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Changes of temperature and bio-optical properties in the South China Sea in response to Typhoon Lingling, 2001

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[1] A large patch of enhanced chlorophyll a concentration (Chla), lower sea surface temperature (SST), and lower sea surface height (SSH) was revealed in the central South China Sea (SCS) in November 2001 after the passage of typhoon Lingling. Maximum SST reduction of 11°C occurred one day after Lingling's passage on 11/11. Subsequently, against a background level of 0.08 mg/m^3, average Chla within the area of 12.60–16.49°N, 112.17–117.05°E increased to 0.14 mg/m^3 on 11/12 and then to 0.37 mg/m^3 on 11/14. Dissolved organic matter and detritus were differentiated from Chla using a recent bio-optical algorithm. They contributed 64% to the increase of total absorption immediately after Lingling, while most of the changes later (74%) were due to phytoplankton. The area under Lingling's impact covered ca. 3° latitude and 4° longitude, which is much greater than the two summer cases previously observed in the northern SCS. This event lasted for ca.15 days, and resulted in carbon fixation in the order of 0.4 Mt. Such a drastic response was attributed to the coupling of typhoon-induced nutrient pumping with the pre-established cyclonic gyre in the central SCS driven by the prevailing northeast monsoon. **Citation:** Shang, S., L. Li, F. Sun, J. Wu, C. Hu, D. Chen, X. Ning, Y. Qiu, C. Zhang, and S. Shang (2008), Changes of temperature and bio-optical properties in the South China Sea in response to Typhoon Lingling, 2001, *Geophys. Res. Lett.*, *35*, L10602, doi:10.1029/2008GL033502.

1. Introduction

[2] Some tropical cyclones have shown great impacts on primary production in the broad oligotrophic ocean, and thus on carbon cycling [e.g., *Babin et al.*, 2004; *Walker et al.*, 2005]. The South China Sea (SCS) is one of the largest semi-enclosed marginal seas subject to frequent tropical cyclones (typhoon hereafter, according to convention in the study region). Two cases of typhoon-forced chlorophyll a (Chla) augmentation have been documented in the northern SCS. One was associated with typhoon Kai-Tak in July 2000, when an average of 30-fold increase in the surface Chla was found during its three-day passage [*Lin et al.*, 2003]. Another was induced by typhoon Damrey in September 2005, when a Chla peak of 4 mg/m^3 was detected [*Zheng and Tang*, 2007]. All these studies were based mainly on satellite remote sensing. However, there was also strong argument that the observed changes in the oligotrophic ocean were not due to Chla but due to vertically mixed chromophoric dissolved organic matter (CDOM) from deeper depths, which has a higher absorption coefficient than the photochemically degraded CDOM within the undisturbed pre-storm upper mixed layer [*Hoge and Lyon*, 2002]. In this study, we present observations of ocean responses in the SCS subsequent to the passage of typhoon Lingling in November 2001, which show strong surface cooling and large scale Chla enhancement in winter. In particular, we applied the most recent satellite algorithms to differentiate Chla explicitly from CDOM, thus removing the ambiguity of whether the observed change was due to phytoplankton or CDOM.

2. Data

[3] Daily TMI (the Tropical Rain Measuring Mission's microwave imager) sea surface temperatures (SSTs) were obtained from the Remote Sensing Systems Company. SeaWiFS (Sea-viewing Wide Field-of-view Sensor) L1A GAC data and L3 Chla derived from OC4 algorithm (OC4_Chla hereafter) were obtained from the NASA DAAC and GSFC. $a_{ph}(443)$ (phytoplankton absorption coefficient at 443 nm) and $a_{dg}(443)$ (CDOM and detritus absorption coefficient at 443 nm) were derived from the SeaWiFS L1A data using the quasi-analytical algorithm (QAA) [*Lee et al.*, 2002] and the SeaDAS software. Spatial resolution was 25 × 25 km^2 for SST and 9 × 9 km^2 for OC4_Chla, $a_{ph}(443)$ and $a_{dg}(443)$. Along track T/P (TOPEX/POSEIDON) gridded sea surface height and anomaly (SSHA) were obtained from NASA JPL. ARGO data collected at 12.71–12.84°N, 116.62–116.67°E were provided by the China Argo Real-time Data Center. Typical temperature and salinity profiles inside the winter gyre (see Section 4.1, 15.00°N, 112.00°E and 15.00°N, 113.00°E) were obtained from one cruise conducted in December 1998. No simultaneous in situ a_{ph} and a_{dg} data in the study region was available until December 2006, which was then used as surrogate by assuming that temporal changes are dominated by seasonal patterns rather than by interannual variations for this oligotrophic ocean that is away from terrestrial discharge. The meas-

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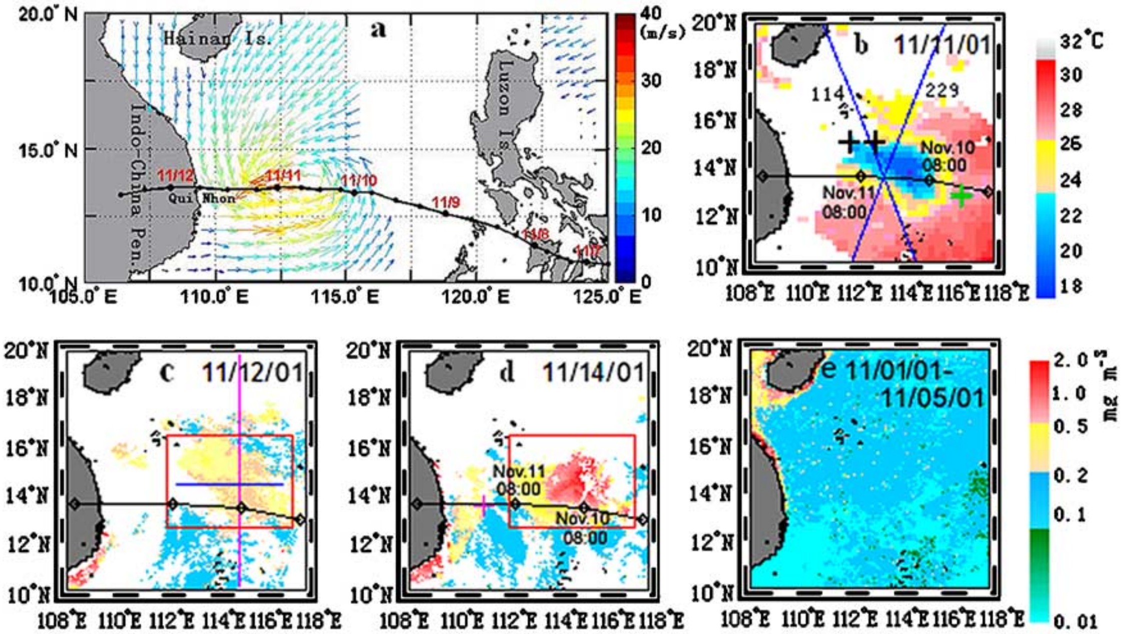

Figure 1. (a) QuikSCAT wind image on 11/11/2001 showing Lingling and the South China Sea. Lingling's 6-hour positions are shown as black dots, while the time of each annotated date is 08:00 local time. "Is." and "Pen." stand for island and peninsula, respectively. (b) TMI SST on 11/11. Black line shows the track of Lingling. (c) SeaWiFS OC4_Chla on 11/12. Blue line: 14.4°N; Purple line: 115.2°E; Red square: area for estimates of the mean Chla. (d) SeaWiFS OC4_Chla on 11/14. (e) SeaWiFS OC4_Chla of 11/1–11/5 (before Lingling).

urements of a_{ph} and a_{dg} were detailed by *Hong et al.* [2005] and *Wu et al.* [2007].

3. Results

3.1. Surface Response

[4] Typhoon Lingling originated in the Philippine Sea on 11/6/2001. It entered the SCS as a weak tropical storm on 11/9 (Figure 1a) and moved slowly at ~4.6–5.1 m/s. Then, it intensified rapidly, with wind speed increased from 65 to 100 knots, and traversed the mid-basin of the SCS as a category 4 typhoon (on the Saffir-Simpson hurricane scale) during 11/9 to 11/12. Maximum wind was 110–115 knots on 11/10 and 11/11. It made landfall near Qui Nhon (Figure 1a) on 11/12, producing heavy rainfall and high winds over the central Indo-China Peninsula (http://metocph.nmci.navy.mil).

[5] Prior to Lingling, SST was 27.0~30.0°C in the study region of 10~20°N, 110~118°E. Shortly after Lingling's passage, significant cooling occurred on 11/11 over an area of ~150,000 km^2 between 12.60–16.50°N, 112.20–117.00°E (Figure 1b), with SST dropped to 17.4~26.0°C. On average, SST dropped 5.5°C with respective maxima of 11°C. The location of the cooling was to the right of the typhoon track, consistent with previous studies [e.g., *Price*, 1981]. However, cooling of such magnitude (11°C) has not been reported previously. For example, typhoon-induced maximum cooling was 9°C in July [*Lin et al.*, 2003] and 5°C in September [*Zheng and Tang*, 2007] in the northern SCS, and 7°C in the Gulf of Mexico [*Walker et al.*, 2005].

[6] Coinciding with the cooling, SeaWiFS images showed enhancement of OC4_Chla on 11/12 and 11/14 (Figures 1c and 1d). Prior to this event, surface OC4_Chla was predominantly 0.1mg/m^3, typical for the SCS (Figure 1e). Higher OC4_Chla values were found from the coast of Vietnam to the mid-basin. The coastal areas were not included in the analysis of typhoon-induced changes because they were likely associated with coastal currents or runoff. Our study focus is therefore bounded to the area east of 112°E.

[7] The high OC4_Chla patch, with the mean value of >0.2 mg/m^3, covered ~130,000 km^2 on 11/12, and was maintained at a similar size until 11/14. Within the rectangular region (red square in Figures 1c and 1d), both $a_{ph}(443)$ and $a_{dg}(443)$ derived from the QAA increased significantly after Lingling's passage (Figure 2a). $a_{ph}(443)$ increased by 75% on 11/12, compared to initial conditions before Lingling (11/1–11/5 composite), and $a_{dg}(443)$ increased by 100%. Two days later, the increase of $a_{ph}(443)$ became four times of that of $a_{dg}(443)$ (160% versus 38%). Their combined increase was 0.025 m^{-1} during the 1st phase (before 11/12), of which 64% was contributed by CDOM and detritus. During the 2nd phase (11/12–11/14), merely 26% of the combined increase (0.046 m^{-1}) was from CDOM and detritus. Our results showed that although more than half of the immediate surface ocean color change was due to CDOM and detritus, most of the delayed changes were due to Chla. Because $a^*_{ph}(443)$ (Chla-specific phytoplankton absorption) was ~0.15 m^2/mg in the study region in winter (J. Wu and S. Shang, manuscript in preparation, 2008), these changes in $a_{ph}(443)$ were equivalent to Chla changes from 0.08 mg/m^3 to 0.14 mg/m^3, and then to 0.37 mg/m^3. Hereafter these values, instead of OC4_Chla, were used to evaluate the impact of Lingling on phytoplankton production and carbon fixation.

[8] In addition to the surface cooling and Chla enhancement, there appeared temporal lag and spatial dislocation between the two responses. It took Lingling 24 hours from

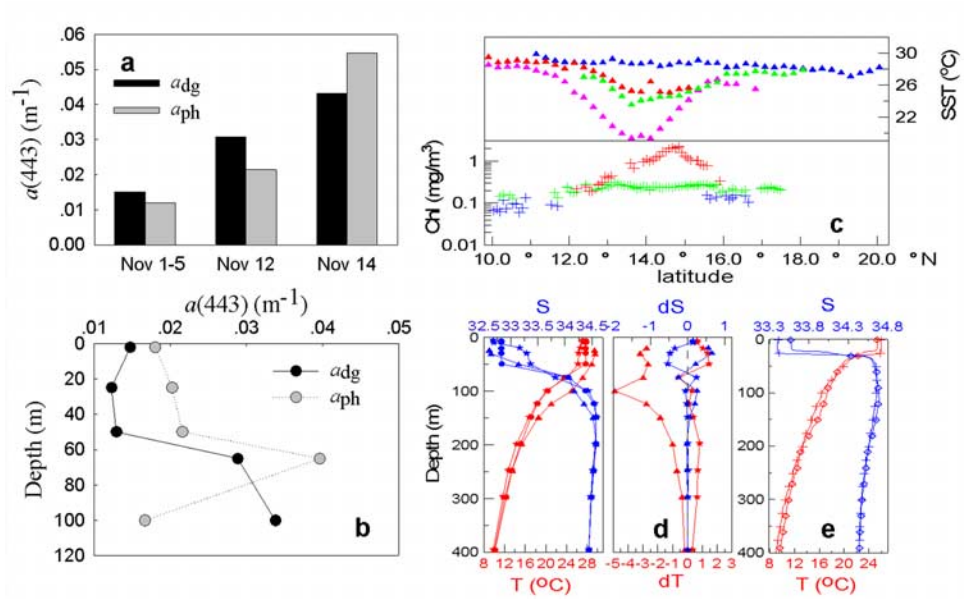

Figure 2. (a) Changes of SeaWiFS a_{ph}(443) and a_{dg}(443) after Lingling. (b) Vertical distribution of a_{ph}(443) and a_{dg}(443) in November 2006, where the sampling location is shown in Figure 1d as a purple cross-mark. (c) TMI SST and SeaWiFS OC4_Chla changes along 115.2°E in November 2001. Blue, 11/5; purple, 11/11; green, 11/12; and red, 11/14. (d) (left) vertical profiles of ARGO temperature (T, red) and salinity (S, blue) in November 2001, where the ARGO locations are shown in Figure 1b as green cross-marks. Triangle, 11/9; star, 11/16; and dot, 11/30. (right) Vertical profiles of ARGO temperature change (dT, red) and salinity change (dS, blue). Triangle, from 11/9 to 11/16; star,11/16 to 11/30. (e) Typical temperature (T, red) and salinity (S, blue) profiles in the winter gyre in December 1998, where the CTD sampling locations are shown in Figure 1b as black cross-marks. Cross, 15°N, 112°E; diamond, 15°N, 113°E.

11/9 to 11/10 to traverse the area where surface cooling was observed immediately after. Then, as Figure 2c shows, SST gradually increased between 11/11 and 11/14. OC4_Chla peaked on 11/14, lagging minimum SST by 3 days and Lingling's departure by about 4 days. This is comparable to previous observations in the northern SCS [*Zheng and Tang*, 2007] and in the Gulf of Mexico [*Walker et al.*, 2005].

3.2. Response at Depth

[9] ARGO profiles recorded at a corner of the cold patch and about 30 km apart from Lingling's track (Figure 1b) showed temperature (T) and salinity (S) contrast at depth before and after Lingling's passage (Figure 2d). Although there was no data in the upper 20 m before Lingling, the values of T and S measured at 23 m and 30 m were close to each other, suggesting that they were within the mixing layer and thus the mixed layer depth (MLD) was ~30 m. After Lingling, MLD deepened to 50 m. T at 23 m decreased by 2.88°C from 11/9 to 11/16, similar to the average change of TMI SST of 2.2°C at the ARGO locations from 11/5 to 11/11. The influence was generally confined to the upper 300 m, where ΔT of -0.36 to -4.89°C and ΔS of -0.25 to $+0.66$ were detectable (Figure 2d).

4. Discussion

4.1. Forcing

[10] In general, the primary mechanisms accounting for typhoon-forced sea surface cooling are vertical mixing (entrainment), transient upwelling (Ekman pumping), and latent heat loss to the atmosphere [*Price*, 1981]. What favored Lingling, a category 4 typhoon, to cause the dramatic cooling (11°C)? Since the estimated latent heat loss it induced (56~59 m/s wind) was <500 w/m^2, which yielded cooling <3°C [*Luis and Kawamura*, 2000], mixing and upwelling were expected to play a critical role.

[11] The role of mixing and upwelling was examined using the ARGO profiles (Figure 2d). From 11/9 to 11/16, T dropped almost throughout the observed water column. S increased above 60 m where mixing dominated, and decreased slightly between 60 m and 80 m as a result of mixing. However, the magnitude of change was much smaller in this layer, suggesting that upwelling made a contribution. Below 85 m, ΔS became positive, indicating that more saline deep water was upwelled. Maximum ΔS occurred at 100 m where minimum ΔT was found, implying that upwelling dominated at 100 m and below. From 11/16 to 11/30, the change patterns of T and S reversed (Figure 2d), suggesting recovery from Lingling's perturbations (mainly mixing and upwelling).

[12] What intensified the cooling effect of mixing and upwelling at the center of the cold patch? In the area of extreme cooling, T/P derived geopotential anomaly showed a pre-existing cyclonic gyre (Figure 3), which appear to be a sub-basin scale seasonal circulation driven by the winter monsoon [*Li et al.*, 2000]. Maximum cooling was found at the gyre center (~14°N, 114°E; Figures 1 and 3) where upward doming of isotherms occurred. Changes of along-track SSHA on Passes 114 and 229 (before and after Lingling) showed that maximum cooling of ~10°C along these tracks was co-located with maximum SSHA change (Figure 3). Along Pass 114, minimum SST of 20.6°C occurred with minimum SSHA of -28 cm at 14.4°N on

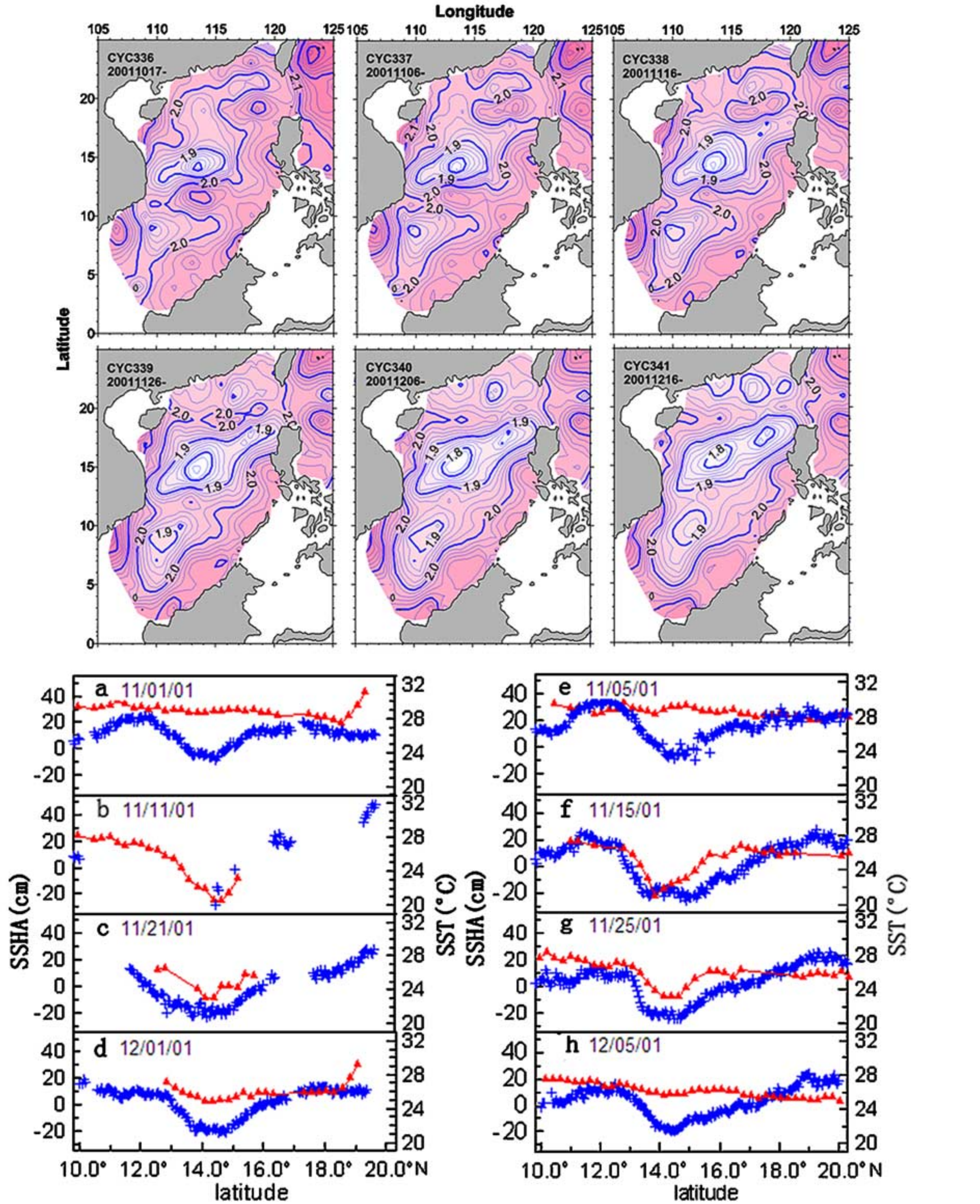

Figure 3. (top) T/P surface dynamic heights from mid-October to mid-December (in dynamic meters). (bottom) Along track T/P SSHA on (a)-(d) Pass 114 and (e)-(h) Pass 229. Blue, SSHA; red, SST. Passes 114 and 229 are shown in Figure 1b as blue lines.

11/11. The magnitude of cooling decreased with increasing SSHA. The maximum SSHA drop of $\geq$20 cm was similar to that detected within post-hurricane cold-core cyclones in the Gulf of Mexico [*Walker et al.*, 2005]. In winter, the thermocline in the SCS is typically 50–100 m below the sea surface, which however domes up to $\sim$30 m at the gyre center (Figure 2e). Shallow mixed layer at the gyre center thus favored a more vigorous cooling (induced by mixing and upwelling) than the area outside of the gyre.

[13] Following *Price et al.* [1994], *Babin et al.* [2004], and *Walker et al.* [2005], the isopycnal displacement of the thermocline due to storm-induced upwelling can be com-

puted based on maximum wind speeds of 110–115 knots, t values of 19.2 N/m^2, and a transit speed of 5 m/s. It was estimated that the scale of isopycnals displacement was about 100 m, which was significant enough to pump waters below the thermocline to the surface. Using SSH data and the ARGO profiles, we also computed isotherm upwelling ($\Delta\eta$) from the change in SSHA (Δh) using the reduced gravity approximation $\Delta\eta = -g/g' \Delta h$ [*Shay et al.*, 2000]. The estimated isopycnal displacement was about 50 m for the observed maximum 28 cm changes in SSHA. This is smaller than the estimate based on wind stress, probably because that the 10 day revisit of the T/P altimeter is not sufficient to resolve short-term SSH changes. However, it consistently indicated that waters below the thermocline were upwelled to the surface.

[14] The same mechanism could explain the Chla enhancement. Typhoon-induced strong upwelling and mixing, together with eddy-pumping before Lingling, resulted in Chla enhancement from both upward entrainment of the deep Chla maxima [e.g., *Walker et al.*, 2005] and new nutrient injection from the deeper water [*Babin et al.*, 2004]. Phytoplankton is known to grow and divide rapidly with upwelled nutrients. However, nutrient-rich waters, once brought to the surface, advect away from the upwelling center. Therefore, phytoplankton tends to bloom off the upwelling center. Further, the amount of carbon fixed per unit time per unit Chla is lower than normal during upwelling [*Mann and Lazier*, 1996]. In addition, heavy cloudiness during the passage of the hurricane might limit production. The combined effect could explain why the temporal lag occurred between the surface cooling and Chla enhancement.

[15] The magnitude of Chla enhancement for Lingling was lower than those reported for Kai-Tak and Damrey [*Lin et al.*, 2003; *Zheng and Tang*, 2007], which were from a band-ratio algorithm (OC4) that does not distinguish CDOM from Chla. But the area under influence was about 4$\sim$10 times bigger for Lingling ($\sim$over 3° latitude and 4° longitude) than for those two.

4.2. Chla or CDOM?

[16] Most published reports on typhoon-induced changes attributed all color changes to biological activity. Using a linear matrix inversion model, *Hoge and Lyon* [2002] suggested that color changes in the oligotrophic oceans were solely due to CDOM, and not due to phytoplankton. Because of the deep nutricline, *Hu and Muller-Karger* [2007] showed one rare case that neither CDOM nor Chla increased after Hurricane Dennis (category 4) in the northern Gulf of Mexico in summer 2005. Here, we showed that the amount of CDOM and detritus mixed and advected upward was equal to that of Chla, but Chla increased more in the later phase after Lingling. The upward transport of CDOM and detritus was verified by $a_{ph}(443)$ and $a_{dg}(443)$ measurements in the study region in winter 2006 (Figure 2b). According to these profiles, that upward advection and mixing in the upper 100 m (where data were available) could lead to surface $a_{dg}(443)$ of $\sim$0.03 m^{-1} and surface $a_{ph}(443)$ of $\sim$0.02 m^{-1}, which were consistent from those derived from the QAA algorithm. Indeed, the ability of the QAA algorithm to decouple phytoplankton and CDOM/detritus has already been verified in an ocean gyre [*Hu et al.*, 2006].

4.3. Impact on Primary Production

[17] The $\geq$2°C cooling did not disappear until 11/20, although the area decreased. Due to heavy cloud cover, it is not clear how long the enhanced Chla persisted. However, a patch of OC4_Chla >0.2 mg/m^3 was observed in the composite SeaWiFS image of 11/24–11/27, suggesting that the Chla enhancement maintained for $\sim$2 weeks, consistent with earlier findings [*Babin et al.*, 2004].

[18] We attributed the initial Chla increase of 0.08 to 0.14 mg/m^3 to upward transport of the deep Chla maxima and the delayed Chla increase of 0.14 to 0.37 mg/m^3 to new production. It was estimated that new production contributed ca.79% to the total production, about 10 % greater than that from Hurricane Ivan in the Gulf of Mexico [*Walker et al.*, 2005]. To assess Lingling's contribution to carbon fixation, a primary production model [*Behrenfeld and Falkowski*, 1997] was used with the observed Chla and SST. Daily rate of carbon fixation for the bloom area increased from $\sim$215 mgC/m^2/d before Lingling to $\sim$924 mgC/m^2/d after Lingling's passage, and this 15-day event had probably fixed 0.4 Mt of carbon. These numbers are lower than those estimated for typhoon Kai-Tak in the northeastern SCS that did not distinguish CDOM from Chla [*Lin et al.*, 2003]. Note that these numbers are conservative estimates because the peak Chla maintained for about three days (the area was not easy to estimate due to heavy cloud cover, however). The contribution of Lingling to oceanic carbon fixation was significant.

5. Conclusions

[19] Our results presented the first case for typhoon-induced enhancement of primary production over the central SCS during winter monsoon. There are several novel aspects that distinguish this work from other studies on typhoon- or hurricane-induced ocean responses. First, maximum cooling was about 11°C and the impacted area was several times larger than those reported earlier for the northern SCS. This is mainly attributed to the pre-existing cyclonic circulation, driven by the prevailing northeast monsoon in this season. Second, the color changes were separated explicitly into Chla and CDOM/detritus using a new algorithm, and attributed to changes in both Chla and CDOM/detritus due to mixing and new production. Finally, the regional $a^*_{ph}(443)$ led to more realistic Chla estimates from satellite measurements.

[20] Hence, these unambiguous results, together with earlier reports for the northern SCS, suggest that typhoons indeed contributed to local primary production and carbon fixation through nutrient pumping to the surface. Because numerous hurricanes/typhoons occur every year in the global ocean, their significance to global primary production deserves more consideration, and further investigation using the most updated bio-optical models is advocated in order to better quantify their contribution and to reduce uncertainty in the global carbon budget.

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