Enhanced primary production in the oligotrophic South China Sea by eddy injection in spring

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[1] In May 2003, a phytoplankton bloom of chlorophyll-a (Chl-a) concentration of 0.3–0.4 mgm^{-3} was observed at the centre of northern South China Sea (SCS) by NASA's Sea-viewing Wide Field-of-View sensor. As this region is remote and known to be oligotrophic in spring (Chl-a concentration typically at ~0.05–0.08 mgm^{-3}), it is intriguing to explore this unusual happening. Based on six different remote sensing data and numerical modelling, the results suggest that the injection of an ocean eddy is the most likely cause of the bloom. Due to long-range transport of a large (700 × 500 km) anti-cyclonic ocean eddy, coastal nutrients and plankton could be brought across hundreds of kilometres to the centre of northern SCS and impact the biogeochemistry. The open ocean part of the northern SCS basin has long been considered generally free from coastal influences. This work provides new evidence that proves otherwise. Moreover, from the perspective of physical oceanography, it is interesting to observe that, outside the monsoon seasons, there can be well-defined anti-cyclonic ocean circulation existing in the SCS without the prevailing monsoonal wind. **Citation:** Lin, I-I, C.-C. Lien, C.-R. Wu, G. T. F. Wong, C.-W. Huang, and T.-L. Chiang (2010), Enhanced primary production in the oligotrophic South China Sea by eddy injection in spring, *Geophys. Res. Lett.*, *37*, L16602, doi:10.1029/2010GL043872.

1. Introduction

[2] Northern South China Sea (SCS) is an oligotrophic tropical ocean, especially towards its centre part [*Liu et al.*, 2002; *Tseng et al.*, 2005; *Chen et al.*, 2007; *Wong et al.*, 2007]. In the centre part of northern SCS, nutrients are depleted because the area is located far away from land and river input (Figure 1a) and cannot be reached by coastal upwelling [*Liu et al.*, 2002; *Xie et al.*, 2003; *Tang et al.*, 2004; *Wong et al.*, 2007]. Except during wintertime, when nutrients can be supplied through convective overturn [*Tseng et al.*, 2005; *Wong et al.*, 2007], and occasionally through passing of cold eddies (*Chen et al.*, 2007) or typhoons [*Lin et al.*, 2003], chlorophyll-a (Chl-a) concentration is predominantly low, only around 0.05–0.08 mgm^{-3}.

[3] In May 2003, a phytoplankton bloom of Chl-a concentration at 0.3–0.4 mgm^{-3} was observed around the centre (17°N, 115°E) of northern SCS (Figure 1b) by NASA's Sea-viewing Wide Field-of-View (SeaWiFS) ocean colour sensor. This bloom (see arrow (Figure 1b)) occurred in a region far away from land. It was also not the season for the passing of typhoons. Exploring this unusual event, especially because there are few prior reports on bloom occurrence during May in this region is thus intriguing.

[4] In this study, a synergy of six types of remote sensing data is used together with numerical modelling to diagnose the nature of the observed bloom. Multiple remote sensing data used were (a) Chl-a concentration data from NASA's SeaWiFS sensor; (b) SeaWiFS ocean colour spectra; (c) sea surface temperature (SST) from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager; (d) ocean surface wind vectors from the NASA/QuikSCAT sensor; (e) sea surface height anomaly (SSHA) data from the TOPEX/Poseidon and JASON-1 altimeters; and (f) fine- and coarse-mode aerosol optical depth (AOD) data from the NASA Terra/MODIS (Moderate Resolution Imaging Spectroradiometer) atmosphere sensor. The SCS model (domain: 99–124°E, 2–27°N) used in this study is based on the Princeton Ocean Model with realistic topography and forcing [*Wu and Chiang*, 2007]. The horizontal grid size is 1/16° and there are 26 sigma levels in vertical. A larger-scale East Asian Marginal Seas model [*Wu and Hsin*, 2005] is used to serve the open boundary condition of the SCS model. Further details can be found in the point 1 of Text S1 of the auxiliary material.[1]

2. Observations of Chl-a, SST, and AOD Conditions

[5] The observed bloom patch (see arrow in Figure 1b) appeared connected with a fine stream of bloom of Chl-a ~0.1–0.3 mgm^{-3} all the way from the coast of Vietnam. This stream started from around 11°N, 112°E northward to 17°N, 109.5°E, turned northeastward to 17.7°N, 110.7°E, and then extended southeastward towards 17°N, 115°E to the bloom location around the centre of northern SCS. This suggests that nutrients of the observed bloom patch may be supplied via long-range transport from the coast of Vietnam. Therefore, it is necessary to identify the physical mechanism responsible for such transport, especially because there are few prior reports on the existence of basin-scale circulation in the SCS during spring season.

[6] Other possibilities should also be considered aside from the possibility mentioned above, including deeper-

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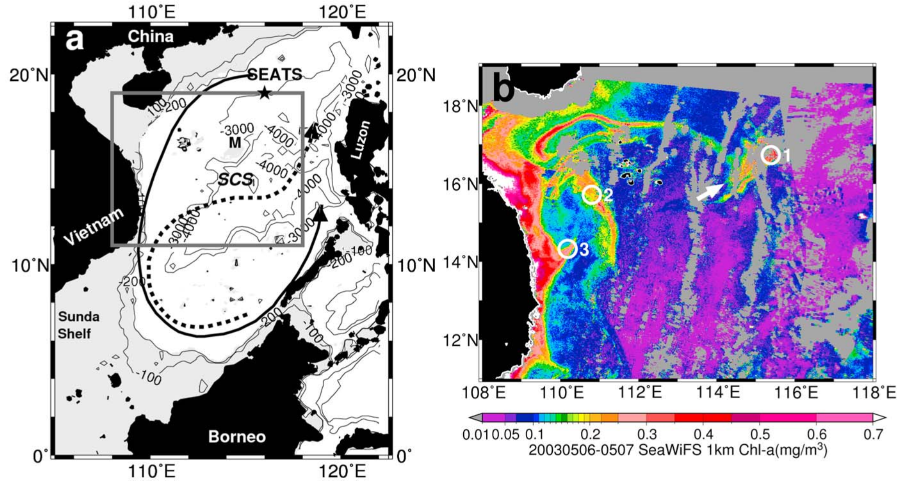

Figure 1. (a) Bathymetry map of the SCS. The solid line indicates the basin-wide cyclonic circulation in winter as driven by the prevailing northeast monsoon. The dashed line indicates the anti-cyclonic circulation over the southern half of SCS in summer as driven by the southwest monsoon [after *Liu et al.*, 2002]. The study area is shown in the box. The location of the SEATS station in northern SCS is depicted by the star. The location of the Macclesfield Bank is depicted by M. (b) SeaWiFS Chl-a image of the study area on 6–7 May 2003 showing the bloom patch (see arrow) observed in the centre of northern SCS. Numbered circles denote the locations where spectra in Figure 4 were acquired.

ocean nutrient supply via wind mixing or upwelling [*Lin et al.*, 2003]. Nutrients may also be supplied via atmospheric aerosol deposition [*Jickells et al.*, 2005; *Lin et al.*, 2007, 2009]. To diagnose these various possibilities, corresponding SST and AOD conditions were examined. Altimetry SSHA, surface geostrophic current field, ocean surface wind, ocean colour spectra, and numerical modelling are discussed in the next section.

[7] With regard to the SST situation, the study area (see grey box in Figure 1a) was characterised by uniformly warm SST of 29–30°C (see Figures A_a and A_b of Text S1) before and during the bloom period, showing little sign of the presence of cold SST associated with deeper-ocean nutrient supply [*Liu et al.*, 2002; *Lin et al.*, 2003; *Xie et al.*, 2003; *Tang et al.*, 2004] at the bloom area. Examining the possibility that the observed bloom could be stimulated by atmospheric aerosols, MODIS fine- and coarse-mode AOD data were processed. As depicted in Figures A_c–A_f of Text S1, both fine and coarse mode AOD were low, typically ≤0.1, suggesting little sign of terrestrial aerosol input to

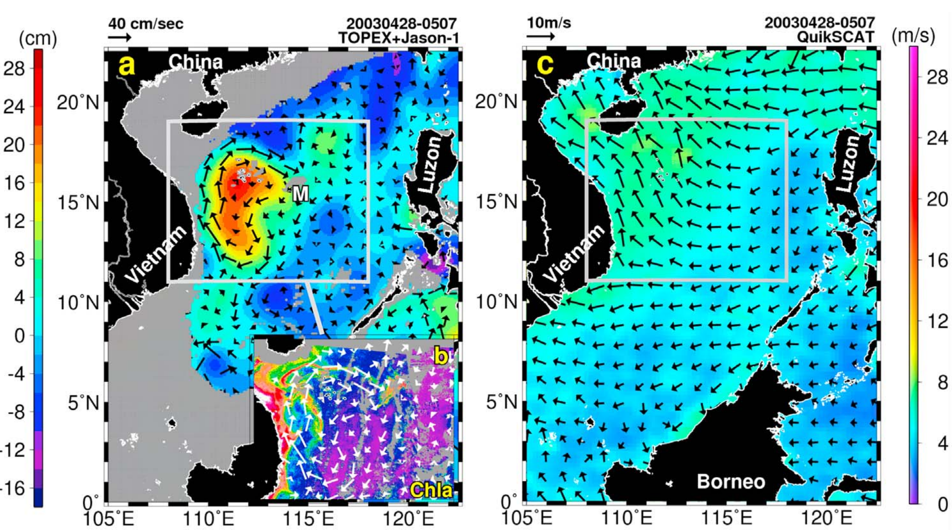

Figure 2. (a) SSHA map (coloured shaded, unit: cm) of the SCS from one 10-day cycle (28 April to 7 May 2003) observations of TOPEX/Poseidon and JASON-1 altimeters during the bloom period. As the current altimetry algorithm is less accurate in the shallow waters, SSHA measurements in regions of bathymetry <200 m are not used (shown in grey). The study area is depicted in the box. Geostrophic currents estimated from the SSHA observation are illustrated by vectors. (b) Chl-a image of the study area as in Figure 1b, but with the geostrophic current vectors overlaid. (c) Corresponding ocean surface wind vector observations of the SCS from the NASA/QuikSCAT scatterometer.

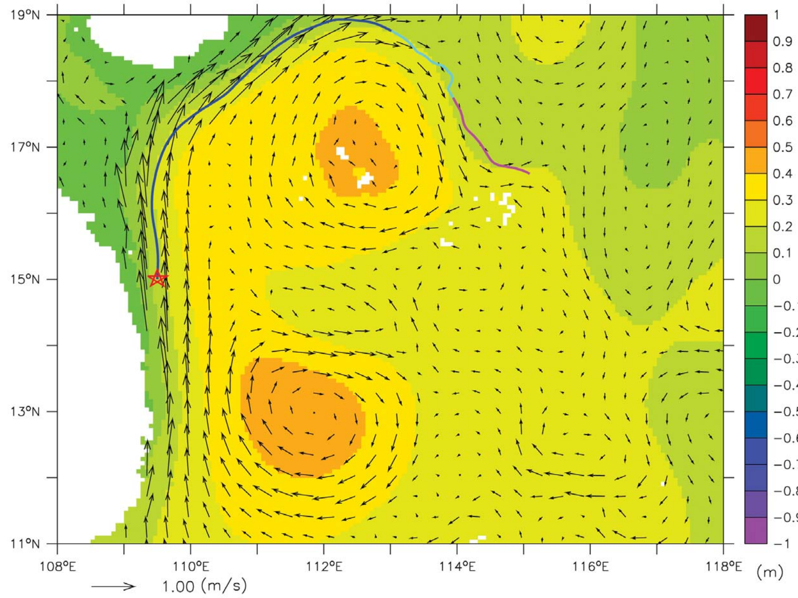

Figure 3. Result from the tracer experiment using the SCS model [*Wu and Chiang*, 2007]. The background vectors are velocity fields and the colour shading is sea surface height averaged over 17 April to 8 May 2003. The tracer (denoted by a red star) was released on 17 April 2003 off the Vietnam coast at around 15°N, 109.5°E. The coloured transects indicate the period of travelling (dark blue transect: 17–24 April 2003; light blue transect: 24 April to 1 May 2003; purple transect: 1–8 May 2003).

stimulate the bloom [*Kaufman et al.*, 2002; *Lin et al.*, 2007, 2009]. Detail discussion can be found in the point 2 of Text S1.

3. Observations of Altimetry SSHA, Ocean Surface Wind, Ocean Colour Spectra, and Numerical Modelling

[8] In the altimetry SSHA observation, a well-defined eddy with the size ~700 × 500 km was found in the study area (boxed region in Figure 2a; location can also be seen in the box in Figure 1a). This large warm eddy was characterised by positive SSHA of 8–30 cm, located from the south at 11°N, 112°E northward to 18°N, 111°E and from the west at 12–17°N, 109.5°E eastward to 15.5°N, 114.5°E (Figure 2a). Observing the geostrophic current field derived from SSHA data, the anti-cyclonic circulation of the eddy could be clearly seen (Figure 2a). Flow speed also increased especially at the western and northern boundaries of the eddy where the SSHA gradients were sharp. The flow slowed down as it approached the shallow Macclesfield Bank (~100 m in bathymetry, denoted as M in Figure 2a).

[9] By over-plotting geostrophic current vectors on the SeaWiFS Chl-a observations, the fine stream of Chl-a bloom is found to follow closely with the geostrophic current field (Figure 2b). Starting off the eastern coast of Vietnam, the fine stream of bloom followed the strong northward current along the western flank of the anti-cyclonic eddy. With the eastward turning of the geostrophic current at the north of the feature, the fine stream of Chl-a bloom followed accordingly (Figure 2b). This fine stream extended south-eastward, and as the flow speed decreased significantly at around 16.5°N, 115°E (i.e., near the Macclesfield Bank), the fine stream stopped and accumulated at the bloom patch identified in Section 1 (Figures 2a and 2b). Consistent with finding bloom accumulation is the convergence in the flow field at the bloom location around 15.5–17°N, 114.5–117°E, wherein the flow is converged by the meeting of weak flows from the west and from the east (Figure 2a). Weak flow from the west was caused by the anti-cyclonic circulation of the large eddy discussed above while weak flow from the east was from another smaller anti-cyclonic eddy-like feature (SSHA ~4–14 cm) at approximately 17–19°N, 114.5–117.5°E (Figure 2a).

[10] The examination of SSHA and of geostrophic current fields points to the possibility that, via the anti-cyclonic circulation of the large eddy, coastal nutrients and phytoplankton could be transported to the centre of northern SCS and contribute to the observed bloom patch. As the SSHA-derived geostrophic current field represented only part of the actual current, a tracer experiment was conducted using the SCS model [*Wu and Chiang*, 2007]. A tracer (see red star in Figure 3) was released on 17 April 2003 off the east coast of Vietnam at around 15°N, 109.5°E. Consistent with the observations in Figures 2a and 2b, the tracer travelled fast (~1–1.2 ms^{-1}) along the large eddy northward and then turned southeast at a slower speed (~0.3–0.4 ms^{-1}) to reach the centre of the SCS near Macclesfield Bank around 5–8 May 2003 (see colour transects in Figure 3). Based on the tracer experiment, it takes approximately two and a half weeks (17 April–5 May) to travel about 900 km from the eastern coast of Vietnam at around 15°N, 109.5°E along the warm eddy to the centre of the SCS.

[11] From the tracer numerical experiment, the lifetime of the warm eddy has to be at least longer than two and a half weeks. Tracing the altimetry observations back to March 2003, the warm eddy could be identified since the end of March 2003, i.e., for more than 40 days (see Figures B_c–B_f of Text S1), therefore giving support to the possibility

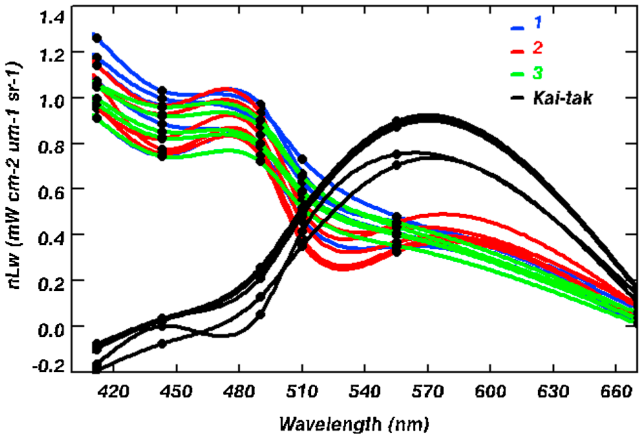

Figure 4. Ocean colour spectra in normalised water leaving radiance (nLw) from the bloom at the centre of northern SCS (blue spectra, location see circle 1 in Figure 1b), from the bloom along the anti-cyclonic eddy (red spectra, location see circle 2 in Figure 1b), and from the Vietnam coast (green spectra, location see circle 3 in Figure 1b). For comparison, spectra from the bloom induced by typhoon Kai-Tak in 2000 [*Lin et al.*, 2003] are also depicted (black spectra).

of nutrient transport from the Vietnam coast to the centre of the SCS via the large eddy.

[12] To further substantiate this possibility, SeaWiFS ocean colour spectra (in normalised water leaving radiance) at various locations from the coast to the centre of northern SCS were examined. Spectra taken from the bloom patch in the centre of northern SCS (blue spectra in Figure 4, location annotated as circle 1 in Figure 1b) were characterised by a trough at 443 nm band and a peak at 490 nm band. Compared with spectra taken from the Vietnam coast (green spectra in Figure 4, location annotated as circle 3 in Figure 1b), very similar spectra, with the same trough and peak locations, were found. For spectra taken from the fine bloom stream along the large eddy, spectra characteristics were again very similar (red spectra in Figure 4, location annotated as circle 2 in Figure 1b). Consistency in the spectra taken from the Vietnam coast, from the bloom stream along the large warm eddy, and from the bloom patch in the centre of northern SCS suggests their similar origin. This further supports the possibility of long-range transport of nutrients and phytoplankton from the coast of Vietnam to the centre of northern SCS via the injection of the large anti-cyclonic eddy. For comparison, spectra from a bloom induced by a typhoon (typhoon Kai-Tak in 2000 [*Lin et al.*, 2003]) at a similar location are presented (black spectra in Figure 4). The typhoon-induced bloom was characterised by a single peak at 560 nm, very different from the bloom associated with coastal injection discussed in this work.

4. Discussion

[13] From the above results, it is interesting to discuss further issues related to basin-scale circulations in the SCS. In exploring the basin-scale circulation of the SCS, the focus of most existing studies has been on winter and summer conditions, exploring little about the conditions in spring and autumn [*Shaw et al.*, 1996; *Liu and Xie*, 1999; *Liu et al.*, 2002; *Xie et al.*, 2003; *Tang et al.*, 2004]. As reported by *Shaw et al.* [1996] and *Liu et al.* [2002], in winter, most of the SCS is dominated by basin-wide cyclonic circulation (Figure 1a) due to the strong prevailing northeast monsoon. In summer, due to the prevailing southwest monsoon, the southern half of the SCS is dominated by anti-cyclonic circulation (Figure 1a) [*Liu and Xie*, 1999; *Liu et al.*, 2002; *Xie et al.*, 2003; *Tang et al.*, 2004]. In this work, it was found that it is possible for well-defined circulation to occur in the SCS not only during monsoon-prevailing seasons like winter and summer, but also during an inter-monsoon season like spring.

[14] Tracing back the origin of this large eddy, it was first identified in the satellite SSHA observation at the end of March 2003 (see Figures B_c–B f of Text S1). During this inter-monsoon period between April and May, the ocean surface wind was weak and variable (Figure 2c and Figures C_c–C_f of Text S1) because the northeast monsoon was retreating while the southwest monsoon was yet to set up. As depicted in Figure C of Text S1, the wind field during this period was first characterised by north-easterly wind in March and then turned easterly and south-easterly with low wind speed of only around 3–6 ms^{-1}. Thus, the situation and the underlying mechanism should be very different from the summer condition since this anti-cyclonic circulation occurred in the absence of the prevailing monsoonal wind.

[15] It was also unlikely that this eddy originated from westward-propagating eddies of the Luzon strait [*Wu and Chiang*, 2007] because no sign of its westward propagation was found and it has a much bigger size (~700 × 500 km.v.s ~200 km × 200 km size of the regular westward-propagating eddies in the SCS). Moreover, it stayed almost stationary off the northeast coast of Vietnam since late March (Figure 2a and Figures B_c–B_f of Text S1). It appears that it was generated locally by the interplay between currents and winds but the exact generation mechanism is yet to be identified and would be an interesting future research issue for physical oceanographers.

5. Conclusion

[16] Using six types of remote sensing data and numerical modelling, this work investigated the phytoplankton bloom event that occurred in the centre of northern SCS in May 2003. Through long-range transport of a large anti-cyclonic eddy, coastal nutrients and plankton could be brought across hundreds of kilometres from Vietnam to the northern centre of SCS and impact the biogeochemistry. Due to its remote location, it has not been known that coastal processes can influence the biogeochemistry of the open ocean part of the northern SCS basin in spring [*Tseng et al.*, 2005; *Wong et al.*, 2007]. This work provides new evidence to demonstrate this possibility. It also adds to growing research reporting the possibility of coastal influence on open ocean biogeochemistry via long-range lateral transport (e.g., *Lam and Bishop*'s [2008] report on the Pacific Ocean).

[17] Finally, from the perspective of physical oceanography, it is interesting to find in this work that, even in the absence of prevailing monsoonal wind, it is possible for strong eddy circulation to occur in northern SCS during an inter-monsoon season like spring. This was not known before because current understanding on basin-scale circulation of the SCS has been focused on monsoon-prevailing seasons

like summer and winter, and monsoon has been identified to be the main mechanism driving such circulations [*Shaw et al.*, 1996; *Liu et al.*, 2002; *Xie et al.*, 2003; *Tang et al.*, 2004].

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