The biophysical responses of the upper ocean to the typhoons Namtheun and Malou in 2004

YUAN-JIAN YANG†‡, LIANG SUN†§*, QI LIU†, TAO XIAN† and YUN-FEI FU†

†Laboratory of Atmospheric Observation and Climatological Environment, School of Earth and Space Sciences, University of Science and Technology of China, Hefei, Anhui, 230026, China
‡Anhui Institute of Meteorological Sciences, Hefei 230031, China
§State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, State Oceanic Administration, Hangzhou, 310012, China

The responses of the upper ocean to typhoons were investigated by the observations of sea surface wind (SSW), sea surface temperature (SST), sea surface height anomaly (SSHA), chlorophyll-a (Chl-a) and Argo floats. Typhoon Namtheun had notable impacts on the upper ocean along its track from July to August 2004. The local processes (entrainment and upwelling) dominated the upper ocean responses in the regions of the pre-existing cold eddy and beneath the typhoon track, where the observed locations of upwelling, SSHA changes, SST cooling, and Chl-a enhancement were consistent with each other. Besides, there were cold tongues extending from the cold centres. The trajectories of Argo floats, along with the cold tongues, indicated that the surface advections induced such non-local responses. On the other hand, the following weak typhoon Malou had few impacts on the upper ocean. Finally, the mechanisms of the Chl-a concentration enhancement were sketched as the effects of both the local upwelling and the non-local advection. This study implies that some non-local processes, e.g. horizontal advections, may play a notable role in the upper ocean responses to the typhoons.

1. Introduction

Typhoons (or hurricanes, tropical cyclones), when passing over the ocean, have both local (entrainment, vertical mixing, and upwelling) and non-local (horizontal advection, horizontal mixing, and pressure gradients) impacts on the ocean (Price 1981, Stramma et al. 1986, Emanuel 1999). The sea surface temperature (SST) cools down due to vertical mixing (or entrainment) and upwelling by strong wind stress of typhoon along its path (Price 1981, Stramma et al. 1986, Price et al. 1994, Emanuel 1999, Liu et al. 2008). Meanwhile, due to such local processes, there is phytoplankton blooming after the typhoon, and thus it makes great impact on the net primary production (NPP) and carbon cycling in the tropics and subtropics (Subrahmanyam et al. 2002, Lin et al. 2003, Babin et al. 2004, Tang et al. 2004a, b; Walker et al. 2005, Zheng and Tang 2007, Gierach and Subrahmanyam 2008, Chang et al. 2008, Sun et al. 2010). The mechanisms of Chl-a enhancement are always related to upwelling of nutrition (Subrahmanyam et al. 2002, Lin et al. 2003, Shi and Wang 2007, Shang et al. 2008), typhoon’s long-term forcing (Sun et al. 2010), cold-core cyclonic eddies (Walker et al. 2005), entrainment in

*Corresponding author. Email: sunl@ustc.edu.cn
the mixed layer (Davis and Yan 2004, Liu et al. 2008), and/or entrainment of phytoplankton from the deep Chl-a maximum (Babin et al. 2004, Gierach and Subrahmanyam 2008).

It is well known that sea surface height anomaly (SSHA) decline is generally correlated with shoaling isopycnals or upwelling (McGillicuddy et al. 1999, Tang et al. 2004a,b). Since there is an inverse correlation between SST cooling and phytoplankton blooming and the phytoplankton blooming data are not sufficient, the SST cooling is always taken as a proxy of phytoplankton blooming (Gierach and Subrahmanyam 2008). In these cases, the local processes were well studied.

There are also non-local processes (e.g. horizontal convection, pressure gradients) in the ocean’s responses (Price 1981), and such phenomena have been noted in the observation (D’Asaro 2003, Walker et al. 2005, Gierach and Subrahmanyam 2008). These non-local processes occurring far from the typhoon track are useful for understanding both the physical oceanography responses and the biologic responses. The consequence of non-local responses will change the distant environments (SST and NPP, etc.). However, they are seldom investigated, and were even ignored in previous studies when typhoons’ impacts are accounted for (Hanshaw et al. 2008). Motivated by this, the typhoons Namtheun and Malou in the summer of 2004 were investigated by the observations. The reason for choosing Typhoon Namtheun for investigation is that it was a typical typhoon, neither too strong nor too weak and that it induced some non-local processes (Sun et al. 2009). Besides, the impact by Malou should also be considered as it passed over the study area just several days after Namtheun.

2. Observational data and methodology

Typhoon track data (www.typhoon.gov.cn), taken every 6 h, including centre location, central pressure, and maximum sustained wind speeds (MSW), were obtained from Shanghai Typhoon Institute (STI) of China Meteorological Administration (CMA). The sea surface wind (SSW) vectors and sea surface temperature data with spatial resolution of 0.25° × 0.25°, which were, respectively, derived from QuickSCAT (Quick Scatterometer) and the tropical rainfall measuring mission (TRMM) microwave image (TMI), are produced by the Remote Sensing Systems (www.remss.com). Two useful values were calculated in this paper by using the sea surface wind data (spatial resolution of 0.25°×0.25°). The wind stress \( \tau \) was calculated with the bulk formula (Garratt 1977), and the upwelling \( V_e \) due to wind was calculated by using the Ekman pumping formula (Price et al. 1994).

\[
V_e = \text{curl} \left( \frac{\tau}{\rho f} \right)
\]

where \( \rho = 1020 \text{ kg m}^{-3} \) is the density of sea water, and \( f \) is the Coriolis parameter.

The sea surface height anomaly (SSHA) data were produced and distributed by AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data, www.aviso.oceanobs.com). Merged Level 3 daily Chl-a data (http://seadas.gsfc.nasa.gov/), with a spatial resolution of 9 km from two ocean colour sensors (Moderate Resolution Imaging Spectroradiometer (MODIS) and Sea-Viewing Wide Field-of-view Sensor (SeaWiFS)), were produced and distributed by the NASA Goddard Space Flight Center’s Ocean Data Processing System (ODPS). The Kuroshio axis data were obtained from the weekly Quick Bulletin Ocean Conditions provided by the Hydrographic and Oceanographic Department of the Japan Coastal Guard (JCG).
The Argo float profiles were extracted from the real-time quality controlled Argo database of China Argo Real-time Data Center (www.argo.org.cn).

Typhoon Namtheun was a super category 4 typhoon (the maximum wind: 59 m s\(^{-1}\)) which lingered westward at a nearly stationary slow speed (\(\approx 2\) m s\(^{-1}\)) between 28 July and 30 July (figure 1). Thereafter, Namtheun moved quickly (\(\approx 6\) m s\(^{-1}\)) towards northwest, and it finally landed on Shikoku island and weakened gradually (Sun et al. 2009). In contrast, Typhoon Malou was a quick (\(\approx 10\) m s\(^{-1}\)) and weak typhoon (the maximum wind: 15 m s\(^{-1}\)).

3. Results

3.1 Upwelling and sea surface height anomaly

The typhoon induced strong winds around the eye and there was upwelling along the typhoon track (figure 2). The winds and upwelling by typhoon Namtheun (figure 2(a)–(d)) were significantly stronger than those by typhoon Malou (figure 2(e), (f)). For example, the upwelling with the maximum values were 6–8 \(\times 10^{-4}\) m s\(^{-1}\) on 28 July (figure 2(a)), 8–12 \(\times 10^{-4}\) m s\(^{-1}\) on the morning of 29 July (figure 2(b)), and 12 \(\times 10^{-4}\) m s\(^{-1}\) on the evening of 29 July (figure 2(c)). Then the upwelling weakened to 6–8 \(\times 10^{-4}\) m s\(^{-1}\) on the morning of 30 July (figure 2(d)). Besides, the typhoon also induced the relatively weak downwelling, however, in a much larger region around the upwelling region (figure 2). In this case, the upwelling occurred with notable right bias on 29 July (figure 2(e)), even when the typhoon was at a very slow speed (\(\approx 2\) m s\(^{-1}\)) and the typhoon winds were nearly symmetric then. It is also noted that the strongest upwelling occurred when the typhoon was the slowest and the strongest (figure 1).

Then the prior upwelling/downwelling induced the sea level changes (figure 3). In general, the SSHA decrease occurred on both sides of the typhoon track (within 50–80 km away) in most of the region. The largest SSHA decrease (\(\approx 60\) cm from 28 July to 6 August), occurring beneath Namtheun’s track at around 137° E, 32° N,
coinciding with the previous-existing cyclonic cold eddy and the upwelling centre (figure 2(c)). There was also another local SSHA decrease maximum at around 139.5°E, 31°N (−30 cm from 28 July to 6 August), which coincided with the upwelling on 29 July (figure 2(b)). The previous study (Sun et al. 2009) has pointed out that the strong winds and upwelling enhanced the cyclonic cold eddy on the right side of the track (figure 1), and consequently led to the Kuroshio large meander in August 2004. Thus, the Kuroshio path shifted to south for about 100 km.

Specifically, there were four sea level decreasing belts (indicated by arrows) like the tongues from the track to the cross direction, where there were a few upwellings.
during the typhoon’s passage (figure 2). The trajectories of the Argo floats clearly showed that there were strong advections along the belts (figure 3). For example, the float 2900 361 moved about 169 km from 141.7° E, 30.0° N on 24 July to 141.2° E, 28.6° N on 29 July (table 1). It implies a strong southwest flow during the typhoon’s passage. The strong southwest flow coincided with the right sea level decreasing belt very well. Thus the sea level decreasing belts seemed to be associated with the advection on the surface, rather than the local upwelling.

### 3.2 Sea surface temperature and chlorophyll-a concentration

The typhoon-induced vertical mixing and upwelling not only changed the SSHA, but also changed the SST. One consequence of the upwelling is sea surface cooling process after the passage of Namtheun (figure 4). Prior to typhoon Namtheun, it was dominated by warm water with SST > 28°C in the study area (figure 4(a)). Then, the significant sea surface cooling appeared along the track after Typhoon Namtheun’s passage, with SST dropping to 22–24°C (figure 4(b)–(d)). Two cooling centres (in figure 4(d), (e)) are identified at the pre-existing eddies in figure 1 and the upwelling centres in figure 2. The cooling process can also be observed from Argo floats data (figure 5), where the temperature dropped 1–3.5°C on the upper ocean.

The largest SST cooling region was well matched with the maximum upwelling zone (figure 2 and figure 3). Besides, there were four cold SST tongues (CT1, CT2, CT3 and CT4), which matched with three SSHA decreased tongues after Namtheun. Among the cold tongues, one of them disappeared several days after the typhoon’s passage. This is because the Kuroshio axis shifted south and brought warmer waters to the region (Sun et al. 2009).

The biological response, indicated by Chl-a concentration, is depicted in figure 6. Prior to Namtheun, there was a typical summer condition of Chl-a concentration, predominantly <0.1 mg m⁻³ in the offshore region, and >0.1 mg m⁻³ in the nearshore region, especially in coastal waters (figure 6(a)). The Chl-a concentration was enhanced after the typhoon’s passage (figure 6(b)). In the nearshore regions and the pre-existing cyclonic eddy, Chl-a concentration increased from 0.1 mg m⁻³ (before typhoon) to 0.2–0.5 mg m⁻³ (after typhoon). And in the offshore regions, the Chl-a concentration increased from 0.07 mg m⁻³ (before typhoon) to 0.1–0.25 mg m⁻³ (after typhoon). The phytoplankton bloom regions matched well with the largest upwelling.
Figure 4. The sea surface temperatures, the four cold tongues (arrows) and the trajectories of the floats.

Figure 5. The pre- and post-typhoon vertical temperature profiles measured by Argo float 2900139 (a) and 2900361 (b). Also shown is the temperature distribution in the cross-section from typhoon track along CT1 (c).
regions in figure 2(b)–(d), especially at the pre-existing cold eddy. The southward shift of the Kuroshio axis also brought the high Chl-\(\alpha\) concentration waters to the south, thus there were obvious Chl-\(\alpha\) concentration enhancements at around 133–139° E, 30–31° N (figure 6(c)). However, the phytoplankton blooming due to typhoon was only a short period event. For example, the typhoon induced phytoplankton blooming at typhoon track around 141–143° E, 31–32° N, though, very significantly, in several days disappeared very quickly (figure 6(c), (d)).

In summary, typhoon Namtheun led to sea-level decrease, sea surface cooling and Chl-\(\alpha\) enhancement in the ocean, especially at cyclonic eddies.

4. Discussion

The mechanisms of the upper ocean responses are illustrated in figure 7. Typhoon Namtheun induced vigorous vertical mixing and upwelling along its track during the passage. The strongest upwelling, occurring at the slowest typhoon track and at the pre-existing eddies, made the sea level and SST change significantly. The nutrient was injected to the upper ocean and induced Chl-\(\alpha\) concentration enhancement 3 days after Namtheun’s passage.

Besides, there were four cold tongues, three of them on the left of typhoon track. The cold water extended more than 300 km away from the typhoon track (figure 4). Among them, CT3 was due to the southward shift of the Kuroshio axis. This non-local process consequently led to the Chl-\(\alpha\) concentration enhancement in CT3 (figure 6), which was left far from the typhoon track. The typhoon impacted the distant ocean environments by this non-local process.

It seems that the other cold tongues were caused by the horizontal advection. The temperature gradients in the cold tongues indicated the directions of the advection,
which agreed well with the trajectories of Argo floats. With the temperature profiles from Argo float 2900361, the cross-section of the cold tongue CT1 is depicted in figure 5(c). It is clear that there was a warm tongue toward typhoon track beneath the thermocline accompanied with the surface cold tongue away from typhoon track, and the subsurface waters beneath the mixed layer became much warmer along the trajectories of floats. This also supports the argument that formations of cold tongues were due to the cold water advection.

In this case, the non-local phytoplankton blooming was due to the advection of offshore upwelling by typhoon Namtheun. It implies that the phytoplankton blooming might appear in much wider regions, even on the left side of typhoon track. The above-mentioned mechanism is something similar to the offshore phytoplankton blooming in the South China Sea (Tang et al. 2004a). In that case, the nearshore upwelling by winds along the coastal then was advected by the circulation.

However, the typhoon Malou had few impacts on the upper ocean, as it was very weak and passing very fast. The upwelling velocities were therefore small (figure 2(e), (f)), and the sea surface cooling was also weak (figure 3(d)–(f)). The impacts of Malou were negligible compared with those of Namtheun. This is consistent with the previous investigations (Subrahmanyam et al. 2002, Lin et al. 2003, Walker et al. 2005, Zheng and Tang 2007, Sun et al. 2010).

5. Conclusion

In summary, local responses of the upper ocean to typhoon Namtheun are investigated by observations of SSW, SST, SSHA, Chl-a and Argo floats. Most of the observed locations of upwelling, sea level changes, SST cooling, and Chl-a enhancement were consistent with each other, which implies that local processes (entrainment and upwelling) dominated the upper ocean responses in this case. Besides, there were
several cold tongues, which were due to the advection of surface flow from the upwelling centres. Finally, the mechanisms of the Chl-\(a\) concentration enhancement were sketched as the effects of both the local upwelling and the non-local advection. This study implies that some non-local processes, e.g. horizontal advections, may play a notable role in the upper ocean responses to the typhoons.

**Acknowledgements**

We thank two anonymous reviewers for their constructive suggestions. This work is supported by Project supported by the National Basic Research Program of China (No. 2007CB816004), the Knowledge Innovation Program of the Chinese Academy of Sciences (Nos KZCX2-YW-QN514 and KZCX2-YW-Q11-04), the National Foundation of Natural Science (Nos 40705027, 40730950 and 40675027), and the Open Fund of State Key Laboratory of Satellite Ocean Environment Dynamics (No.SOED0902). We thank Shanghai Typhoon Institute (STI) of China Meteorological Administration (CMA) for providing typhoon track data, NASA's Ocean Colour Working Group for providing merge MODIS and SeaWiFS data, Remote Sensing Systems for TMI sea-surface temperature and QuikScat wind-vector data, AVISO for SSHA data and geostrophic current data, Japan Oceanographic Data Center (JODC) for ocean current data and physical–chemical oceanographic data, and China Argo Real-time Data centre for the Argo float profiles.

**References**

- Babin, S.M., Carton, J.A., Dickey, T.D. and Wiggert, J.D., 2004, Satellite evidence of hurricane-induced phytoplankton blooms in an oceanic desert. *Journal of Geophysical Research*, **109**, C03043, doi: 10.1029/2003JC001938.
- Chang, Y., Liao, H.-T., Lee, M.-A., Chan, J.-W., Shieh, W.-J., Lee, K.-T., Wang, G.-H. and Lan, Y.-C., 2008, Multisatellite observation on upwelling after the passage of Typhoon Hai-Tang in the southern East China Sea. *Geophysical Research Letters*, **35**, L03612, doi: 10.1029/2007GL032858.
- D'Asaro, E.A., 2003, The ocean boundary layer below Hurricane Dennis. *Journal of Physical Oceanography*, **33**, pp. 561–579.
- Davis, A. and Yan, X.H., 2004, Hurricane forcing on chlorophyll-\(a\) concentration off the northeast coast of the U.S. *Geophysical Research Letters*, **31**, L17304, doi: 10.1029/2004GL020686.
- Emanuel, K.A., 1999, Thermodynamic control of hurricane intensity. *Nature*, **401**, pp. 665–669.
- Garratt, J.R., 1977, Review of drag coefficients over oceans and continents. *Monthly Weather Review*, **105**, pp. 915–929.
- Gierach, M.M. and Subrahmanyam, B., 2008, Biophysical responses of the upper ocean to major Gulf of Mexico hurricanes in 2005. *Journal of Geophysical Research*, **113**, C04029, doi: 10.1029/2007JC004419.
- Hanshaw, M.N., Lozier, M.S. and Palter, J.B., 2008, Integrated impact of tropical cyclones on sea surface chlorophyll in the North Atlantic. *Geophysical Research Letters*, **35**, L01601, doi: 10.1029/2007GL031862.
- Lin, I., Liu, W.T., Wu, C.-C., Wong, G.T.F., Hu, C., Chen, Z., Liang, W.-D., Yang, Y. and Liu, K.-K., 2003, New evidence for enhanced ocean primary production triggered by tropical cyclones. *Geophysical Research Letters*, **30**, 1718, doi: 10.1029/2003GL017141.
- Liu, L.L., Wang, W. and Huang, R.X., 2008, The mechanical energy input to the ocean induced by tropical cyclones. *Journal of Physical Oceanography*, **38**, pp. 1253–1266.
McGillicuddy, D.J., Johnson Jr, R., Siegel, D.A., Michaels, A.F., Bates, N.R. and Knap, A.H., 1999, Mesoscale variations of biogeochemical properties in the Sargasso Sea. *Journal of Geophysical Research*, 104, pp. 13381–13394.

Price, J.F., 1981, Upper ocean response to a hurricane. *Journal of Physical Oceanography*, 11, pp. 153–175.

Price, J.F., Sanford, T.B. and Forristall, G.Z., 1994, Forced stage response to a moving hurricane. *Journal of Physical Oceanography*, 24, pp. 233–260.

Shang, S., Li, L., Sun, F., Wu, J., Hu, C., Chen, D., Ning, X., Qiu, Y., Zhang, C. and Shang, S., 2008, Changes of temperature and bio-optical properties in the South China Sea in response to Typhoon Lingling, 2001. *Geophysical Research Letters*, 35, L10602, doi: 10.1029/2008GL033502.

Shi, W. and Wang, M., 2007, Observations of a Hurricane Katrina induced phytoplankton bloom in the Gulf of Mexico. *Geophysical Research Letters*, 34, L11607, doi: 10.1029/2007GL029724.

Stramma, L., Cornillon, P. and Price, J.F., 1986, Satellite observations of sea surface cooling by hurricanes. *Journal of Geophysical Research*, 91, pp. 5031–5035.

Subrah manyam, B., Rao, K.H., Srinivas Rao, N., Murty, V.S.N. and Sharp, R.J., 2002, Influence of a tropical cyclone on chlorophyll-a concentration in the Arabian Sea. *Geophysical Research Letters*, 29, 2065, doi: 10.1029/2002GL015892.

Sun, L., Yang, Y.J. and Fu, Y.F., 2009, Impacts of typhoons on the Kuroshio large meander: observation evidences. *Atmospheric and Oceanic Science Letters*, 2, pp. 40–45.

Sun, L., Yang, Y.J., Xian, T., Lu, Z., and Fu, Y.F., 2010, Strong enhancement of chlorophyll-a concentration by a weak typhoon. *Marine Ecology Progress Series*, 404, pp. 39–50.

Tang, D.L., Kawamura, H., Dien, T.V. and Lee, M.A., 2004a, Offshore phytoplankton biomass increase and its oceanographic causes in the South China Sea. *Marine Ecology Progress Series*, 268, pp. 31–41.

Tang, D.L., Kawamura, H., Hai, DQAN-NHU and Takahashi, W., 2004b, Remote sensing oceanography of a harmful algal bloom (HAB) off the coast of southeastern Vietnam. *Journal of Geophysical Research*, 109, C03014, doi: 10.1029/2003JC002045.

Walker, N.D., Leben, R.R. and Balasubramanian, S., 2005, Hurricane-forced upwelling and chlorophyll a enhancement within cold-core cyclones in the Gulf of Mexico. *Geophysical Research Letters*, 32, L18610, doi: 10.1029/2002GL015892.

Zheng, G.M. and Tang, D.L., 2007, Offshore and nearshore chlorophyll increases induced by typhoon winds and subsequent terrestrial rainwater runoff. *Marine Ecology Progress Series*, 333, pp. 61–74.