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Short-term variability of chlorophyll associated with upwelling events in the Taiwan Strait during the southwest monsoon of 1998

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Abstract

SeaWiFS chlorophyll and AVHRR SST time series as well as in situ measurements in August 1998 were used to evaluate short-term variability of chlorophyll associated with upwelling events in the western Taiwan Strait. The extent of eutrophic waters (SeaWiFS Chlorophyll $>1\,\mathrm{mg/m^3}$), colder upwelling waters, and upwelling index were calculated for the western strait and for the northern and southern portions. Large extents of eutrophic waters were always accompanied by colder upwelling waters, indicative of the tight coupling of chlorophyll with upwelling activities. The phytoplankton growth lagged the upwelling activities by about 2 days. The temporal changes of upwelling events were found different in the northern and southern Taiwan Strait. A short relaxation of upwelling probably occurred between early and mid-August in the northern portion. One strong upwelling event likely lasted from early through mid-August, peaking before August 13 in the southern portion. It resulted in chlorophyll enhancement but with different timing of chlorophyll reaching maximum values in these two upwelling zones. The duration of one upwelling event in the western Taiwan Strait in August was estimated to be about 12 days. It seems that two distinctive northern and southern upwelling systems in the western Taiwan Strait were connected with, and affected by, the East China Sea and the South China Sea, respectively.

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1. Introduction

Coastal upwelling ecosystems, for example, Peru (Mann and Lazier, 1996) and the California Upwelling System (Pennington and Chavez, 2000), are well known to feature cold, nutrient-rich water and high biological production, which contribute to rich fisheries. Some of upwelling systems bring continuous, and others periodic, pulses of nutrients to the surface. Due to logistics, ship surveys are unlikely to capture periodic upwelling events and associated ecological response. On the other hand, remote sensing has the advantage of synoptic and repetitive coverage, so that it is a useful tool to identify and monitor the upwelling pulses (Ho et al., 2000). Furthermore, remote sensing data allow estimation of the size of upwelling area (Nixon and Thomas, 2001) and the migration path of upwelling centers (Kuo et al., 2000). However, ecological responses to periodic upwelling events have not been well investigated due to a paucity of time-series data. For example, Takahashi et al. (1986) observed daily changes in nutrient concentrations and phytoplankton biomass during an upwelling event around the Izu Peninsula, Japan, but the observation period only covered 6 days. Kudela et al. (1997) reported short-term variation of carbon and nitrogen uptake by phytoplankton in response to an upwelling event in Monterey Bay using a holey-sock drifter that tracked the upwelled waters for 5 days.

The Sea Wide Imaging Field Sensor (SeaWiFS) and the Advanced Very High Resolution Radiometer (AVHRR) provide us a high-resolution time series of surface Chlorophyll a (Chl) and sea-surface temperature (SST). A series of upwelling events occurred in the Taiwan Strait during August 1998. SeaWiFS Chl and AVHRR SST daily data during this period enable us to investigate temporal changes of surface Chl in responses to the upwelling events.

Taiwan Strait (Fig. 1) is a shallow shelf channel linking the East China Sea (ECS) and the South China Sea (SCS), characterized by seasonal and year-round upwelling (Chen et al., 1982; Xiao, 1988). Taiwan Bank is the shallowest area in the entire region, with water depths varying from 10 to 30 m. Northeast monsoon prevails during winter, while winds are predominantly southwesterly in summer. Under the monsoonal forcing, water

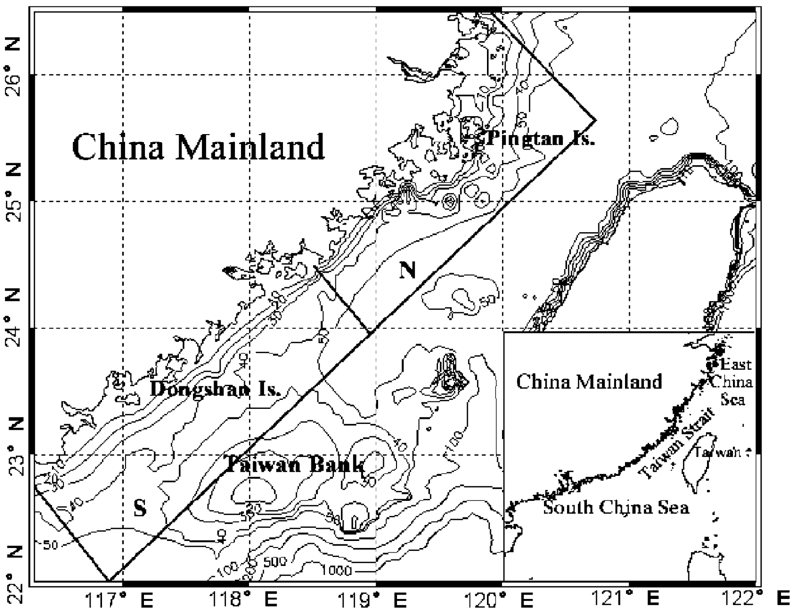

Fig. 1. Map of the study region with the grid of two sub-areas, forming zones of southern Taiwan Strait (S) and northern Taiwan Strait (N).

enters into the Taiwan Strait from the ECS during winter and from the SCS during summer (Guan, 1985; Wang and Chern, 1992; Fu and Hu, 1995; Jan et al., 1998; Chai et al., 2001). As a consequence, the northern Taiwan Strait and the southern Taiwan Strait exhibit different physical and biogeochemical structures (Huang et al., 1997). During summer monsoon, nutrient-poor warm SCS water covers the whole region. However, alongshore northward winds during summer induce coastal upwelling in the western side of the strait off mainland China. In the vicinity of Taiwan Bank, year-round upwelling exists due to the local topography. The combination of the coastal and Taiwan Bank upwelling systems produces a broader area with cold and nutrient-rich waters in the southern region than in the northern region (FJIO, 1988; Hong et al., 1991; Huang, 1991). Hence, in northern Taiwan Strait, phytoplankton blooms generally occur during inter-monsoon (spring and autumn) when there are high-nutrient waters from the ECS, and temperature and solar radiation are favorable for phytoplankton growth. In the southern Taiwan Strait, Chl reaches its peak only in summer due to broader upwelling coverage (Chen et al., 1996; Zhang et al., 1997). Recently, Tang et al. (2002) investigated the upwelling events in the Taiwan Strait with AVHRR SST and SeaWiFS Chl data, and reported the size and intensity of those upwelling activities. Detailed responses of surface Chl to the upwelling events, especially at daily time scales, have not been documented for the Taiwan Strait. This paper investigates the Chl evolution in response to upwelling events in the Taiwan Strait. Using daily SeaWiFS Chl, AVHRR SST and in situ measurements, we focus our study in the western region of the Taiwan Strait, excluding the Taiwan Bank region. The results show short-term variability of Chl and SST induced by the upwelling pulses in the Taiwan Strait during August 1998.

2. Data and methods

AVHRR imageries of SST were obtained from the Second Institute of Oceanography, State Ocean Administration of China. The MCSST algorithm was chosen to derive SST products from L1 data. SeaWiFS L1 data, and ancillary ozone and meteorological data, were acquired from NASA Goddard Space Flight Center. SeaDAS 4.0 was used to generate L3 imagery from L1 data. A multi-scattering with the 765/865 Gordon–Wang model was used for atmospheric correction, and the OC4 algorithm was used for retrieving Chl. Mercator projection was chosen for mapping. We did our calculations on time-series Chl and SST in a grid of two sub-areas. The study region was defined generally by the geographical mid-line of the Taiwan Strait, and was further divided into two zones separating the northern zone (N) from the southern zone (S) (Fig. 1).

To evaluate the temporal change of Chl, we followed the algorithm of Kahru and Mitnchell (2000), calculating the areal extent of eutrophic waters. Pixels with Chl greater than 1.0 mg/m^3 were classified as eutrophic water. The spatial mean of SST was removed from each AVHRR image to produce the images of SST anomaly fields. As a measure of the spatial distribution of upwelling water, the areas with values ranging from -1–-4 °C were highlighted.

For each of the AVHRR images, we calculated the mean SST in area bounded between 22.00°N 116.26°E and 21.50°N 120.00°E, as representative of non-upwelling water. For this study of the western Taiwan Strait (Zone S plus N, Fig. 1), we calculated the areal extent of waters colder than the non-upwelling water by, respectively, 1 °C and 2 °C, as a proxy for the area influenced by upwelling. For Zone S and Zone N only the extent of waters colder than the non-upwelling water by 2 °C was calculated.

In their study on the upwelling offshore Vietnam, Kuo et al. (2000) defined an upwelling intensity R to characterize the coastal upwelling using AVHRR and ERS-2 remote sensing data. We adopted their algorithm as

$$R = \Sigma \Delta T_i \mathrm{d}_i A_i, \tag{1}$$

where A_i is the area of the upwelling region, ΔT_i is the decreased SST relative to the mean SST of neighboring non-upwelling water, and d_i refers to the upwelling depth. Pond and Pickard (1983) estimated d_i by

$$D = \frac{4.3V_i}{\sqrt{\sin|\varphi_i|}}, \quad (2)$$

where V_i is the wind speed and φ_i is the latitude of the upwelling zones. Here we simplified the estimation by considering two upwelling zones, Zone S and Zone N. Wind speed and latitude at DongShan and PingTan Islands (Fig. 1) were used for Zone S and Zone N, respectively. $\Delta T_i A_i$ was calculated pixel by pixel on the waters colder than non-upwelling water by 2 °C in the two zones as described above.

In situ measured Chl and temperature data were collected during the 1998 summer cruise (August 11–15) to study biogeochemical processes of bioactive elements in the Taiwan Strait (Fig. 1). During the cruise, surface temperature and salinity were continuously measured by a thermosalinograph SeaBird SBE21. A SeaBird SBE19 conductivity-temperature-depth (CTD) instrument and a WETLab Chla fluorometer were used to measure temperature, salinity and Chlorophyll a profiles. The fluorometer was not calibrated with in situ samples, so the results are given as normalized readout.

3. Results

3.1. Chl enhancement related to coastal upwelling: in situ observations

In situ observations provide supplementary information to the remote sensing data, such as the vertical distribution of chlorophyll. In situ Chl fluorescence profiles observed during August 11–15, 1998 (Fig. 2B–D) represent the southern, middle and northern regions of the Taiwan Strait, respectively. In the middle and northern regions, Chl values were higher in the west than in the east, decreasing offshore. In contrast, Chl distribution in the south appeared relatively homogeneous. Similar spatial distributions of Chl during summers of 1983, 1987, and 1994 were reported by Zhang et al. (1997). In the northern Taiwan Strait during summer, Chl greater than 1 mg/m^3 occurred only in the coastal water, while offshore waters were low in Chl (Zhang et al., 1997). However, mean Chl values could be as high as 2 mg/m^3 throughout the entire southern Taiwan Strait, including nearshore and offshore regions. During summer 1998, the Chl fluorescence in the southern region (Fig. 2B) was similar in magnitude in both nearshore and offshore stations, whereas values of nearshore stations were higher than the offshore stations in the northern and middle regions (Fig. 2C and D). In the south, upwelling along the coast combined with upwelling in the vicinity of the Taiwan Bank provided nutrients for both nearshore and offshore areas, resulting in a broad area of high-Chl water (FJIO, 1988; Hong et al., 1991; Chen et al., 1996; Huang et al., 1997; Yan et al., 1997; Zhang et al., 1997; Hu, 2002). Relatively flat and broad bathymetry in the southern region also may be favorable for the broad distribution of high-Chl waters.

To illustrate the coastal upwelling during the summer of 1998, we show the (SST) and sea-surface salinity (SSS) along the mainland coast sampled by the continuous flow system on August 11 and 15 (Fig. 3). On the T11-T13 transect (Fig. 2), SST exceeded 27 °C over a distance of 25 km and then dropped sharply to 23.5 °C in the vicinity of DongShan Island (see Fig. 1 for the location). Low SST persisted for about 60 km. SSS was relatively constant between 34 and 34.5 over the entire transect. On the T04-T16 transect (Fig. 2), SST was low for the first 100 km (26–26.5 °C), falling then to 24.5 °C near PangTan Island. SSS ranged from 34 to 34.25. South of the PingTan Island, SST increased rapidly to 27.5 °C and maintained about that value, while SSS gradually decreased to 33.5. Relatively low SST and high SSS on both transects indicated coastal upwelling signatures clearly during summer, and the locations of lowest SST, i.e. near PingTan and DongShan Islands, were consistent with well-defined upwelling centers (Hu, 2002). It was also obvious that the decrease of SST on the T11-T13 transect on August 11 was greater than that on the T04-T16 transect on August 15. The former was about 4 °C and the latter was less than 3 °C.

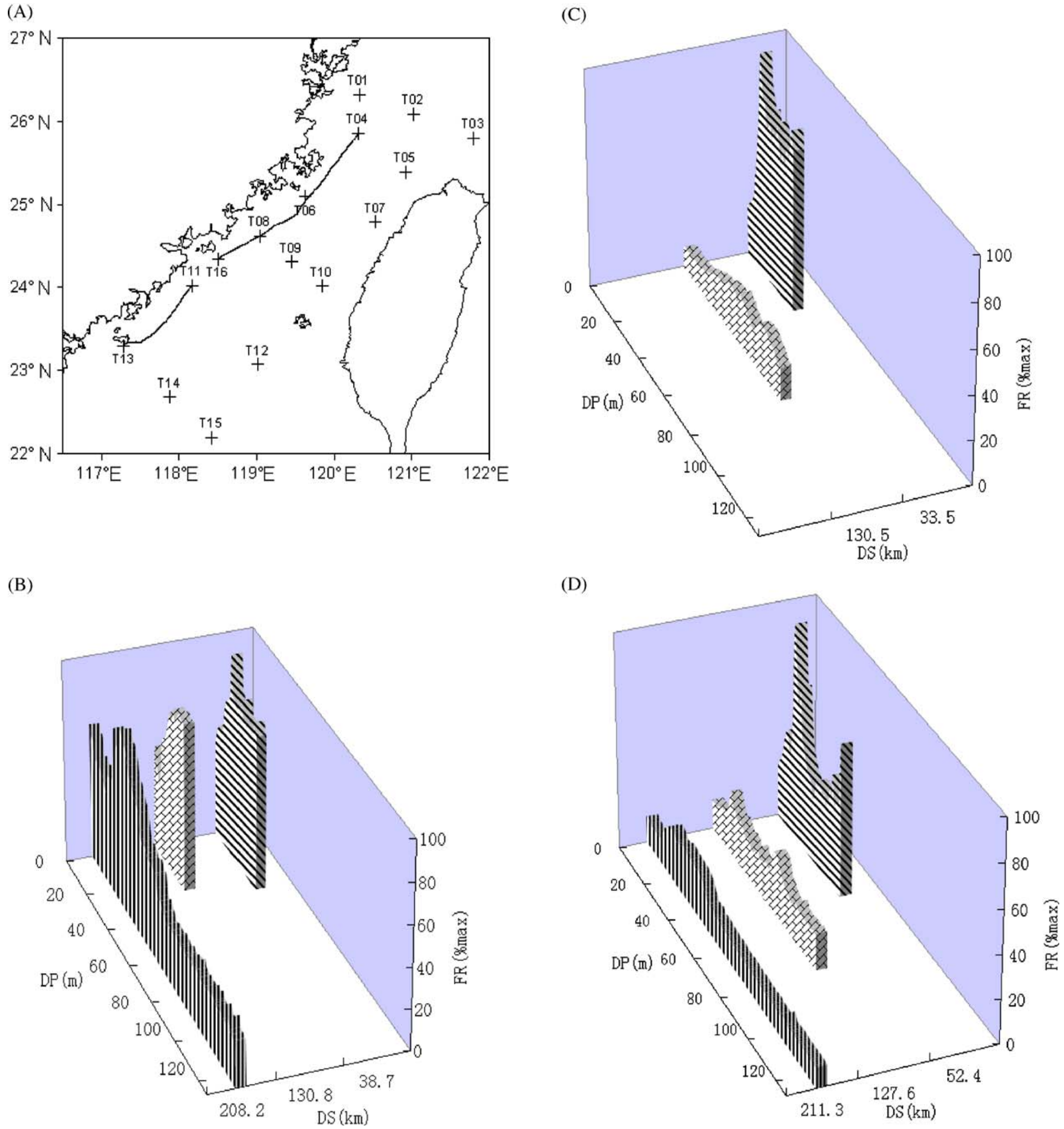

Fig. 2. Map of the Taiwan Strait showing in situ sampling stations and two Mainland China coastal transects along which the continuous flow system went (A) Depth profiles of flouorescence reading at transect T13 to T15 (B) T06 to T07 (C) and T01 to T03 (D) Fluorescence (FR) was normalized to the maximum observed withing each transect. DP: water depth (m); DS: distance offshore mainland (km).

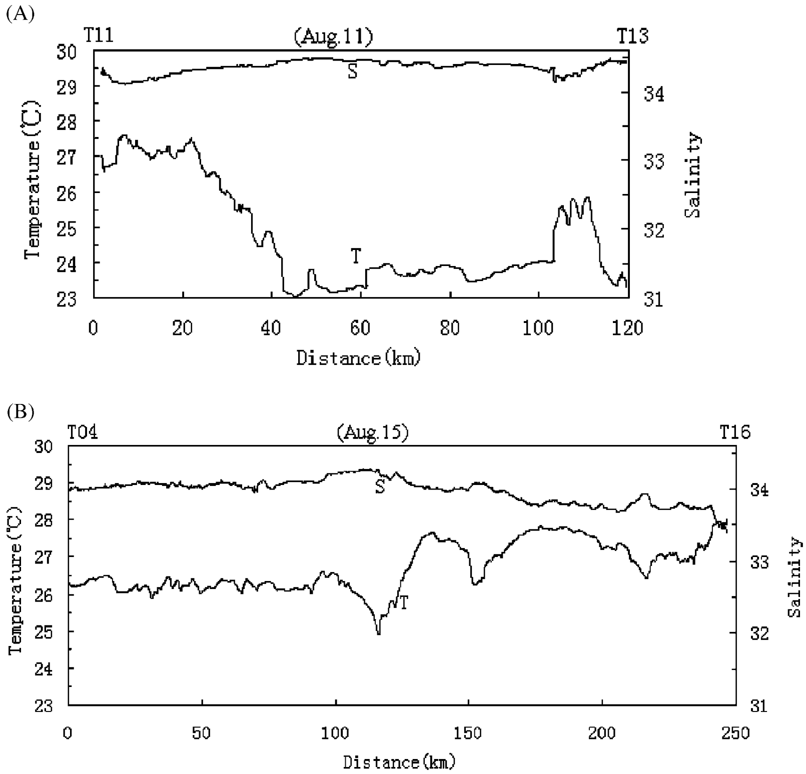

Fig. 3. Surface temperature and salinity along coastal transects shown in Fig. 2A. (A) transect T11 to T13; (B) transect T04 to T16.

3.2. Temporal changes of chlorophyll and SST: satellite observations

SeaWiFS Chl and AVHRR SST images captured the upwelling events in the Taiwan Strait in August 1998, showing a consistent spatial distribution of high surface Chl and low surface temperature in the western Taiwan Strait (Figs. 4 and 5). The relative temporal patterns of Chl should be useful as a time-series, although there could be artifacts in the Chl data, especially in the waters just close to the shore and near the area of Taiwan Bank. Waters very nearshore might be influenced by both non-pigment particles and bottom reflection. The Taiwan Bank water is most likely affected by bottom reflection (C. McClain and C. Hu, personal communication), considering that the beam attenuation coefficient is lower than 0.8/m in this region (Zhang et al., 2001). Nevertheless, temporal patterns of Chl should be useful as a time series, especially as we focus our study on the western region of the Taiwan Strait, excluding the Taiwan Bank region, to investigate the responses of Chl and SST to upwelling events.

3.2.1. Chlorophyll

The area coverage of high Chl and low SST is a good indicator of upwelling activities, which changed notably in the western Taiwan Strait over a period of 25 days (Fig. 4). The variability is shown by the areal extent of eutrophic waters ($>1.0\,mg/m^3$) for the study regions (Fig. 6A), which was higher in mid-August than the previous or subsequent days, peaked on August 13. In late August, the extent of eutrophic water decreased considerably. From August 13–15, eutrophic waters increased only by about 15%. From August 18–23, a 40% decrease in the areal extent of eutrophic waters was detected and decreased continuously to a minimum on August 26. However, on the next

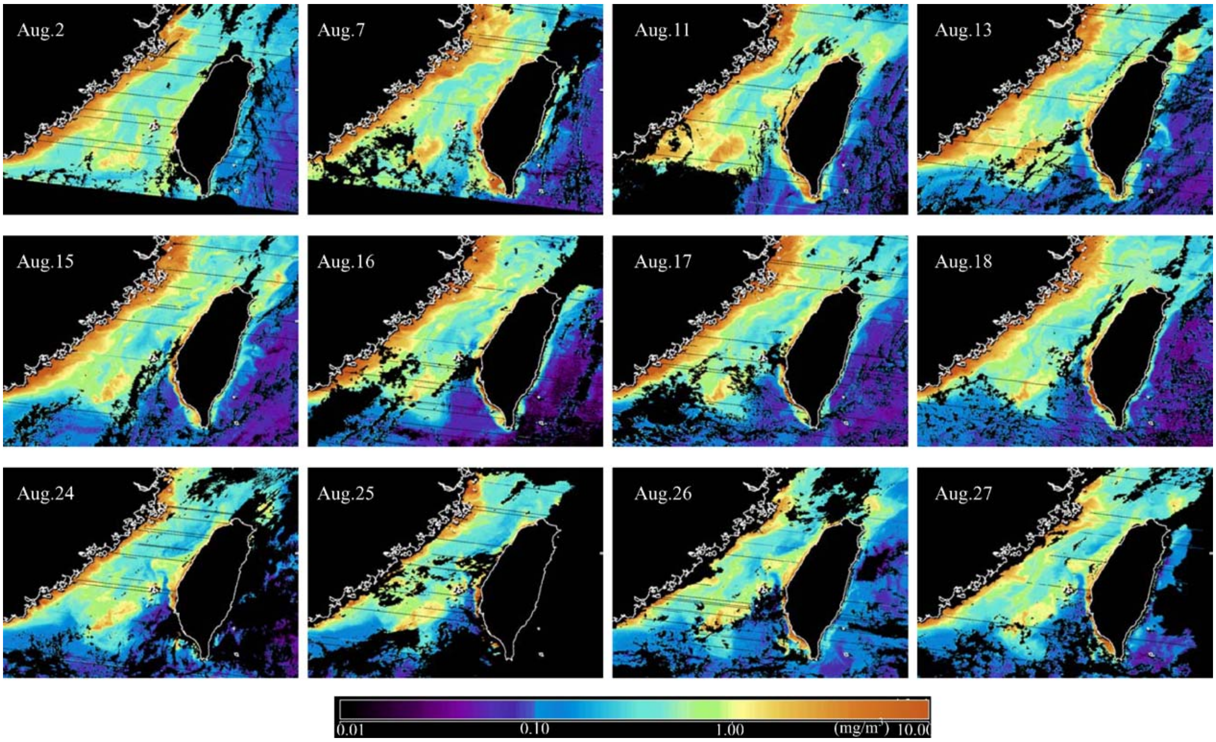

Fig. 4. Sea WiFS Chl daily images of the Taiwan Strait region in August 1998.

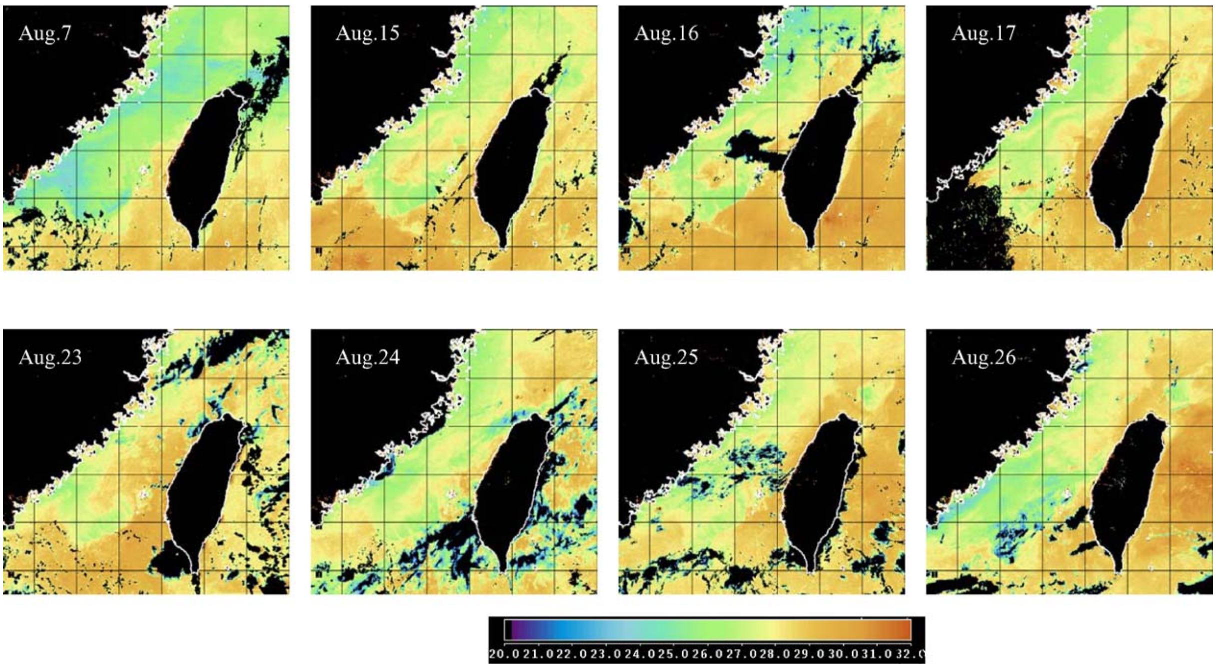

Fig. 5. AVHRR SST daily images of the Taiwan Strait region in August 1998.

day there was a sudden increase of more than 100%. Although we missed as much as 5 days between each two records due to cloud cover, the coverage of eutrophic waters apparently remained broad in extent throughout early and mid-August, but dropped substantially later in the month.

However, there was a north–south difference in the pattern (Fig. 6B). The maximum areal extent of eutrophic water in Zone S on August 13, and was the main factor in the maximum extent of the zone combined. In Zone N maxima occurred on August 7 and 16. For Zone S, from August 11–15, the extent of eutrophic waters varied rapidly, increased first and then dropped 30% within 5 days. For Zone N, eutrophic waters increased in extent during this period, but decreased nearly by 50% in later August. The maximum in Zone S was higher than that of Zone N. The temporal pattern of the whole region was largely determined by the pattern of Zone S.

3.2.2. SST

The SST spatial pattern experienced rapid changes during August 1998 (Fig. 7) with area of SST colder than 27 °C being highly variable (Fig. 5). Water 1–4 °C colder than the mean of the entire region covered nearly the whole Taiwan Strait except in the southeastern part on August 7. That area decreased both in the southern and the northern zones on August 15. The decreasing

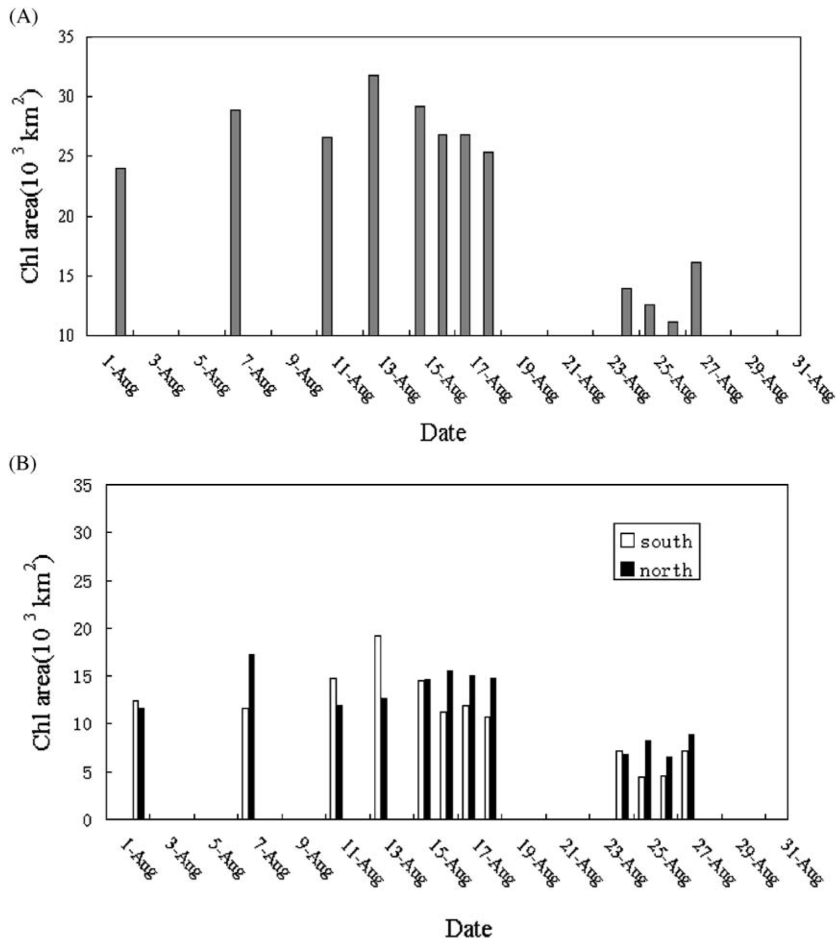

Fig. 6. Time series of the areal extent of eutrophic waters in August 1998 (A) in the western Taiwan Strait; (B) in the southern (Zone S) and northern Taiwan Strait (Zone N) separately.

trend persisted for the southern zone at least until August 17. The northern zone cold water coverage did not change significantly between August 15 and 17. On August 23, a small area of cold water was found in the southern zone, which disappeared by August 25. However, it reappeared one day later. For the northern zone, cold water was not seen between August 23 and 26.

The areal extent of upwelled (defined as colder than the area-averaged mean SST) was maximum on August 7 and minimum on August 25 in the western Taiwan Strait (Fig. 8A). The area with SST anomaly $>2\,^{\circ}\mathrm{C}$ appeared to be a better indicator of upwelling than the area with SST anomaly $>1\,^{\circ}\mathrm{C}$. The greatest change in area with SST anomaly $>2\,^{\circ}\mathrm{C}$ was about 3-fold, but only 1-fold for the area with SST anomaly $>1\,^{\circ}\mathrm{C}$. For Zone S, the maximum areal extent of water $>2\,^{\circ}\mathrm{C}$ colder than non-upwelling waters appeared on August 7, and then decreased 30% by August 15 (Fig. 8B). On August 17, it decreased to less than half of the maximum extent. For Zone N, the extent on August 15 was as high as that on August 7, and then decreased gradually. On August 17, it decreased only by 20% of the maximum extent. In late August, both north and south zones exhibited low extents of colder than non-upwelled waters, and both zones had a recovery on August 26. The recovery for Zone S was much larger compared to that for Zone N.

3.3. Short-term variability of upwelling intensity

The temporal pattern in upwelling intensity index R (Fig. 9) was generally similar to that of the extent of colder than non-upwelled waters (Fig. 8). For Zone S, R decreased 45% from August 7 to 15; while for Zone N, R remained nearly the same. From mid-August (15–17) to August 23–27, R decreased by more than 70% for Zone N and about 30% for Zone S. In addition, the R value appear much greater for Zone N than for Zone S, especially during early and mid-August. Because the strength of southwesterly winds at PingTan Islands was several times stronger than that at DongShan Islands, the upwelling depth derived from wind speed would be deeper in Zone N than in Zone S. Using only wind data collected at these two coastal islands,

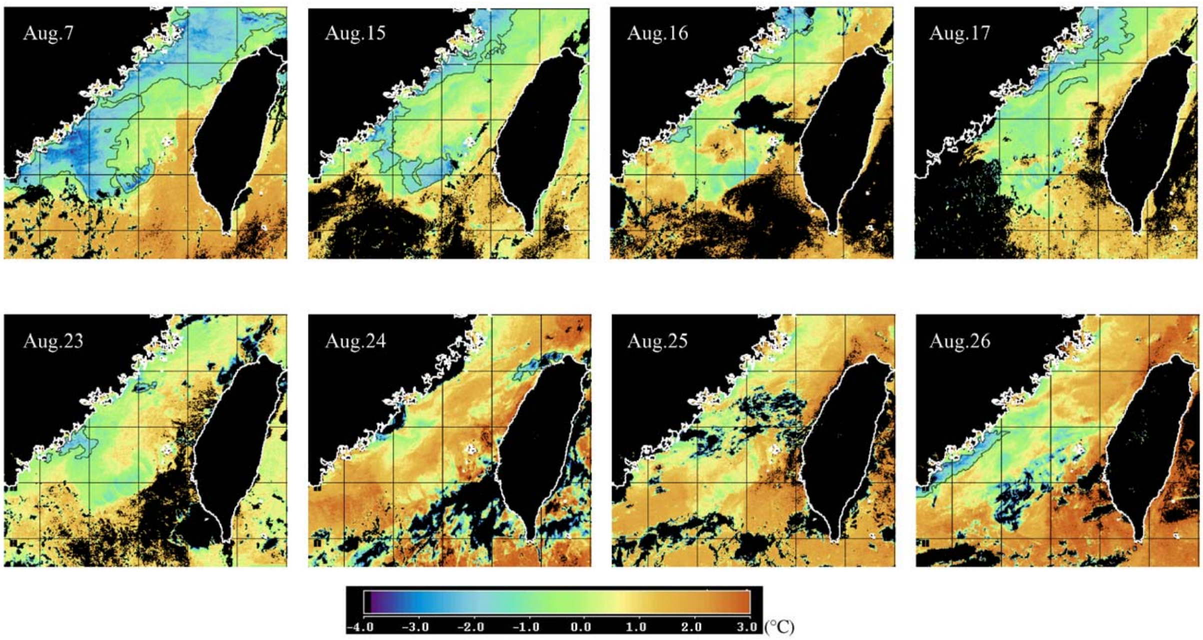

Fig. 7. AVHRR SST daily images with spatial mean removed in August 1998. The areas bounded by black lines highlighted the waters colder than spatial mean by 1–4 °C.

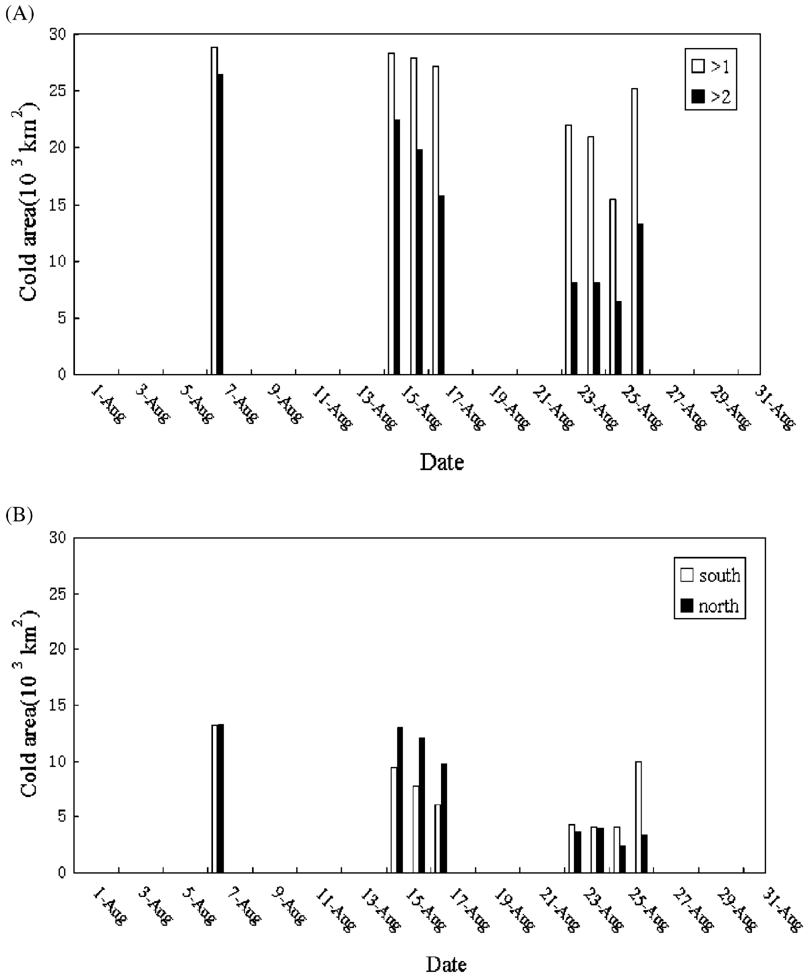

Fig. 8. Time series of the areal extent of colder than non-upwelling waters in August 1998 (A) in the western Taiwan Strait; (B) in the southern (Zone S) and northern Taiwan Strait (Zone N) separately.

the *R* values might not be good indicators for comparing the upwelling activities between the entire northern and southern Taiwan Strait, where wind speed might vary drastically.

4. Discussion

4.1. Coupling of Chl variability with SST

Comparing the areal extent of eutrophic waters (Fig. 6) with the extent of colder upwelling waters (Fig. 8), a tight relationship was found between surface Chl and SST in the Taiwan Strait. Several earlier and recent works with coastal zone color scanner (CZCS), ocean color and temperature scanner (OCTS) and SeaWiFS imagery demonstrated similar relationship as well, but for different regions (Abbott and Zion, 1985; Saino et al., 1998; Kahru and Mitnchell, 2000; Thomas et al., 2001). High Chl waters are always associated with the cold surface waters, which are consistent with the upwelling manifestation that provides cold deep nutrient-rich waters to the surface, and results in phytoplankton biomass enhancement. To illustrate this point further, we combined surface areal extent of eutrophic waters (high in Chl) and areal extent of upwelling waters (low in

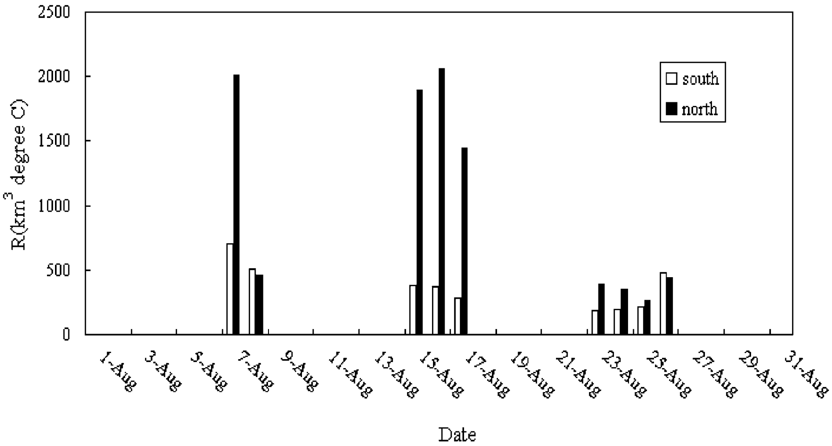

Fig. 9. Time series of the upwelling intensity index in the southern (Zone S) and northern Taiwan strait (Zone N) in August 1998.

SST, hereafter indicated as T) (Fig. 10). Two groups are easily distinguished: one has high Chl and high T values, and the other is low Chl and low T, Fig. 10A and B. The high Chl and high T groups were associated with upwelling waters during early and mid-August, and low Chl and low T groups with non-upwelling waters during later August. In the southwest Taiwan Strait (Fig. 10C), the relationship was not as tight as in other regions (Fig. 10A, b). It was mainly due to August 26, when local upwelling had reemerged in the southwest Taiwan Strait again (high T value), but surface phytoplankton biomass had not had time to accumulate yet (low Chl value). Such delayed phytoplankton response to pulse upwelling nutrient supplies was also reported in other upwelling systems (Takahashi et al., 1986; Kudela et al., 1997).

4.2. Temporal change of upwelling events

The coastal upwelling along the Mainland China coast in the Taiwan Strait is forced by southwesterly winds. The wind at PingTan Island (Fig. 11A) was southwesterly most of the time from July 15 to August 19, except it changed direction for about three days between August 2 and 5. The strength of the southwesterly wind from August 6 to 19 was reduced compared to that from July 15 to August 1. After August 19, southwesterly wind occurred only between August 23 and 27, and it was weak. On the other hand, the wind at DongShan Island was much weaker throughout July and August, and the direction was generally southerly as it was less organized than at the PingTan Island.

From the evolution of upwelling favorable wind at the PingTan Island, we link the upwelling intensity with variability of local SST and surface Chl in the northwest Taiwan Strait. For example, on August 7, the upwelling intensity (Fig. 9), Chl (Fig. 4), and SST (Fig. 5) were high. Between August 11 and 18, surface Chl concentration was enhanced (Fig. 4) and the areal extent of eutrophic waters increased (Fig. 6). Comparing to mid and late July wind, the wind in the mid August (15–17) was slightly weaker, which resulted decreased the upwelling intensity index *R* (Fig. 9). From August 23 to 25, upwelling weakened significantly (Fig. 9).

Based upon wind observations at the PingTan Island and the upwelling intensity calculation, there were three coastal upwelling events in the northern Taiwan Strait during August 1998 (Table 1). A strong upwelling event occurred in early August, followed by a less strong one during mid-August, and a weak one in late August. The duration of upwelling events in the Taiwan Strait was between 7 and 12 days. This does not agree well with the results of Hu and Chen (1991) from statistical analysis based on the data derived from a numerical model, although their study targeted solely in the southern Taiwan Strait. Hu and Chen

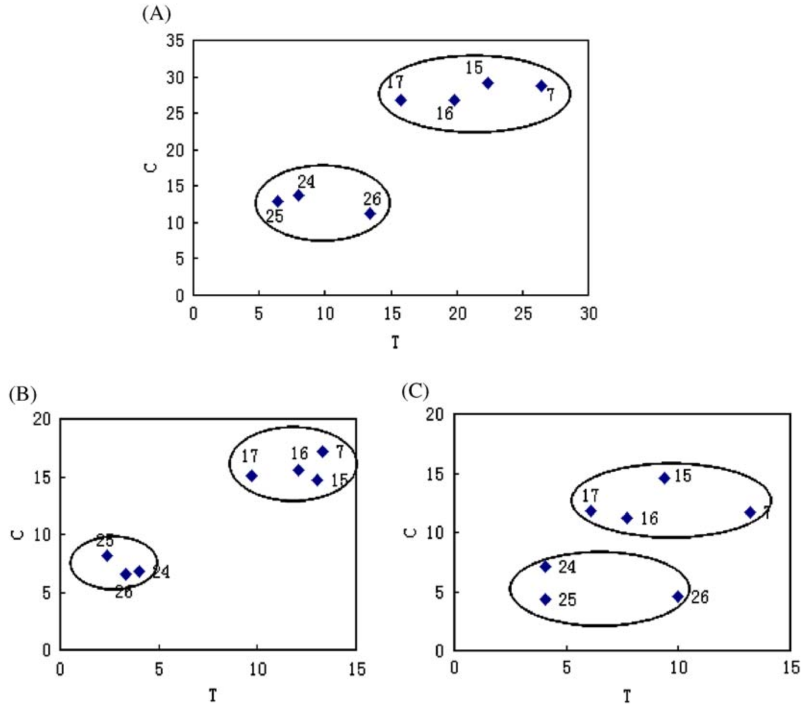

Fig. 10. Diagrams of the extent of eutrophic waters versus the extent of colder than non-upwelling waters. Chl is a simplified expression of the extent of eutrophic waters (10^3 km^2), T was a simplified expression of the extent of colder than non-upwelling waters (10^3 km^2). Numbers indicated the dates in August 1998. (A) the western Taiwan Strait; (B) the northern (Zone N) Taiwan Strait; (C) the southern Taiwan Strait (Zone S).

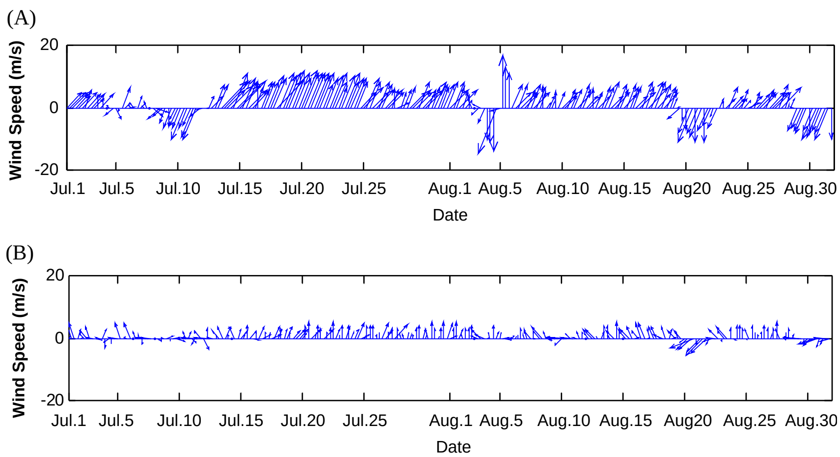

Fig. 11. Stick diagram of wind velocity from July–August 1998 at weather stations on PingTan Island (A) and DongShan Island (B). Winds were observed four times each day: PingTan Island at 2:00, 8:00, 14:00 and 20:00, and DongShan Island at 8:00, 11:00, 14:00 and 17:00.

Table 1
Coastal upwelling events in the northern Taiwan Strait during August 1998

Starting	Ending	Intensity
Aug. 1	Aug. 7	Strong
Aug. 9–11	Aug. 18–22	Less strong
Aug. 18–22	Aug. 31	Weak

(1991) documented that in the southern Taiwan Strait, coastal upwelling only lasted for about 15 days during summer monsoon. However, our analysis shows that upwelling events occurred for at least 14 days in August 1998 (August 1–7 and August 11–18) in the northern region. Considering that coastal upwelling had been observed early in June (Huang, 1991; Zhang et al., 1997), and likely also in July as suggested by the wind data (Fig. 11), we conclude that episodic upwelling events in the Taiwan Strait occur throughout entire summer during southwest monsoon.

4.3. *Difference of upwelling systems between the northwest and southwest Taiwan Strait*

Temporal changes of the upwelling events in the southern Taiwan Strait (Zone S) are different comparing to the upwelling events in the northern (Zone N). In Zone N, there were two peaks in the areal extent of eutrophic waters, first on August 7 and second on August 16 (Fig. 6B), but for Zone S, there was only one peak on August 13. The upwelling in Zone S strengthened after August 7, and thus produced the surface Chl peak on August 13. The lowest in situ SST (23.5 °C) along the southern coast was observed on August 11, which was 1 °C lower than the lowest SST observed along the northern coast on August 15 (Fig. 3), suggesting a rather strong upwelling occurred in Zone S on August 11. It seems there were only two upwelling events occurred in Zone S, compared to three in Zone N. A strong upwelling event lasted from early August through mid-August, and a weak one during the late August. Spatial variations in surface wind stress over the strait determine the difference in upwelling patterns between the northern and the southern regions. The wind intensity and direction observed at two islands (Fig. 11), PingTan (Zone N) and DongShan (Zone S), showed such difference clearly. A more detailed wind field for the entire Taiwan Strait would provide a better picture on how upwelling events may response to surface wind field.

We think that upwelling along the Mainland China coast is also influenced by water masses transported into the Taiwan Strait from the ECS and the SCS (Chai et al., 2001). For example, the AVHRR SST images (Fig. 5) show that cold waters in the northern strait and the southern strait were blocked by relatively warm waters, and the cold water in the northwest strait was connected to the cold water from the ECS. Huang et al. (1997) had reported the different phytoplankton communities for the northern and southern Taiwan Strait. The phytoplankton community in the northern Taiwan Strait was similar to the one from the ECS, and the southern Taiwan Strait exhibited the same features as in the SCS water. Therefore, the hydrodynamics and associated upwelling events in the Taiwan Strait might play a significant role in water exchange between the SCS and the ECS, which has been pointed out by other studies as well (Liu et al., 2000; Chung et al., 2001).

5. Summary

SeaWiFS Chl, AVHRR SST time series, and in situ measurements during August 1998 were used to evaluate short-term variability of Chl associated with upwelling events in the western Taiwan Strait. Surface Chl varied significantly within a short period of time; for example, Chl increased by 30% and then decreased by 30% within five days. Large areal extent of eutrophic waters was always accompanied by large areal extent of colder upwelling waters, indicative of the tight coupling of Chl with upwelling activities. Phytoplankton growth lagged upwelling activities by about two days.

The temporal change of upwelling activities was found quite different between the northwest and southwest Taiwan Strait. Though upwelling strength in both regions was weak during the late

August, a short relaxation of upwelling probably occurred between early and mid-August in the northern portion, but not in the south. In the southern portion, one strong upwelling event lasted from early to mid-August, peaking on August 13. The duration of upwelling events in the western Taiwan Strait in August was more than two weeks. In addition to local wind effects, the northwest coast upwelling system is also influenced by the inflow of water from the East Chin Sea (ECS), whereas the southwest region is affected by the South China Sea (SCS). The Taiwan Strait plays an important role in water exchange between the ECS and the SCS. Large variation of areal extent of eutrophic waters indicates rapid response of phytoplankton to upwelling events. Such strong phytoplankton blooms would increase organic material export from the upper water column, but could not be measured efficiently by traditional ship surveys. There may not be a simple answer on how coastal upwelling systems contribute to ocean carbon budget, especially considering the significance of short-term variability of various coastal upwelling systems.

By combining the remote sensing data with in situ underway mapping data, for the first time we observed the temporal and spatial synoptic features of coastal upwelling events and associated chlorophyll response in the Taiwan Strait. However, one should keep in mind that the wind data used here were observed at two coastal islands (PingTan and DongShan), and time series satellite data were actually not continuous throughout August 1998. Understanding short-term variability and evolution of physical and biological processes requires a combination of multiple sources of information, such as in situ mooring observations, ship surveys with underway mapping systems, satellite observations, as well as numerical modeling.

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