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Impacts of the binary typhoons on upper ocean environments in November 2007

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Abstract. Using multiple satellite observations, Argo floats profiles, and one-dimensional (1-D) ocean mixed layer model, this study systematically investigated the impacts of the binary typhoons Hagibis and Mitag [which coexisted respectively in the South China Sea (SCS) and western North Pacific (WNP) during November, 22 to 26, 2007] on upper ocean environments. It was observed that intense Ekman pumping and two mesoscale cold, cyclonic eddies, which, induced by long forcing time of strong wind stress curls, appeared respectively in two certain areas instead of after the binary typhoons’ trails. Both cyclonic eddies retained for ∼39 days, accompanied with maximum sea surface height anomaly (SSHA) reduction of ∼25 cm induced by Hagibis and of ∼44 cm induced by Mitag, respectively. The largest sea surface temperature (SST) drop of 7°C and 2°C, the maximum chlorophyll a (Chl-a) enhancement respectively was >20 times and ∼3 times in these two eddies’ regions induced by Typhoon Hagibis and Mitag, respectively. The results of the 1-D ocean mixed layer model showed that, given its 84 h forcing time, the simulated MLT cooling and mixed layer deepening induced by Hagibis were ∼-2.8°C and 45 m, respectively, ∼-0.5°C and 25 m for Mitag at its 66 h forcing time. This work provides convincing evidences that typhoons, which appear frequently in the SCS and the WNP, play a notable role in the activities of mesoscale eddies in these areas. © 2012 Society of Photo-Optical Instrumentation Engineers (SPIE). [DOI: 10.1117/1.JRS.6.063583]

Keywords: binary typhoon; cold cyclonic eddy; cooling; forcing time; upwelling.

1 Introduction

Typhoons moving above a warm ocean surface represent an extreme case of air-sea interaction.1–8 Specially, it is well known that typhoons influence the upper ocean drastically.1–2 When typhoons (or hurricanes, tropical cyclones) pass over the ocean, local (entrainment, vertical mixing, and upwelling) and nonlocal (horizontal advection, horizontal mixing, and pressure gradients) processes of upper ocean are induced by the strong wind stress along their paths.9–17 As a result, some important indicators for physical responses were changed obviously, e.g., the deepening of the mixed layer, the cooling of the sea surface, the decrease of the sea surface...
height, and so on.1,12,16–24 Accompanying with these physical response processes, the phytoplankton blooms were stimulated, which were relative to the facts that typhoon-induced upwelling and vertical mixing bring cold and nutrient or chlorophyll-rich water up to the euphotic layer.15,16,19,22,25–33 Moreover, some previous researchers concluded that the cyclonic eddy were generated by a looping trajectory typhoon in the South China Sea,10,18 even that the large meander of the Kuroshio path south of Japan was mainly triggered by typhoons in 2004.21

According to previous studies, impacts of typhoons on the upper ocean depend on many factors including typhoon intensity, typhoon translation speed, typhoon long-term forcing, initial mixed-layer depth (MLD), Ekman pumping velocity (EPV) and pre-existing ocean circulation pattern.1,13,19,22,26,29–31 These different factors imply that different typhoons would influence the upper ocean environment in various degrees. The South China Sea (SCS) and the western North Pacific (WNP), where the locations of typhoon genesis display evident seasonal changes, are regions with a high frequency of typhoon genesis.5,22,34 In the present study, we selected two special and simultaneous cases of typhoons: Hagibis (November 2007) in SCS and Mitag (November 2007) in WNP, which were designated as binary typhoons following previous studies.35–39 The changes of separation distance, typhoons intensity, and typhoons translation speeds of this binary typhoons were investigated. Furthermore, the impacts of the binary typhoons on the upper ocean environments were also explored, e.g., physical environment (mixed layer depth, sea surface temperature, sea surface height) and biological environment (chlorophyll a concentration).

2 Data and Methods

2.1 Typhoon Data and Forcing Time

Typhoon track data (www.typhoon.gov.cn), taken by every 6 h—including center location, central pressure, and maximum sustained wind speeds (MSW)—were obtained from Shanghai Typhoon Institute (STI) of the China Meteorological Administration (CMA). The other is the “best track datasets” of the western North Pacific Ocean, obtained from the Joint Typhoon Warning Center (JTWC). Each best-track file contains tropical cyclone center locations and intensities (i.e., the maximum 1-min mean sustained 10 m wind speed) at 6-h intervals and wind radius and the radii of specified winds (17, 25, 33, or 51 m/s) for four quadrants. Following the method of Sun et al.,22 we calculated the forcing time of typhoons, i.e., the typhoons’ winds (speed > 17 m/s) blowing time in the area using JTWC best-track data.

2.2 Sea Surface Wind, Ekman Pumping Velocity, and Ekman Layer Depth

The sea surface wind vectors (SSW) with spatial resolution of 0.25 deg × 0.25 deg, which were derived from QuikSCAT (Quick Scatterometer), are produced by Remote Sensing Systems (www.remss.com). Two useful values were calculated by SSW in this paper. The Ekman pumping velocity was calculated by using the formula as follows:1,2

\[ V_E = -\text{curl} \left( \frac{\vec{z}}{\rho f} \right), \]  

(1)

where \( \vec{z} \) is the wind stress following previous studies,22,40,41 \( \rho = 1020 \text{ kg m}^{-3} \) is the density of seawater, and \( f \) is the Coriolis parameter.

Moreover, the Ekman layer depth (DE) is the depth where Ekman pumping exists, whose value cannot only represent the physics of SSW but also indicates the intensity of subsurface ocean process at fixed latitude. It can be computed from:42,43

\[ D_E = \frac{7.6}{\sqrt{\sin |\varphi|}} U_{10}, \]  

(2)

where \( U_{10} \) is the wind speed at 10 m above the sea, and \( \varphi \) is the latitude.
2.3 Sea Surface Temperature and Chlorophyll-A Concentration

A new generation of the sea surface temperature (SST) data with global high-resolution of 9 km, which were derived from microwave image (AMSR-E/TMI) merged with infrared image (MODIS), are produced by Remote Sensing Systems.

Merged level 3 daily chlorophyll-a concentration (Chl-a) data with a spatial resolution of 9 km from two ocean color sensors (MODIS and SeaWiFS) were produced and distributed by the NASA’S Ocean Color Working Group (available at http://oceancolor.gsfc.nasa.gov/).

2.4 Sea Surface Height Anomalies and Ocean Features

The altimeter data were derived from multisensors. These sensors include Jason-1, TOPEX/POSEIDON, GFO (Geosat Follow-On), ERS-2 and Envisat. Data were produced and distributed by AVISO (Archiving, Validation and Interpretation of Satellite Oceanographic data). Near-real-time merged (TOPEX/POSEIDON or Jason-1 + ERS-1/2 or Envisat) sea surface height anomaly (SSHA) data, which are high resolutions of the $1/4^\circ \times 1/4^\circ$ Mercator grid, are available at www.averse.oceanobs.com. According to previous studies, three categories of primary ocean features are defined as follows: positive-SSHA feature (averaged SSHA $>6$ cm), negative-SSHA feature (averaged SSHA $<-6$ cm), and no-feature condition (averaged SSHA between $-6$ and 6 cm).

2.5 Mixed Layer Depth and 1-D Ocean Mixed Layer Model

Due to the lack of in situ and real-time upper ocean profiles in some study regions, the climatological-monthly mean mixed layer depth (MLD) fields, temperature, phosphate and nitrate profiles were derived from the National Oceanographic Data Center (NODC). The Argo float profiles, which are located nearest to study regions, were also obtained from the real-time quality controlled Argo data base of China Argo Real-time Data Center (www.argo.org.cn). The MLD data were computed from Argo float profiles of potential temperature based on temperature change from the ocean surface of 0.5°C.

To examine the variations of the upper ocean MLD and mixed layer temperature (MLT) induced by typhoon, a new 1-D ocean mixed layer model (hereafter OMLM-Noh), which improved from the Mellor-Yamada (MY) 1-D ocean mixed layer model, was run with wind forcing from JTWC’s best track 10-min sustained wind and with air-sea fluxes from Woods Hole Oceanographic Institution (http://seaflux.org/seaflux_data/). The drag coefficient (Cd) was the high wind coefficient from Powell et al. Initial inputs were the in situ ocean depth-temperature profiles that came from the Argo floats, and they realistically represented the profiles of mixed layer. The 1-D OMLM-Noh was run according to the forcing time of the typhoon’s passing in an objective point location, where forced integratively by the impacts of the different radii of specified winds (e.g., 17, 25, 33, and 51 m/s and maximum sustained wind). The OMLM-Noh is able to correctly predict the evolution of vertical profiles of physical quantities including MLD, MLT, and SST with real observational data from the Patches experiment.

3 Binary Typhoons in November 2007

Typhoon Hagibis and Mitag coexisted, respectively in SCS and WNP after Mitag forming at 0000 UTC, November 20, 2007 (Fig. 1), and the developing tendency of typhoons Hagibis and Mitag presented similarly (Fig. 1). Hagibis (2007) was a weak typhoon and had a special track (Fig. 1). It was generated from a tropical depression east of the Philippines on November 19, 2007, and was upgraded to a tropical storm when it moved into the SCS at 1800 UTC on November 20. On November 22, the storm strengthened to category 1 typhoon and was named Hagibis. This category 1 typhoon moved slowly in the middle SCS, with a horizontal “V”-type track, and it passed over the middle of the SCS twice. It stayed in the SCS for more than five days. Finally, Hagibis dissipated to tropical storm status at 0000 UTC November 24 and made landfall on the Philippines around 0000 UTC November 27. Mitag (2007) was recorded as a...
tropical depression at 0000 UTC November 20, 2007, and then moved northwestward as a tropical storm after soon. It turned to the west at 1800 UTC November 21 and strengthened to category 1 typhoon after 6 h. Mitag moved westward steadily and intensified to its peak value at 0000 UTC November 25; after this, it began to move northwestward and then weakened gradually to tropical storm in the Luzon strait at 0000 UTC November 27. Finally, it disappeared as a weak depression system east of Luzon strait.

Many studies showed that the typhoons direct interactions were significant when their separation distance was 10 to 15 deg latitude.\textsuperscript{35–39} Figure 2(c) shows that the separation distance between Hagibis and Mitag was about 15 deg latitude during November 23 to 24, thus these two typhoons might interact directly. According to previous studies,\textsuperscript{35–39} the interaction of binary typhoons frequently caused shape change of their tracks and translation speeds ($U_t$). For example, in this case, the binary typhoons Hagibis and Mitag almost simultaneously reached typhoon intensity on November 22 [Figs. 1 and 2(a)]. While both typhoons began to loop half after 00UTC on November 23, both Hagibis and Mitag began to move slowly [Figs. 1 and 2(a) to 2(b)]. Especially, the binary typhoons simultaneously experienced stagnancy during 00UTC November 23 to 00UTC November 24 [Figs. 1 and 2(b)].

4 Impacts of the Binary Typhoons on Upper Ocean Environments

4.1 Upwelling in the Upper Ocean

Strong winds around each eye of the binary typhoons were captured by QuikSCAT during November 22 to 24 (Fig. 3). During the passage of the binary typhoons, strong Ekman pumping mainly appeared on November 22, 23, and 24 (Fig. 3), and the strong typhoon-wind stress curls have induced seawater upwelling (positive shaded in Fig. 3) along both typhoons’ tracks. The wind-induced Ekman layer depth was also marked in Fig. 3 (black solid line). The maximum depth of the Ekman layer reached $\sim$600 m on November 22 after Hagibis’ passage and $\sim$500 m on November 23 after Mitag’s passage, respectively (Fig. 3).

4.2 Sea Surface Cooling

Figure 4 shows MV-IR derived SST serial images, which reveal the evolution of sea surface cooling induced by Hagibis and Mitag during their passages. Before the binary typhoons’
passage, there was warm water in the middle of SCS (with SST > 28°C) and south of WNP (with SST > 28°C), respectively [Fig. 4(a)]. After their passages, two distinctly cold patches were observed [box C1 and C2 in Fig. 4(b)] in two certain regions instead of their whole trail paths, with a maximum temperature cooling of −7°C in C1 and −3°C in region C2 around the tracks of Hagibis and Mitag, respectively [Fig. 4(b)]. These two cold patches lasted for more than a week [Fig. 4(b) to 4(h)]. Moreover, when Mitag arrived at Luzon Strait on November 26, 2007, there was another cold SST patch [C3 in Fig. 4(e)], where SST dropped ∼2°C.

4.3 Chl-a Bloom
The obvious biological response, indicated by Chl-a concentration, is depicted in Fig. 5. Similarly, the sea surface Chl-a bloom regions matched well with the SST cooling regions after the passage of the binary typhoons (Figs. 4 and 5). The pre-Hagibis Chl-a concentration was 0.1 to 0.15 mg/m³ in region C1 [Fig. 5(a)]. It was notable that the post-Hagibis Chl-a concentration increased to more than 3.0 mg/m³ (that is 20 ~ 30 times of its primary value) in some places during the period from November 23 to 30 [Fig. 5(b)]. After the passage of Mitag in region C2, Chl-a concentration increased from <0.05 mg/m³ (before Mitag) to 0.12-0.2 mg/m³ (after Mitag), about four times enhancement [Fig. 5(c) and 5(d)]. In region C3, the Chl-a concentration increased from 0.25 to 0.5 mg/m³ (before Mitag) to >1.0 mg/m³ (after Mitag) [Fig. 5(e) and 5(f)].
**Fig. 3** Daily QuikScat wind-vector (green arrow, unit: m/s), Ekman pumping depth (black contour, unit: m) and Ekman pumping velocities (shaded, positive value indicated upwelling, unit: $10^{-4}$ m/s) during (a) to (c) Hagibis’ passage and (b) to (d) Mitag’s passage. Dates are hhUTC mm/dd/yy.

**Fig. 4** Observations of SST before (a) and after (b) to (h) the binary typhoons’ passage. Dates are mm/dd/yy. The tracks of typhoons are indicated by the lines. The boxes are shown as the study regions (C1, C2, and C3)
4.4 Two Cold Cyclonic Eddies after the Passage of the Binary Typhoons

The binary typhoons have also influenced SSHA in the above sea surface cooling and Chl-$a$ bloom regions, except in region C3 (Fig. 6). Typhoon Hagibis induced a cold cyclonic eddy as the SSHA decreased >25 cm immediately in region C1 (Fig. 6), where extreme cooling occurred (Fig. 5). Meanwhile, the SSHA decrease only occurred in region C2 and didn’t appear in other regions (e.g., C3) along Mitag’s path. On November 24, 2007, a distinctly mesoscale cyclonic eddy (SSH < −15 cm) was observed [C2 in Fig. 6(b)] at Mitag’s track, with a diameter of...
In comparison with the pre-typhoon condition (>10 cm), the maximum SSHA dropped 25 cm in region C2, accompanying with a mesoscale cyclonic eddy generation induced by typhoon Mitag. The long forcing periods of strong wind stress curls during the passages of the binary typhoons (Table 1), which were much longer than the geostrophic adjustment time, have intensively contributed to the formations of the two cyclonic cold eddies. Within region C1, ocean features changed from no-feature (before Hagibis) to cold cyclonic eddy with negative-SSHA feature (on November 23, 2007), and this eddy well developed and lasted for more than 39 days [Fig. 6(b) to 6(h)]. Its diameter and area reached the maximum (~437 km and ~150,000 km², respectively) on November 29, 2007 [Fig. 6(d) and Table 1]. In region C2, ocean features changed from positive-SSHA feature (before Mitag’s passage) to cold cyclonic eddy with negative-SSHA feature (on November 23, 2007). This eddy was also well-developed and lasted for more than 39 days [Fig. 6(b) to 6(h)]. Its diameter and area reached the maximum (~400 km and ~90,000 km², respectively) on November 29, 2007 [Fig. 6(d) and Table 1].

4.5 Time Series of Typhoon-induced $V_E$ and $D_E$, SST, Chl-a, and SSHA

To examine the variability in upper ocean conditions, Fig. 4 illustrates quantitatively the time series of typhoon-induced $V_E$ and $D_E$, SST, and Chl-a concentration at the three regions. Due to frequent cloud coverage, only Chl-a data were obtained for these series. Obviously, the ocean physical response (SST and SSHA) and the biological response (Chl-a) delayed the occurrence of typhoon-induced $V_E$ and $D_E$.

![Fig. 7](http://remotesensing.spiedigitallibrary.org/063583-8.png) Time series observations ($D_E$, $V_E$, SST, Chl-a, and SSHA) in the cooling and bloom regions: (a) C1, (b) C2, and (c) C3 (see boxes in Fig. 4) in November and December 2007. Black arrows correspond to the binary typhoon. Dates are mm/dd.
Before Hagibis, averaged SST in region C1 was ∼28°C, Chl-a concentration was ∼0.12 mg/m³ and SSHA was ∼5 cm [Fig. 7(a)]. During Hagibis’s passage in region C1, averaged $V_E$ and $D_E$ reached their maximum: 428 m on November 21 and $6.244 \times 10^{-4}$ m/s on November 22, respectively [Fig. 7(a)]. However, there was no substantial SST decrease during this period. The averaged SST in C1 reached the lowest level (∼20.9°C) on November 25.

![Initial MLD climatology of November derived from temperatures profiles, locations of the Argo floats (5900059 and 2900433) are indicated by closed circle. Boxes are shown as study regions (C1, C2, and C3); (b) the depth-temperature profiles from Argo floats and climatological data in November of NODC; (c) results from the 1-D ocean mixed layer numerical experiments for the binary typhoon cases (the y axis indicates typhoon induced mixed layer response; the x axis is typhoon’s forcing time); (d) the depth-phosphate and depth-nitrate profiles from Argo floats and climatological data in November of NODC.]
Unfortunately, as would be expected, there was no ocean color data available during the Hagibis period. The emerging phytoplankton bloom could be detected on November 30 with an averaged Chl-$a$ concentration of $\sim$1.79 mg/m$^3$, up from the pre-Hagibis value of $\sim$0.12 mg/m$^3$. It reached $\sim$2.65 mg/m$^3$ the next day on December 1 [Fig. 7(a)]. Daily-SSHA data provided by AVISO gave us a clear view of SSHA changes. Averaged SSHA decreased by about 22.5 cm (from 4.5 to $-18$ cm) in the first three days after Hagibis had passed C1 and then rapidly decreased to $-24.9$ cm, with maximum reduction ($>29$ cm) on the fourth day [November 29, Fig. 7(a)].

Similarly, during Mitag’s passage, both averaged $V_E$ and $D_E$ within region C2 reached their maximum on November 22, about 417 m and $4.324 \times 10^{-4}$ m/s, respectively [Fig. 7(b)]. In region C3, however, because $V_E$ and $D_E$ were slightly enhanced on November 26 and 27, the ocean physical response and the biological response were also slightly induced [see in Fig. 7(c), not specific below]. Averaged SST in region C2 decreased by 1.7°C (from 28.6°C to 26.9°C) in the first day after Mitag’s passage, and the maximum reduction ($\sim$2°C) was on the fifth day [November 28, Fig. 7(b)]. Before Mitag, averaged Chl-$a$ concentration was $\sim$0.05 mg/m$^3$ in region C2. Chl-$a$ concentration increased to its maximum of 0.15 mg/m$^3$ on June 27, four days after the passage of Mitag, and then reached another peak value (0.13 mg/m$^3$) on June 28 [Fig. 7(b)]. The averaged SSHA decreased by about 25 cm (from 13 to $-12$ cm) in the first three days after Mitag had passed region C2 and then rapidly decreased to $-21.3$ cm, with maximum reduction ($>44$ cm) on the sixth day [November 29, Fig. 7(b)].

In general, the binary typhoons impacted intensively on the two certain regions (C1 and C2) instead of the whole regions around their trails. Within both regions, C1 and C2, SST cooling and phytoplankton bloom retained for more than two weeks, while SSHA reduction lasted for more than a month.

### 4.6 Variations of MLD and MLT

Figure 8(a) showed the distribution of MLD climatology in November. The Argo floats 5900059 and 2900433, which, respectively are located nearest to region C1 and C2 before the binary typhoons’ passage, are also marked in Fig. 8(a). In contrast, the climatology of temperature profiles at the locations of these two Argo floats are very similar with those in regions C1 and C2 [Fig. 8(b)]. Meanwhile, Argo floats 5900059 and 2900433 located in union pre-typhoon ocean features with regions C1 and C2, respectively. As a result, the pre-typhoon temperature profiles of these two Argo floats could be input into 1-D OMLM-Noh and simulate the variations of the MLD and MLT in regions C1 and C2.

Figure 8(c) depicted the results of the 1-D typhoon induced MLT cooling and MLD simulation with respect to forcing time in Table 1. Consistency could be found as in the observation that Hagibis’s responses in the mixed layer of region C1 were much stronger than Mitag’s response in the mixed layer of region C2. It could be seen that given its 84 h forcing time, the simulated MLT cooling and mixed layer deepening induced by Hagibis were $\sim$2.8°C and 45 m, respectively, $\sim$0.5°C and 25 m for Mitag at its 66 h forcing time [Fig. 8(c)]. Compared with sea surface cooling observed by satellite [Fig. 7(a) and 7(b)], simulation results of the MLT cooling were smaller, because 1-D ocean mixed layer models only consider the contribution of entrainment mixing. Under slow translation speeds ($U_t \leq 4$ m/s), it is also necessary to consider the contribution from upwelling in addition to entrainment mixing. Therefore for this binary typhoon cases in regions C1 and C2, the contributions to the MLT cooling also came from upwelling under slow translation speeds [Figs. 1 and 2(b)].

### 5 Discussion

According to previous studies,$^{1,12-14,19,22,24,26,27,30,31,47}$ five main factors may influence the intensity of upper ocean response to a typhoon. The first is the typhoon’s intensity, as it is the wind forcing to induce obvious ocean response of dynamics, e.g. Ekman pumping, entrainment, and mixing. The second and third are typhoon’s translation speed and size in vortex diameter because...
they determine the forcing time. The fourth and fifth are pre-typhoon ocean features and initial MLD, since they determine how deep (or how shallow) the cold, nutrient-rich water lies. Any one of the above factor being unfavorable would lead to weakening in response; this is why a slight response occurred within region C3 [Figs. 7 and 8(a)] and the binary typhoons have a strong impact on regions C1 and C2. Similarly, a cyclonic cold eddy generated and well developed in regions C1 and C2, respectively. In general, the long forcing time of strong wind stress curls has mainly contributed to the formations of the two cyclonic cold eddies during the binary typhoons’ passage. Differently, much more sufficient SST cooling and biological responses have occurred in region C1 than in region C2, the reasons are summarized as follow:

1. Sufficient wind-induced upwelling and long forcing time. Recently, Sun et al. (2010) indicated that the upwelling velocity would reach its maximum when the forcing time of a typhoon’s impact reached geotropic adjustment time. That is, the forcing time of a typhoon is long enough to establish strong upwelling. Both within regions C1 and C2, the forcing times were much longer than the geostrophic adjustment times (Table 1), combined with sufficient typhoon-induced upwelling (Figs. 3 and 7), it must contribute to induce strong upper ocean response. However, it is obvious that little shorter forcing time and little weaker induced-upwelling of Mitag in C2 than those of Hagibis in C1. As a result, the impacts of Mitag on C2 would be weaker than those of Hagibis on C1.

2. Pretyphoon ocean features and MLD. The previous studies provided convincing evidences that preexisting negative sea surface features or mesoscale cyclonic eddy—which could provide a relatively unstable thermodynamic structure, and therefore cold and nutrient-rich water, would be brought up easily—played important roles in biophysical responses of the upper ocean to typhoon. Moreover, Price suggested that discrepancy of initial MLD is an important factor influencing upper ocean response to a typhoon. For example, the SST response is largest where cold water is near the sea surface, i.e., where the initial MLD is thin. Before the binary typhoons, region C1 and C2 presented no-feature [Figs. 6(a) and 7(a)] and significant positive-SSHA feature [Figs. 6(a) and 7(b)], respectively. Especially in the region C2 the mixed layer and nutricline were much deeper than in region C1 [Fig. 8(b) to 8(d)]. Therefore, it would be unfavorable ocean precondition for strong response in region C2 because it encountered a prominent warm and positive-SSHA ocean feature and deeper MLD, which acted as insulators to restrain the cold, nutrient-rich water to be entrained to the surface layer.

6 Summary

The binary typhoons Hagibis and Mitag, which respectively lingered for a long time at certain locations in SCS and WNP, coexisted during November 22 to 26, 2007. Satellite-derived SST, SSHA, and Chl-a measurements with Argo floats profiles and 1-D ocean mixed layer model clearly revealed the impacts of the binary typhoons on upper ocean environments at two certain locations along the typhoons’ tracks. Especially in these two certain areas after the binary typhoons’ passages, intense upwelling and two mesoscale cyclonic eddies appeared, which were induced by long forcing time of strong wind stress curls. The results are summarized as follows.

(1) Within Hagibis-induced eddy region (region C1), the largest averaged SSHA decrease was about 25 cm after Hagibis’s passage. Ocean features changed from no-feature (before Hagibis) to cold cyclonic eddy with negative-SSHA feature, and the eddy in region C1, whose diameter and area respectively reached ~437 km and ~150,000 km² on November 29, 2007, was well developed and lasted for more than 39 days. The observed Chl-a concentration increased from the pre-typhoon value of 0.1 to 0.15 mg/m³ to >3.0 mg/m³ and the associated SST cooling was ~7°C.

(2) In the Mitag-induced eddy region (region C2), ocean features changed from positive-SSHA feature (before Mitag) to cold cyclonic eddy with negative-SSHA
feature accompanied with maximum SSHA reduction (>44 cm). And also this eddy was well developed and lasted for more than 39 days, whose diameter and area reached their maximum values (~400 km and ~90,000 km²) on November 29, 2007, respectively. However, the observed Chl-a concentration slightly increased from the pre-typhoon value of ~0.05 to 0.15 mg/m³ and the associated SST cooling was only ~2°C.

(3) Before the binary typhoons, the initial MLD were ~25 and ~80 m in regions C1 and C2, respectively. During the binary typhoons’ passages, the contributions of entrainment mixing to upper mixed layer cooling were considered and simulated by a new 1-D ocean mixed layer model. It could be seen that with 84 h forcing time, the simulated MLT cooling and mixed layer deepening induced by Hagibis were ~ − 2.8°C and 45 m, respectively, ~ − 0.5°C and 25 m for Mitag at its 66 h forcing time.

(4) Due to encountering a prominent warm and positive-SSHA ocean feature and deeper MLD in region C2, which acted as insulators to restrain the cold, nutrient-rich water to be entrained to the surface layer, the physical and biological responses in region C2 were weaker than those in region C1, although both the binary typhoons had similar, sufficient wind-induced upwelling and long forcing time in regions C1 and C2.

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Biographies and photographs of the other authors not available.
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