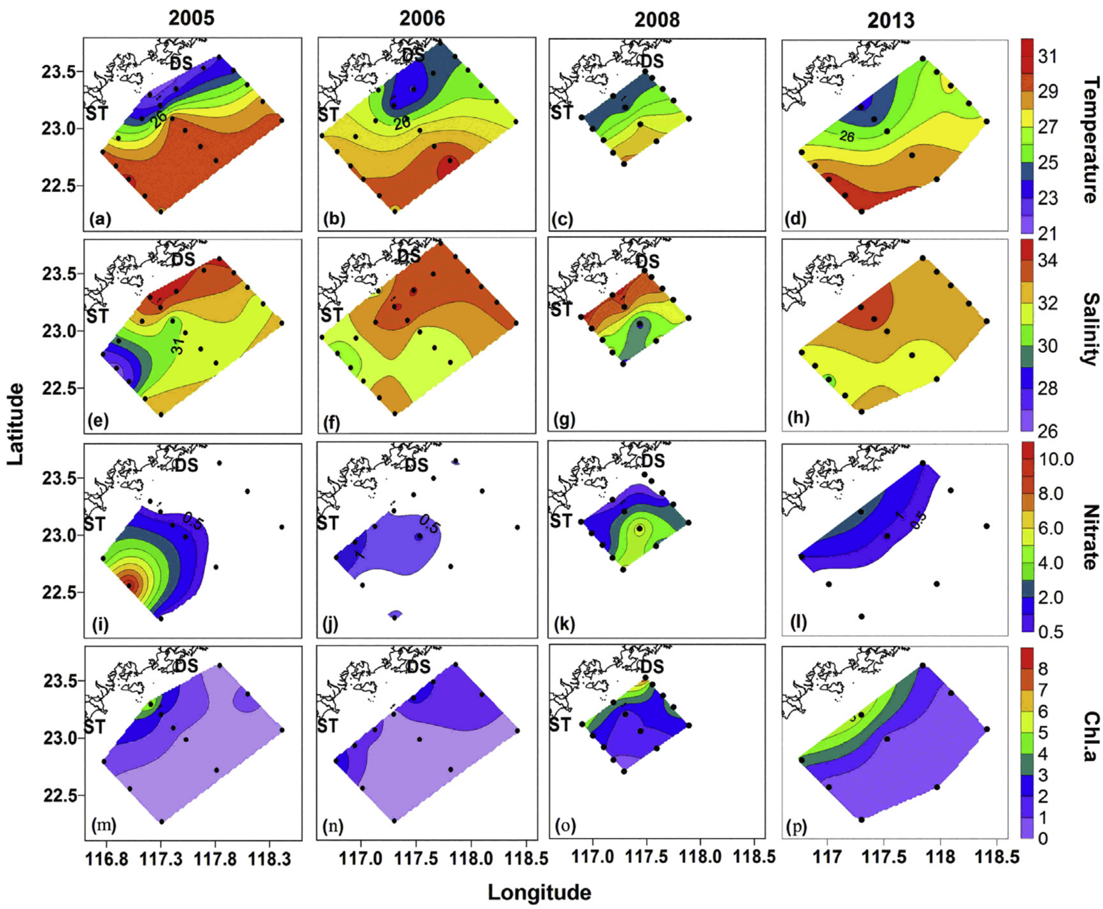

Fig. 3. Horizontal distribution of temperature (a–d,°C), salinity (e–h, psu), nitrate (i–l, μmol·L^{-1}) and Chl.*a* (m–p, μg·L^{-1}) in the surface (or near surface) water in the study area during the summer cruises of 2005 (a, e, i, m), 2006 (b, f, j, n) 2008 (c, g, k, o) and 2013 (d, h, i, p). Temperature and salinity are at 5 m depth, and others from the surface water.

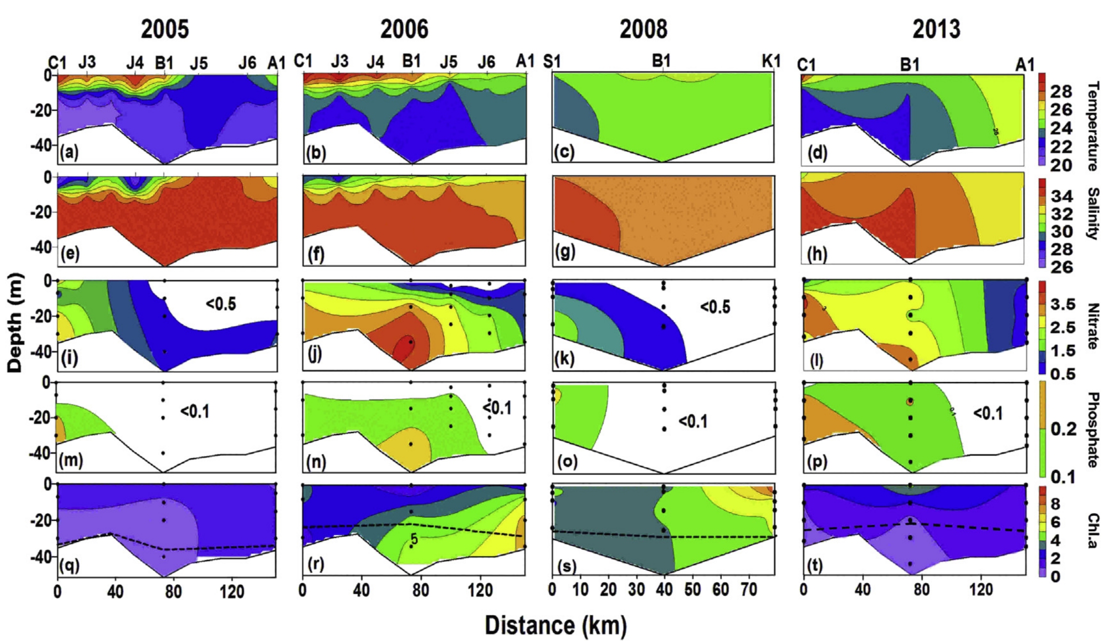

Fig. 4. Distribution of temperature (a–d, °C), salinity (e–h, psu), nitrate (i–l, μmol·L^{-1}), phosphate (m–p, μmol.L^{-1}) and Chl.*a* (q–t, μg·L^{-1}) in alongshore transects during the summer cruises of 2005 (a, e, i, m, q), 2006 (b, f, j, n, r) 2008 (c, g, k, o, s) and 2013 (d, h, i, p, t) in the coastal upwelling areas in the southern Taiwan Strait. *The dashed lines are the depth of 1% surface PAR (Photosynthetic Available Radiation), showing the euphotic zone.

smaller surface expression than on the other cruises (Fig. 3d, h). Considering the wind field, the surface temperature and salinity, the upwelling was strongest in the 2008. As shown in Fig. 4a–h, at the depth below 10 m, weak gradients of salinity and temperature were observed in the alongshore transect from off Shantou (at Stns. C1 or S1) to off Dongshan (at Stns. A1 or K1), showing increased temperature and decreased salinity. This implied that the upwelled water (with low temperature and high salinity) was transported along the alongshore transect from off Shantou to off Dongshan, and ascended to the surface off Dongshan.

3.3. Nutrients

In the surface water, nitrate concentration was below the detection limit in the upwelled water with low temperature and high salinity (Fig. 3i–k), while it had a higher value in the Pearl River plume during the cruises of 2005, 2006 and 2008 (high temperature and low salinity water) (e.g. the nitrate concentrations were 10.2 $\mu mol \cdot L^{-1}$ at Stn. C3, 1.86 $\mu mol \cdot L^{-1}$ at Stn. C1 and 5.58 $\mu mol \cdot L^{-1}$ at Stn. B3 in 2005, 2006 and 2008, respectively). During the summer of 2013, the highest concentration of nitrate located at the station B1 where affected by the upwelling water (Fig. 3). The phosphate concentrations were below the detection limit in the surface water of all stations during these four cruises (figure omitted).

In the alongshore transect (Fig. 4i–p), both nitrate and phosphate concentrations showed their higher concentration in the bottom layer near Shantou (at Stns. C1 or S1), and drastically decreased from the waters off Shantou to those off Dongshan (at Stns. A1 or K1) during the all four cruises. When the water reached the place where it outcrops, both nitrate and phosphate were below the detection limit at the upper layer even in the whole water column during the summers of 2005, 2006 and 2008 (Fig. 4i–p), while only phosphate was below the detection limit during 2013.

Where the place the nutrients presented very low level matched well with the upwelling region, which was indexed by a surface temperature 2 °C colder than the spatial mean SST over the whole study area.

3.4. Phytoplankton biomass (chlorophyll a)

Contrary to the pattern of nutrients, surface Chl.*a* presented its highest value in the upwelled water with low nutrients during the summer cruises of 2005 (4.08 $\mu g\ L^{-1}$ at Stn. B0) and 2008 (8.51 $\mu g\ L^{-1}$ at Stn. A1). In summer 2006, although the highest Chl.*a* concentration (3.17 $\mu g\ L^{-1}$) was located in the plume (at Stn. C1), high Chl.*a* (2–3 $\mu g\ L^{-1}$) also appeared in the coastal upwelling area with low concentration of nutrients (e.g. Stns. B1, J5 and J6). But the highest Chl.*a* presented at Stn.B1 where with highest concentration nitrate during the summer of 2013.

In the alongshore transect, the Chl.*a* also showed a contrary distribution pattern to that of nutrients in that Chl.*a* increased from Shantou to Dongshan in all four cruises (Fig. 4q–t), suggesting that phytoplankton grew during the transportation of the upwelled water from Shantou to Dongshan. In the upwelling region, the mean Chl.*a* concentrations were 1.98 ± 0.98, 3.50 ± 2.28, 3.56 ± 1.23 $\mu g \cdot L^{-1}$ and 1.54 ± 0.97 $\mu g \cdot L^{-1}$ for the summer cruises of 2005, 2006, 2008 and 2013, respectively.

In general, high Chl.*a* was observed in the coastal upwelling areas, which were characterized by low temperature, high salinity and nutrient-poor water during the summer stronger upwelling cruises of 2005, 2006 and 2008 in the southern Taiwan Strait (Fig. 3i–k, 3 m-o), while during the weaker upwelling year, the surface upwelling water present low phosphate while with high chl.*a*.

4. Discussion

The field data from the four summer cruises of 2005, 2006 2008 and 2013 indicated that the strength of the coastal upwelling in the southern Taiwan Strait presented interannual variability, and a low nutrient with high Chl.*a* water is observed in the coastal upwelling area off Dongshan in the southern Taiwan Strait during the upwelling stronger year. This region, with low temperature and high salinity, matched well with the DSU referred to in Tang et al. (2002, 2004) and Hu et al. (2003). This low nutrient with high Chl.*a* phenomena was significantly different to typical eastern boundary upwelling ecosystems such as Peru, California, Benguela and Oregon, where there were high nutrients and high Chl.*a* in the surface or near surface water (Table 1) (Probyn, 1985; Dugdale and Wilkerson, 1986; Dickson and Wheeler, 1995; Wilkerson et al., 2006). The unique physical, chemical and biological processes described in the following sections are the main reasons for the formation of the low nutrients and high Chl.*a* phenomena in this coastal upwelling ecosystem in the southern Taiwan Strait.

4.1. The dynamic mechanism of coastal upwelling in the southern Taiwan Strait

In the southern Taiwan Strait, several studies note that this coastal upwelling is principally induced by the southwest monsoon (Hu et al., 2003; Shang et al., 2004; Hong et al., 2009). However, the low temperature and high salinity water at the surface was seen to have a smaller surface expression in the coastal region off Dongshan during unfavorable monsoon (e.g. 2013) (see Figs. 2 and 3). These phenomena confirmed the model result that without the upwelling favorable wind, the cold water still exists near Dongshan Island, while reducing the upwelling area (Jiang et al., 2011). A similar phenomenon has been seen elsewhere on shallow shelves, where cold, high nutrient waters are upwelled onto the shelf, but do not reach the surface until the wind stress strengthens (e.g., Bailey and Chapman, 1985; Kämpf et al., 2004). Jiang et al. (2011) indicated that the upwelling water is advected upslope from its origin in deeper water to the south, and has been transported a long distance (150–300 km) from the upwelled region (off Shanwei) to the outcropped area (off Shantou-Dongshan) (Gan et al., 2009a). Our results showed that the cold, high salinity water outcropped in the coastal region off Shantou due to the stronger southwest wind drove the stronger vertical movement of the cold water and the Pearl River plume water move to offshore in this coastal area during the summer of 2008 (see Figs. 2 and 3c, f, Fig. 4c, f), while the upwelling with smaller size during the summer of 2005 (Fig. 3a, e, and Fig. 4a, e), 2006 (Fig. 3b, f, Fig. 4b, f) and 2013 (Fig. 3d, h, Fig. 4d, h) due to the weak southwest wind or upwelling unfavorable wind. Consequently, the size of upwelling and the exactly where the upwelled water outcropped mostly depended on monsoons and the Pearl River plume.

4.2. Low nutrient concentration of the upwelled water

The upwelled water with low temperature and high salinity off Dongshan came from the subsurface water (50–100 m) of the southern Taiwan Strait (Hu et al., 2003; Gan et al., 2009b), which climbed in the coastal region off Shanwei (see Fig. 1a). Low nutrient concentration was noted in the water of such layers, where nitrate and phosphate levels were below 7.5 $\mu mol \cdot L^{-1}$ and 0.5 $\mu mol \cdot L^{-1}$, respectively (Yuan, 2005). Compared to other typical upwelling ecosystems, such as Peru–Chile (Morales et al., 1996; Silva et al., 2009), Oregon (Huyer, 1976; Geen et al., 2000), Benguela (von Bodungen et al., 2008) and California (Segovia-Zavala et al., 1998; Pennington and Chavez 2000; Wilkerson et al., 2006), the

Table 1
Comparison of surface (or near-surface) nutrient and Chl.*a* among coastal upwelling systems.

Upwelling sites	Nitrate μmol·L^{-1}	Phosphate μmol·L^{-1}	Chl. *a* μg·L^{-1}	References
Oregon	5–25	0.7–1.8	0.5–38	Dickson and Wheeler, 1995 Geen et al., 2000
California	10–20	0.5–2	3–8	Haury and Shulenberger 1998 Pennington and Chavez 2000
Peru	9–25	0.6–1.4	0.9–18	Dugdale and Wilkerson, 1986 Silva et al., 2009
Benguela	5–20	0.75–2	7	Probyn, 1985 Giraudeau and Bailey 1995
Southern Taiwan Strait	<0.5–4	<0.2	1–8.51	Present study

nutrient concentrations of the upwelled water and the source water were lower in the southern Taiwan Strait (Tables 1 and 2).

4.3. *Phytoplankton growth and nutrient consumption during transportation of the upwelled water*

Environmental conditions were quite suitable for phytoplankton growth during alongshore transportation of the upwelled water. Firstly, the transport path of the upwelled water was situated in the euphotic zone (<30 m, 1% of surface PAR; see dashed line in Fig. 4m–o). Secondly, the temperature of the upwelled water was about 21–25 °C, which is appropriate for the growth of phytoplankton. Thirdly, the N:P ratio of the upwelled water was 15.7 ± 0.9: 1, 15.4 ± 0.4: 1 and 15.1 ± 4.1: 1 during the summer cruises of 2005, 2006 and 2008, respectively, which were close to the Redfield ratio and suitable for phytoplankton growth. The high primary productivity (722 mg Cm^{-2} d^{-1}) revealed using a ^{14}C radiotracer, and high phytoplankton growth rate (1.12 ± 0.27 d^{-1}) revealed using the dilution method in the summer cruises confirmed the above fact (Huang et al., 2011). Moreover, the negative relationship between nutrients and Chl.*a* implied that nutrients were being consumed by phytoplankton growth (Fig. 5). Therefore, the dynamic balanced status of this coastal upwelling system meant that phytoplankton grew showing high Chl.*a*, and nutrients were consumed revealing low concentrations during the long-term transportation of the upwelled water in the euphotic zone continually from Shanwei to Shantou-Dongshan in the sorthern Taiwan Strait. While during the summer of 2013, the N:P ratio was only 9.8 ± 2.0: 1, which much lower than the Redfield ratio, resulting in less phytoplankton growth so that the nitrate was not exhausted.

In the alongshore transect, the velocity of the northeastward bottom current is about 20–50 cm s^{-1} in the coastal upwelling region off Dongshan (Hong et al., 1991; *Gan*, personal communication), if taking Stns. C1 and A1 as the starting and terminal points, respectively. Using the concentrations of nitrate and Chl.*a* of Stns. A1 and C1, we estimated the Chl.*a* specific nutrient uptake rates using the formula as following:

$$V^{Chl}_{nutrient} = \frac{\left(C^{nutriens}_{C1} - C^{nutrien}_{A1}\right) \times V_{current} \times 60}{\left(C^{Chl}_{A1} - C^{Chl}_{C1}\right) \times D \times 10^2}$$

Here the $V^{Chl}_{nutrients}$ is the Chl.*a* specific nitrate or phosphate uptake rate (nmol mg^{-1} h^{-1}), $C^{nutriens}_{C1}$ and $C^{nutrien}_{A1}$ are the mean concentration of nutrient at Stations C1and A1(μmol L^{-1}), C^{Chl}_{A1} and C^{Chl}_{C1} are the mean concentration of Chl.*a* at Stations A1 and C1(μg L^{-1}), D is the distance between the Stations C1 and A1 (km), $V_{current}$ is the speed of alongshore current (cm s^{-1}).

Using this formula, the estimated Chl.*a*-specific nitrate uptake rates (V^{Chl}_{NO3}) were 11.6–29, 4.6–11.6, 2.5–6.3 and 3.2–7.9 nmol μg^{-1} h^{-1} during the summer cruises in 2005, 2006, 2008 and 2013, which are much lower than the mean V^{Chl}_{NO3} in the coastal upwelling systems of Oregon, California, Peru and Benguela (25.3 ± 1.8, 24.4 ± 4.4, 36.5 ± 4.1 and 35.9 nmol μg^{-1} h^{-1}) (Dickson and Wheeler, 1995). Even at this lower value of V^{Chl}_{NO3}, when the upwelled water was introduced into the euphotic zone in the coastal region off Shanwei, the concentrations of nutrients in the upwelled water would be below the detect limits during the long-term transportation from Shanwei to Shantou-Dongshan in the southern Taiwan Strait. Yentsch and Vaccaro (1958) indicated that the ratios of cellular nitrogen (mg L^{-1}) to Chl. *a* (mg L^{-1}) in the cultures of marine phytoplankton are range from 1.7 to 14.7, that means less than1 μmol L^{-1} nitrate is enough for the synthesize of 1 μg L^{-1} phytoplankton Chl.*a*. So it is possible for the water upwelled from 50 to 100 m off Shantou present high Chl.*a* concentration (8.51 μg L^{-1}) when it move to the place where it outcrops.

During the weak upwelling summer of 2013, the upwelling water presents high nitrate with high Chl.*a*, which might be due to the lower N:P ratio (9.8 ± 2.0: 1) leading to P limitation, lower phytoplankton growth rate and residual nitrate concentrations.

5. Conclusion

We report here a new finding of low nutrient while high Chl.*a* water in a coastal upwelling ecosystem during three stronger

Table 2
Comparison of the nutrient concentrations in the upwelling source waters of the different upwelling systems.

Upwelling Sites	Source water	Nitrate μmol·L^{-1}	Phosphate μmol·L^{-1}	References
Oregon	20–25 km offshore and from depth between 100 and 200 m	15–25	2.0–2.8	Huyer, 1976 Geen et al., 2000
California	From 60 to 100 m	20–40	0.75–2.0	Wilkerson et al., 2006 Segovia-Zavala et al., 1998 Pennington and Chavez 2000
Benguela	From around 150–300 m	21–38	1.5–2.3	von Bodungen et al., 2008
Peru–Chile	Equatorial subsurface water	20–40	1.8–3.0	Morales et al., 1996; Silva et al., 2009
Southern Taiwan Strait	From 50 to 100 m of northern SCS	<7.5	<0.5	Gan et al., 2009 Yuan, 2005

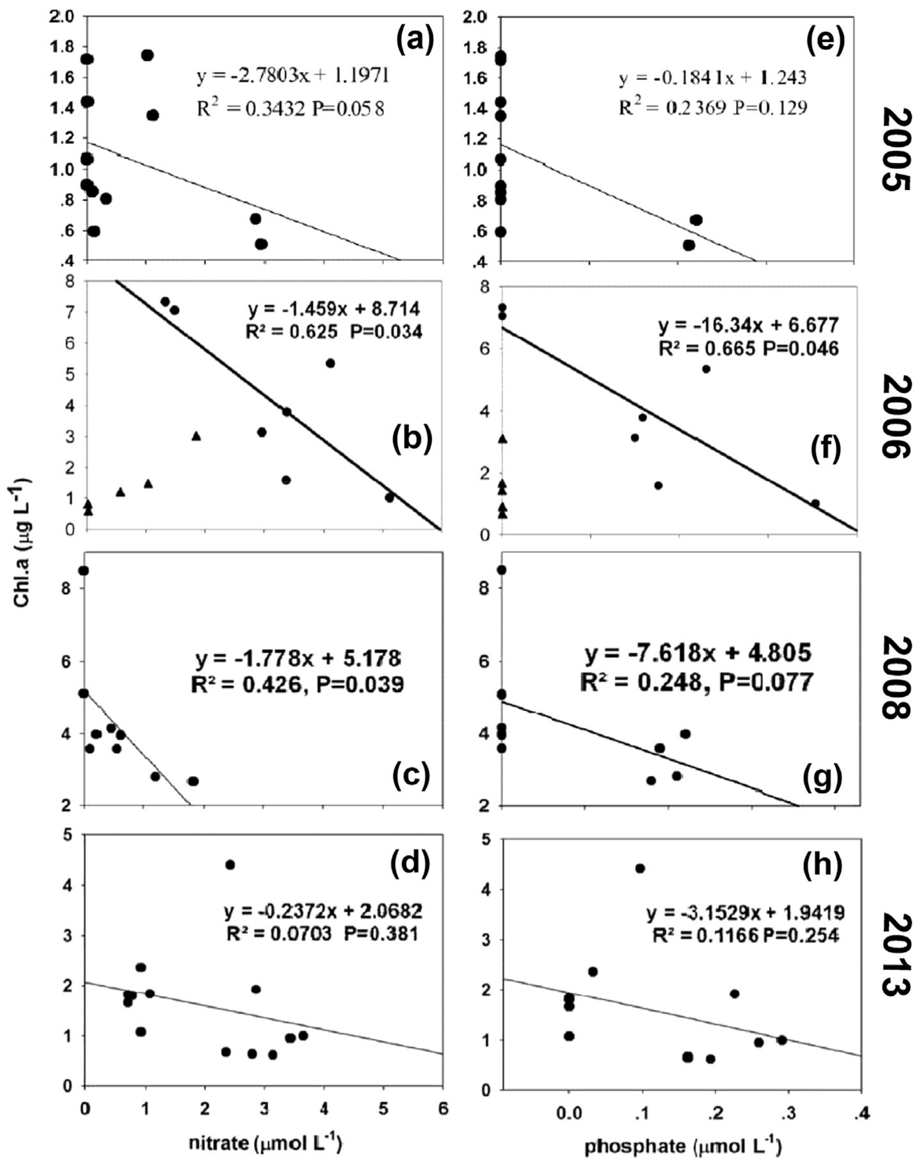

Fig. 5. The relationship between nutrients (nitrate and phosphate) and Chl.*a* in alongshore transects during the summer cruises of 2005 (a, e), 2006 (b, f), 2008 (c, g) and 2013 (d, h) respectively in the coastal upwelling areas in the southern Taiwan Strait. *The triangle points in the b and f represent the data of Pearl River plume.

summers upwelling cruises of 2005, 2006 and 2008 in the Southern Taiwan Strait. The formation of such a phenomenon was due to unique physical-chemical-biological processes. The upwelled water came from the deep (50–100 m) layer off Shanwei, which had low nutrient concentrations transported in the euphotic zone. Phytoplankton grew at a high rate during the upwelling process from Shanwei to Shantou-Dongshan because conditions were suitable for its growth such as the almost Redfield N/P ratio, the temperature and light intensity. The nutrients were consumed and keep at very low level and the low nutrient while high Chl.*a* water was finally formed in this coastal upwelling ecosystem in the southern Taiwan Strait.

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