Seasonal variability of chlorophyll $a$ fronts in the Luzon Strait based on satellite observations

Chunhua Qiu,1,2 Dongxiao Wang,1,* Zhigang He,1 and Chuqun Chen1

1State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanography, Chinese Academy of Sciences, No.164 West Xingang Road, Guangzhou, China 510301
2Center for Atmospheric and Oceanic Studies, Graduate School of Science, Tohoku University, Japan
*Corresponding author: dxwang@scsio.ac.cn

Fronts are important sources of variability in the South China Sea basin, and they play significant roles in controlling bio-physical interactions in the Luzon Strait. We evaluated seasonality of chlorophyll $a$ (chl-$a$) fronts in the Luzon Strait (LS) based on satellite observations from September 1997 to October 2007. Monthly-mean chl-$a$ concentration at the front was highest in winter (0.8 mg m$^{-3}$) and lowest in summer (0.3 mg m$^{-3}$). Additionally, both the probability of frontal occurrence and the seasonal cycle of the gradient between offshore and nearshore chl-$a$ showed that the chl-$a$ front in the LS was the strongest in winter and weakest in summer. Pseudo wind stress played the most important role in shaping the spatial distribution of chl-$a$ concentration, indicating that wind-driven upwelling is the mechanism involved.

Keywords: thermal front, edge-detection, monthly-mean image, wind-driven upwelling

Introduction

The Luzon Strait (LS) is more than 320-km wide, and located between the islands of Taiwan and Luzon (Figure 1). It connects the South China Sea (SCS) with the Philippine Sea to the east. Oceanic fronts are known to be associated with enhanced biological activity; they can also modulate mixing processes and the accompanying flux of energy and water mass (Blanton, 1986). Thermal fronts in the northern South China Sea (NSCS) have been studied based on satellite and in situ observations. For example, six persistent thermal fronts were identified in the NSCS. However, the thermal front near the Luzon Strait did not have a strong sea surface manifestation (Wang et al., 2001).

Some researchers detect surface features based on satellite-derived chlorophyll-$a$ (chl-$a$). Legeckis et al. (2002) used 8-day composites of ocean color (chlorophyll) from SeaWiFS to delineate the position of oceanic fronts. Takahashi and Kawamura (2005) detected the Kuroshio Current front in summer based on chl-$a$ images. The present study evaluates the chl-$a$ front in the LS.

There are two methods to detect fronts: gradient magnitude (GM) and edge-detection method. We assume chl-$a$ as $C(x,y)$. The gradient of $C$ is defined as $|C| = \sqrt{\left(\frac{dC}{dx}\right)^2 + \left(\frac{dC}{dy}\right)^2}$. Researchers usually give a threshold $|C|_{\text{min}}$ of $|C|$. Only when the $|C| \geq |C|_{\text{min}}$, can the pixel can be regarded as a front. This method can detect the front’s strength; however, it loses some signal due to eddies, especially in summer, when the front is weak. Therefore, we used the edge-detection method. It has been commonly used in finer scale front detection (Shimada et al., 2005; Chang et al., 2006) since Cayula and Cornillon (1992, 1995).
Chl-α concentration tracks the occurrence of phytoplankton blooms. Upwelling was identified as an important mechanism for winter phytoplankton blooms in the southwestern LS from 1979–1985 (Tang et al., 1999). Wind-driven upwelling can deliver nutrients to the ocean surface, contributing to phytoplankton growth (Shen et al., 2006). Warm eddies shed from the Kuroshio front are suggested to influence the phytoplankton production (Tang et al., 1999; Yuan et al., 2006). In addition, Chen et al. (2007) discussed effects of cold eddies on phytoplankton production, and pointed out that phytoplankton influenced the biochemical cycle in the LS in late spring, a relatively unproductive season in the SCS. These previous studies indicate that chl-α fronts may be related to the ocean currents. The present study investigates chl-α fronts in more recent data from 1997–2007.

The goals of our present study are (1) to detect the seasonality of chl-α front in LS and (2) to understand the mechanism of chl-α front seasonal variation.

**Methods**

**Remote sensing tools**

Monthly averaged Sea Surface Temperature (SST) data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Pathfinder 5.0 SST Project. This reprocessing uses an improved version of the Pathfinder algorithm and processing steps to produce twice-daily global SST and related parameters as far back as 1985, at a resolution of approximately 4 km (Kilpatrick et al., 2001). The key improvements over the original 9-km Pathfinder SST data set include a more accurate, consistent land mask, higher spatial resolution, and inclusion of sea ice information. In our study, monthly data were used. The Advanced Very High Resolution Radiometer (AVHRR) SST has a regional bias of −0.4K in the NSCS (Qiu et al., 2009). However, the bias has no influence on gradients associated with thermal fronts.

Monthly-mean chl-α concentration at resolution of 9 km were obtained from SeaWiFS (Sea-viewing Wide Field-of-view Sensor) from September 1997 to October 2007. It is a part of NASA’s earth science enterprise. SeaWiFS was launched onboard the Orbview-2 satellite in August 1997. The chl-α data were calculated by the OC4 algorithm (O’Reilly et al., 2000). Suspended sediments in coastal areas bias chl-α concentration so water depths shallower than 50 m were omitted.

The microwave scatterometer SeaWinds launched on the QuikBird satellite (QuikSCAT) in June 1999 is essentially a radar device that transmits radar pulses down to the Earth’s surface and then measures the power that is scattered back to the instrument. Wind speed and direction over the ocean surface are retrieved from measurements of the backscattered power (Wentz et al., 2001). Monthly $0.25^\circ \times m0.25^\circ$ pseudo wind stress was obtained from the Remote Sensing System (RSS). Pseudo wind stress is derived from these data.

Merged Sea Level Anomaly (SLA) data were used to calculate eddy kinetic energy (EKE). The data came from two satellite missions, TOPEX/Poseidon and ERS, followed by Jason-1 and Envisat. This merged dataset provides uniform sampling in time (AVISO, 2006). The gridded altimetry dataset includes one map every 7 days with a $(1/3)^\circ$ spatial resolution on a Mercator grid (Le Traon et al., 1999; Ducet et al., 2000). For more detailed information about the calculation, readers are referred to He et al. (2002).
Hydrographic data were provided by the SC-SIO. The R/V Shiyan 3 has conducted the open experimental cruises routinely, in which SST are mainly measured by Conductivity Temperature Depth (CTD). The CTD measurements in LS in September 2006 are used in this study for comparison to the satellite data (Figure 1).

Data analysis

Chl-a and thermal fronts were detected by the edge-detection algorithm developed by Cayula and Cornillon (1995). This algorithm utilizes a combination of window-level and pixel-level tests to detect fronts in SST or chl-a images. The basic principle of the window-level test is that pixel values will be bimodal, with the front located at the threshold pixel value dividing the two populations. A $10 \times 10$ pixel window was used for SST images and a $5 \times 5$ pixel window for chl-a images during the first step, with the threshold value determined by maximizing values. Regarding all possible thresholds, the fraction of the variance within the window is explained by the segmentation into two populations. Windows in which this fraction was greater than 0.65 and in which the mean values of the two populations were separated by at least 0.001 were identified as fronts. Isolated frontal pixels were connected to form frontal segments using a contour-following procedure. The output of each edge-detection image is a list of contours. Further details of the edge-detection and contour-flowing methodology are within Cayula and Cornillon (1992, 1995). A total of 132 monthly chl-a and thermal images were used in this study.

Results

Using the edge-detection method, the climatic probability of chl-a and SST fronts, which is the ratio of frontal times to all the times (132 months) for a stable pixel, were derived. There was a high front occurrence in the LS (Figure 2). The probability of chl-a fronts (Figure 2a) was higher than that of the collocated thermal fronts (Figure 2b). Two pathways of water entrance into SCS could be seen much clearer from the structure of the chl-a front than that from SST front. Chl-a was highest (>0.4 mg m$^{-3}$) in the winter and lowest (<0.3 mg m$^{-3}$) in the summer (Figure 3). Note that in Figure 3A, there is a high chl-a core at around (120°E, 20°N). Chl-a front probability was similar to that of the chl-a concentration (Figure 4). The area where front probability >0.4 includes nearly the whole NSCS in winter. In summer, the highest front probability was in the coastal area.

To better understand the vertical structure of front, we used in situ temperature profile data along 120°E in September, 2006 (Figure 5). The 29°C isotherm outcropped at 20.3°N, which is consistent with the contour of chl-a front probability (0.3) in autumn (Figure 4). The upper mixed layer was up to 50 m deep. Note that the chl-a front in autumn (Figure 4d) was a band from 19° to 20.3°N, but the thermal front only occurred at 20.3°N. It indicates that the chl-a front is much clearer than the SST front in this region, which confirms blooms occur above the thermal stratification (Tang et al., 1999) in LS.

To study the seasonal cycle of chl-a front strength, a cross-front difference was calculated. Suitable locations of sections used for these calculations were identified after some comparison over the seasonal front probability composite and seasonal maps. Finally, Locations A (19°N, 121°E) and B (19°N, 122.5°E) were selected (Figures 1 and 6). The magnitude of front strength was large from autumn to spring and very weak in summer.
In order to understand the possible dynamics of seasonal variability of chl-\(a\) fronts in the LS, we also calculate the EKE difference (Figure 6) and wind stress difference (Figure 7a). The cross-front wind stress difference is large from October to March and small from May to August. From autumn to early spring, the strong northeastern wind stress domains the LS, while from late spring to summer, the
Discussion

This study shows that the chl-$a$ front is strong during autumn to spring and weak in summer. (Figure 4). The chl-$a$ front in winter is located within a high chl-$a$ area (Figure 3), while the high chl-$a$ within the sill bridge may come from river discharge or benthic regeneration (Tang et al., 1999). The high chl-$a$ area extends or contracts with season.

The possible mechanisms of chl-$a$ peaks (phytoplankton blooms) are (1) surface Ekman forcing (advection) (2) Ekman upwelling and (3) diffusion from eddies, jets or entrainment from the bottom of mixed-layer depth. When the southeast wind prevails in winter to spring (Figure 7), Ekman pumping brings up high-nutrient deepwater to sea surface within the shallow sill bridge. Also, Ekman transport extends peaks in chl-$a$ from the sill bridge northward. (Figure 3). Chl-$a$ variation results from the balance between the Ekman transport and sill bridge effect. In winter, the Ekman transport is strong enough to cross over the sill bridge, leading to high chl-$a$ in the SCS. In autumn and spring, the sill bridge hinders the Ekman transport.

A potential mechanism for the chl-$a$ front is illustrated in Figure 8. The Cagayan River discharges rich nutrients in the sill bridge area (Tang et al., 1999) and the upwelling lifts these nutrients into the surface layer. When the northeast wind stress is strong enough to drive Ekman transport over the sill bridge, phytoplankton/nutrients are advected. The Kuroshio Current branches may also affect the chl-$a$ pattern, as suggested by Yuan et al (2006). These advection mechanisms are not in conflict with the upwelling mechanism supported by Tang et al. (1999), since our focus area is different. Their mechanism explains the off-shore blooms southwest of Chl-$a$ levels are also tracers of the Kuroshio Current. Tang et al. (1999) firstly suggested that warm core eddies from the Kuroshio may be related to phytoplankton blooms. Through long-term investigation, the path of the Kuroshio Current and the anticyclonic eddy have been tracked by the low ocean color of this feature (Yuan et al., 2006). The primary production in a cold-core eddy is 2–3 times that outside the cold eddy (Chen, et al., 2007). Sun and Liu (2011) detected two cold cores around LS: one located at $[117^\circ E, 17.5^\circ N]$; the other located at $[118.5$–$120.5^\circ E, 18.75$–$20.75^\circ N]$. The former eddy is triggered by wind stress curl and associated with the high chl-$a$ core in southwest of LS (Tang et al., 1999). The latter one is triggered by Kuroshio, and its position is consistent with the high chl-$a$ core from long-term mean images (Figure 3a) northwest of LS. It suggests that the chl-$a$ front at that location may be related to the Kuroshio Current.

Besides the wind stress and the Kuroshio Current, the effect of land might also be very important for the chl-$a$ distribution. In spring and autumn, the high levels of chl-$a$ are located within the sill area (Figure 3). Chl-$a$ variation results from the balance between the Ekman transport and sill bridge effect. In winter, the Ekman transport is strong enough to cross over the sill bridge, leading to high chl-$a$ in the SCS. In autumn and spring, the sill bridge hinders the Ekman transport.

Figure 6. Seasonal cycles of chl-$a$ and EKE differences between sites A ($19^\circ N, 121^\circ E$) and B ($19^\circ N, 122.5^\circ E$).
LS associated with the southward eddy as mentioned by Sun and Liu (2011), while our mechanism explains the extension of the chl-α front from Cagayan River, where it is close to the Kuroshio. The offshore upwelling area revealed by them is far from the Kuroshio axis, while the chl-α extension proposed here is close to it. Therefore, we suggested that wind stress together with Kuroshio/sill bridge, play important roles in the chl-α extension.

Figure 7. Long-term climatological, monthly-mean pseudo wind stress in the LS: (a) climatological mean of monthly pseudo wind stress magnitude, and (b) monthly pseudo wind stress vectors.

Figure 8. Schematic of chl-α frontal formation. Wind stress (black arrow), Kuroshio Current (white thick dotted line) with two branches (white dotted line 1 and 2), sill bridge (triangle) and the mean chl-α map (shaded).
Conclusions

We studied the seasonal variability of chl-α fronts in the LS based on satellite data. Chl-α fronts are the strongest in winter and weakest in summer. The seasonal cycle of the contrast between nearshore and offshore chl-α showed that the chl-α difference was strongest in winter and weakest in summer. Monthly-mean chl-α concentrations were also highest in winter and lowest in summer. Through the year, pseudo wind stress played the most important role in shaping the pattern of chl-α concentration. The sill bridge and the Kuroshio Current also played important roles in the chl-α fronts.

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