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- Terrestrial material was transported to Okinawa Trough triggered by the typhoon
- Three sources were identified by satellite-derived water transparency images
- Phytoplankton blooms about 300 km length were observed induced by the typhoon

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Satellite views of the episodic terrestrial material transport to the southern Okinawa Trough driven by typhoon

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Abstract Using satellite-derived water transparency (alias Secchi depth) images, we found clear signals of terrestrial material transport to the southern Okinawa Trough triggered by the Typhoon Morakot in August 2009. Three sources were identified: one is from the eastern coast of Taiwan, another is from the western coast of Taiwan, and the other is from the coast of mainland China. Carried by northward flows, typhoon-triggered terrestrial materials from both sides of Taiwan's coasts were transported to the region northeast of Taiwan. Moreover, the terrestrial material from the coast of mainland China could cross the Taiwan Strait and be further transported to the region northeast of Taiwan. These typhoon-induced terrestrial materials off northeastern Taiwan could then be transported to the southern Okinawa Trough along the western edge of the Kuroshio. In addition to the particulate terrestrial material transported, nutrients might also be transported to the Kuroshio main stream. A significant phytoplankton bloom was observed along the Kuroshio path for about 300 km off northeast of Taiwan. Our results indicate that episodic cyclone-driven terrestrial material transport could be another source of mud in the southern Okinawa Trough.

1. Introduction

The East China Sea (ECS, Figure 1), with an area of 7.7×10^5 km^2, is the 11th largest marginal sea in the world [*Chen et al.*, 2010]. A recent study suggests that the continental shelves are a sink for atmospheric CO_2 at mid-high latitudes [*Cai et al.*, 2006]. The ECS may absorb 20–30 Mt Cy^{-1}, mostly in the inner and middle shelves adjacent to the Changjiang River mouth [*Peng et al.*, 1999; *Tsunogai et al.*, 1999; *Wang et al.*, 2000], and about 10 Mt Cy^{-1} is buried in the shelf sediments [*Chen and Wang*, 1999]. To balance the carbon budget, a major fraction of absorbed carbon must be exported out of the shelf, and the most likely deposition site of the exported particulate matter from the ECS shelf is the Okinawa Trough [*Kao et al.*, 2003; *Bian et al.*, 2010]. Researchers agree that most of the sediments in the western slope of the Okinawa Trough are terrigenous, but the source and path of the mud in the Okinawa Trough are still unclear [*Bian et al.*, 2010].

Previous studies have shown that the transport of terrigenous material to the Okinawa Trough from the ECS occurs mainly in winter through strong wind-driven bottom flows. Three suggestions have been offered. One group of researchers believes that most terrestrial sediments in the Okinawa Trough are from the Changjiang River. About 70–90% of the suspended particulate matter is deposited in the Changjiang River Estuary and the Zhejiang-Fujian coast, while the rest is transported to the outer shelf and the Okinawa Trough, mostly by wind-driven transverse circulation in winter [*Yuan et al.*, 1987; *Milliman et al.*, 1989; *Lin*, 1989; *Yanagi et al.*, 1996; *Peng and Hu*, 1997; *Hoshika et al.*, 2003; *Iseki et al.*, 2003; *Lin et al.*, 2003b]. The second group believes that most terrestrial sediments in the Okinawa Trough come from the Old Huanghe River submarine delta. Sediments are resuspended by strong winds in winter and carried to the continental shelf and the Okinawa Trough by the Yellow Sea Warm Current [*Hu and Yang*, 2001; *Milliman et al.*, 1985; *Wang and Jiang*, 2008; *Yuan et al.*, 2008]. The third pathway is more indirect: particles discharged by the Changjiang River extend southward first. Then, carried by bottom currents during the northeast monsoon period in winter, they veer offshore toward the southern Okinawa Trough [*Liu et al.*, 2000; *Kao et al.*, 2003;

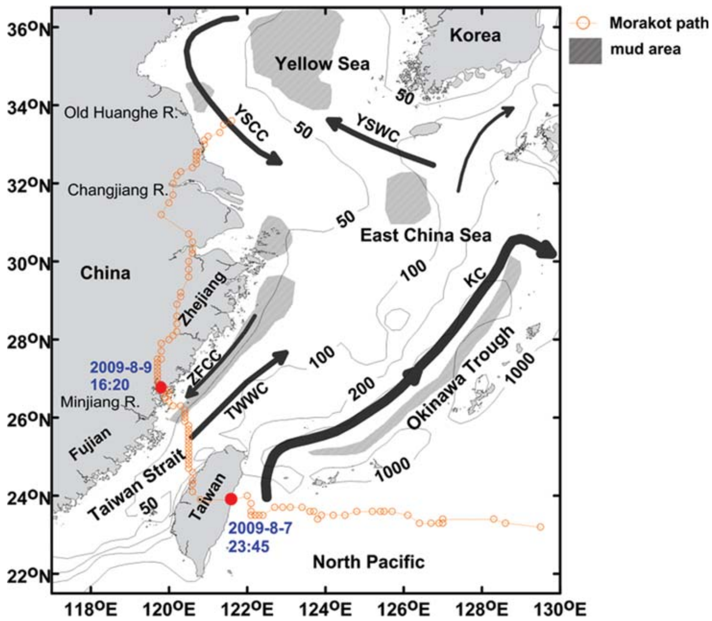

Figure 1. Bathymetry, regional ocean circulation, distribution of mud, and the path of Typhoon Morakot. Shaded regions show the distribution of mud at the bottom of the ocean [*Bian et al*., 2010]. Arrows indicate the Kuroshio Current (KC), the Taiwan Warm Current (TWWC), the Zhejiang-Fujian Coastal Current (ZFCC, in winter), the Yellow Sea Warm Current (YSWC), and the Yellow Sea Coastal Current (YSCC).

Zhu et al., 2008]. In summary, these studies have shown that terrigenous transport to the Okinawa Trough from the ECS occurred mainly in winter through strong wind-driven bottom flows. Yet a few studies have considered the terrestrial material transport to the Okinawa Trough that is caused by the typhoon events in summer due to the "bad sea condition" for carrying out cruises.

There are on average 3.7 typhoons passing across or near Taiwan every year [*Huang et al*., 2011]. Typhoons bring tremendous rainfalls and cause severe mudflows, which eventually discharge into coastal estuaries through rivers. For example, the heavy rainfall brought by the Typhoon Morakot in August 2009 was the highest recorded in the past 50 years in Taiwan, and the maximal river runoff was up to 6 $\times$ 10^4 m^3/s which is comparable to the Changjiang River [*Jan et al*., 2013]. Based on in-situ measurement about 1 week after Morakot, *Jan et al*. [2013] observed an Ω-shaped freshwater pulse off the northern tip of Taiwan. Yet due to the low spatiotemporal coverage of the field measurement, it is hard to understand the sources and evolution of the observed freshwater pulse [*Jan et al*., 2013].

Comparing with the in situ measurement, the satellite observation has the unique advantage of global coverage and daily observing capacity, which is ideal for the observation of the highly dynamic processes such as typhoon induced phenomena [*Lin et al*., 2003a]. The motivation of this study is to take the advantage of satellite observation to track the sources and transportation of terrestrial material triggered by typhoon taking Morakot for an example. Morakot is a unique typhoon though it is only a weak category-2 tropical cyclone with a maximum landfall wind speed of 40 m/s [*Kao et al*., 2010]. It landed on Taiwan at 23:45 on 7 August 2009, moved to the north slowly ($\sim$10 km/h) across the Taiwan Strait, and then landed on Fujian province at 16:20 on 9 August 2009 (Figure 1). It brought huge runoff with record-breaking rainfall of 2900 mm over 3 days in the southern Taiwan, triggering high sediment discharge in Taiwanese rivers and resulting in huge terrestrial material transport to the surrounding oceans [*Hilton et al*., 2011; *West et al*., 2011].

2. Data and Methods

2.1. Satellite Remote Sensing Data

Daily satellite-derived suspended particulate matter concentration (*SPM*), chlorophyll concentration (*Chl*) and sea-surface temperature (*SST*) pre and postpassage of Morakot were obtained from the satellite data receiving station of the Second Institute of Oceanography of China (SIO/SOA). The *SPM* and *Chl* were retrieved from the Aqua/MODIS and Terra/MODIS data using the SeaWiFS Data Analysis System (SeaDAS), and the *SST* was retrieved from the NOAA-17/AVHRR data. Based on the satellite-derived *Chl* and *SPM*, the water transparency (alias Secchi depth, *SD*) can be retrieved using the semianalytic algorithm [*He et al*., 2004; *Jiao et al*., 2007] as

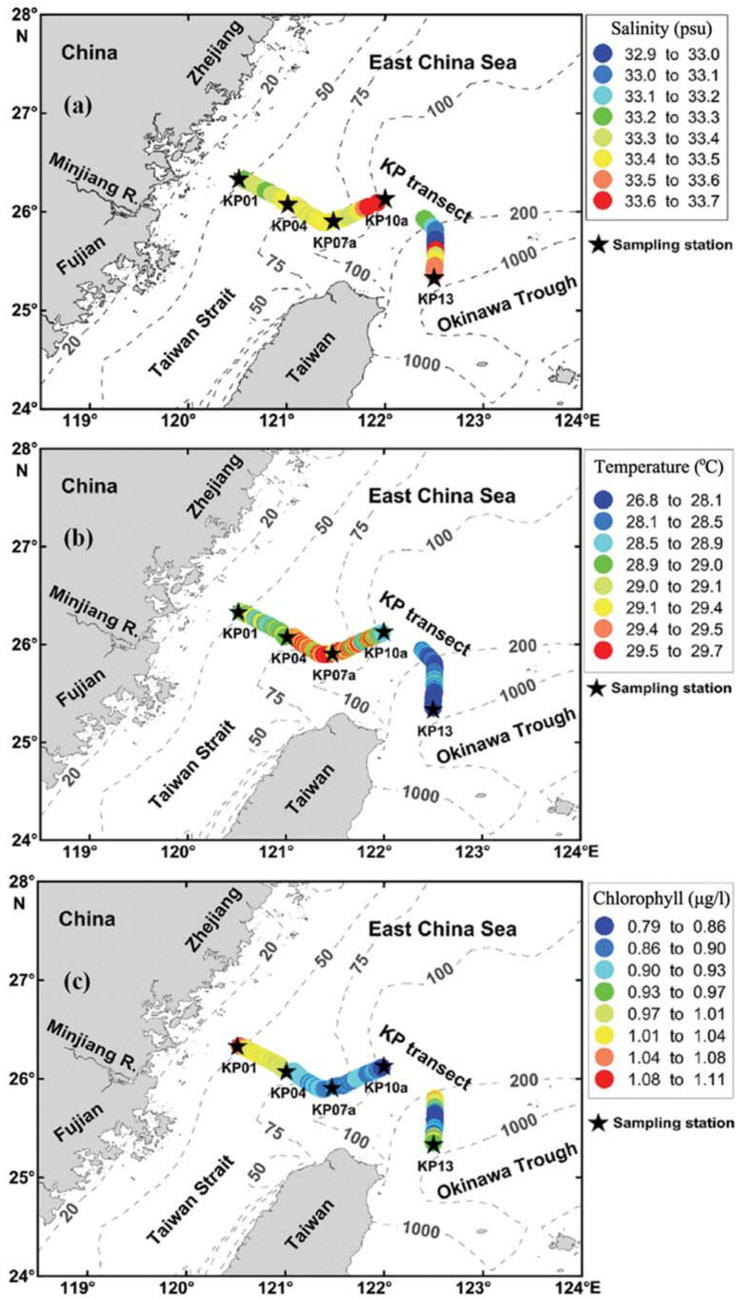

Figure 2. (a) Distributions of the underway surface salinity, (b) sea surface temperature, (c) and surface chlorophyll concentration measured by the CHOICE-C summer cruise in the region off northern Taiwan. Black stars are the sampling stations.

$$SD = \frac{1}{4(a+b_b)} \ln\left(\frac{\rho_d \alpha\beta}{C_e R}\right), \quad (1)$$

where a and b_b are the water absorption and backscattering coefficients, which are the functions of the *Chl* and *SPM*; α and β are the refractive and reflective effects of the air-sea interface, respectively, with the value of 0.35 for the $\alpha\beta$; ρ_d is the reflectance of Secchi Disc in water with the value of 0.75; C_e is the threshold contrast of human eye-brain system with the value of 0.02; R is the irradiance reflectance just beneath the water surface, which is the function of a and b_b. This semianalytic algorithm had been validated by $>$500 in situ data in the northwestern Pacific Ocean with the mean relative error of 22.6% [*He et al*., 2004]. In the highly turbid coastal waters, the satellite-derived *Chl* may be overestimated significantly [*He et al*., 2013a], and the Secchi depth can be retrieved more reliably by using the water absorption and backscattering coefficients [*Lee et al*., 2007]. Yet in this study, we prefer to use the relative changes of the Secchi depth and chlorophyll concentration induced by typhoon instead of the absolute values; thus, the impacts of the systematic overestimation or underestimation by satellite retrieval on the results are expected to be limited.

Besides the daily satellite-derived water transparency images obtained from the SIO/SOA, the 8 day composite chlorophyll concentration data retrieved by the Aqua/MODIS pre and postpassage of Morakot were obtained from the NASA ocean color website (http://oceancolor.gsfc.nasa.gov). Notably, because the atmospheric correction algorithm based on the ultraviolet wavelength was used additionally for the turbid waters by the SIO/SOA [*He et al*., 2012, 2013b], the satellite-retrieved *Chl*, *SPM*, and *SDD* from the SIO/SOA have more valid data than the NASA standard products especially at the turbid coastal waters.

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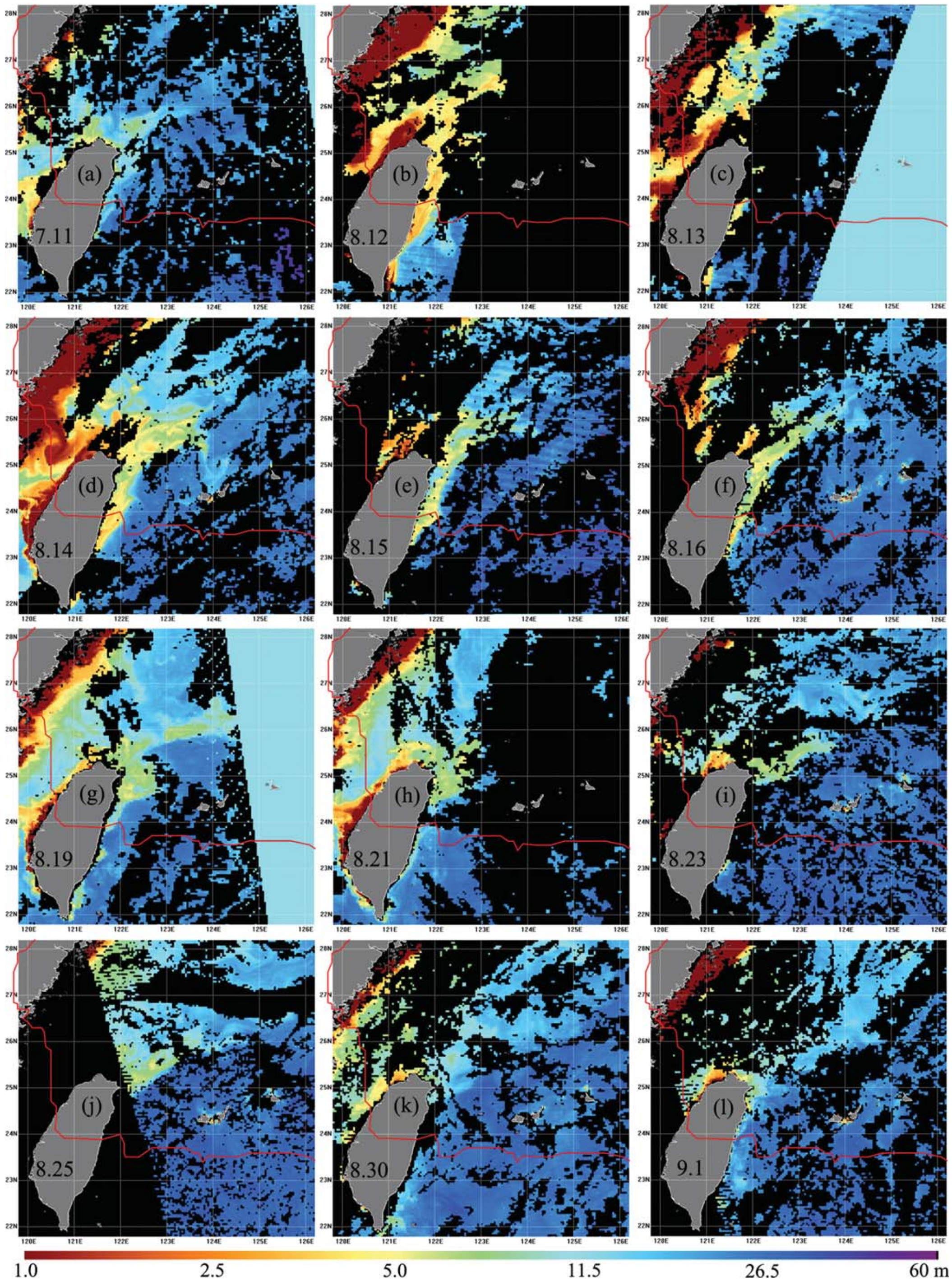

Figure 3. Satellite-derived daily water transparency images pre (for 11 July) and postpassage (for other days) of the Typhoon Morakot in 2009. The black regions are covered by clouds or sun glints. The red solid line from east to west is the track of the Morakot. (a) 13:41 on 11 July; (b) 10:25 on 12 August; (c) 11:07 on 13 August; (d) 13:29 on 14 August; (e) 10:56 on 15 August; (f) 13:17 on 16 August; (g) 13:48 on 19 August; (h) 13:36 on 21 August; (i) 13:24 on 23 August; (j) 13:12 on 25 August; (k) 13:31 on 30 August; (l) 13:17 on 1 September.

2.2. In Situ Measurement

About 10 days after the passage of Morakot, the CHOICE-C summer cruise took place in the sea off northern Taiwan on the R/V Dong Fang Hong 02, following the KP transect as shown in Figure 2. The measuring time at station KP01 was at 8:48 on 18 August, and that at station KP13 was at 2:39 on 19 August. The water temperature and salinity profiles were measured using a SeaBird Conductivity-Temperature-Depth Unit (CTD)

(SBE 911plus; Sea-Bird Electronics, Inc., USA). Besides the vertical profiles of temperature and salinity measured at stations, the underway surface water salinity, temperature, and chlorophyll fluorescence were measured using an Idronaut Multiparameter "Flow Through" CTD, as shown in Figure 2.

2.3. Model Simulation

To study the hydrographic mechanism of the terrestrial material transport in the Taiwan Strait during the period of Typhoon Morakot, the flow fields were numerically simulated by the East Asian Marginal Seas (EAMS) model which was based on the Princeton Ocean Model [*Hsin et al*., 2008, 2012]. Based on the hydrostatic approximation, this model solves three-dimensional primitive equations for the momentum, heat, and salt and evaluates turbulence by the 2.5-level Mellor-Yamada scheme. The EAMS model covers a domain extending zonally from 99°E to 140°E and meridionally from 0°N to 42°N with a horizontal resolution of 1/8° × 1/8°, and it has 26 sigma levels in the vertical. On open boundaries, the lateral boundary conditions are daily one-way nested in a 1/4° × 1/4° North Pacific Ocean (NPO) model having an expanded domain of 99°E–71°W and 30°S–65°N. The EAMS model has been validated carefully with observational data around Taiwan, and it has been used to investigate variations of the current in the Taiwan Strait and the Kuroshio around Taiwan for wide time scales from days to years [*Wu and Hsin*, 2005; *Hsin et al*., 2008; *Wu et al*., 2008a; *Hsin et al*., 2010, 2012]. The model was forced by the 6 h 1/4° × 1/4 ° Cross-Calibrated Multiplatform (CCMP) Ocean Surface Wind, which was derived through cross calibration and assimilation of ocean surface wind data from SSM/I, TMI, AMSR-E, SeaWinds on QuikSCAT, and SeaWinds on ADEOS-II, and by the 6 h 2.5° × 2.5° NCEP-DOE reanalysis II heat flux data set.

3. Results

3.1. Water Transparency Variation Caused by the Typhoon Morakot

Figure 3 shows the satellite-derived water transparency distributions before and after the passage of Morakot. Beforehand, as revealed by the water transparency images on 11 July (Figure 3a), the waters at the eastern coast of Taiwan are quite clear, with a water transparency of >20 m, owing to the pass of the Kuroshio. Turbid waters with transparencies <5 m are present only in the shallow coastal areas off the mainland China and west of Taiwan. The southwester monsoon in summer causes the surface currents everywhere in the Taiwan Strait to be directed northward, carrying the oligotrophic South China Sea surface waters and a branch of the Kuroshio to the southern ECS. As a result, the water transparency exceeds 15 m in the center of Taiwan Strait and the southern ECS. In addition, owing to the intrusion of the Kuroshio subsurface water and runoff from the northern Taiwan with high nutrient content, the chlorophyll concentration is relatively high off northeastern Taiwan, and the water transparency is relatively low [*Chen and Wang*, 2006; *Chen*, 2009], but still >10 m.

After the passage of Morakot, as revealed by the satellite-derived water transparency on 12–14 August (Figures 3b–3d), the record-breaking rainfall (2900 mm within 3 days in the southern Taiwan) caused a huge amount of terrestrial material to enter the coastal waters off both sides of Taiwan. Off the eastern coast of Taiwan, the water transparency was reduced to <5 m by river runoff. The turbid waters joined the Kuroshio surface water directly, and were able to be followed to area northeast of Taiwan (light brown/green in Figures 3b–3d). In the shallow water off the western coast of Taiwan, the bottom sediments could be resuspended by the typhoon and tidal disturbance. Together with the runoff input of terrestrial material, these processes reduced water transparency to <1 m. The turbid waters along the western coast of Taiwan were transported to the area northeast of Taiwan by the northward current in the Taiwan Strait (dark to light brown in Figures 3b–3d) (see modeled flow fields in section 4.2). In addition, triggered by typhoon, the highly turbid water from the coast of mainland China could cross the Taiwan Strait and be further transported to the region northeast of Taiwan. Under normal condition in summer, the along-strait northward current obstructs the turbid coastal water in the western Taiwan Strait from crossing the strait and reaching the eastern Taiwan Strait [*Wu et al*., 2007]. However, as the strong winds associated with Morakot blew for >3 days, the surface current in the northern Taiwan Strait was redirected southward, as was modeled during Morakot (see section 4.2) and measured directly during typhoons Rusa and Sinlaku in 2002 [*Chen et al*., 2003]. Forced by the collision with the northward surface current in the southern Taiwan Strait, the southward turbid waters turn to the east

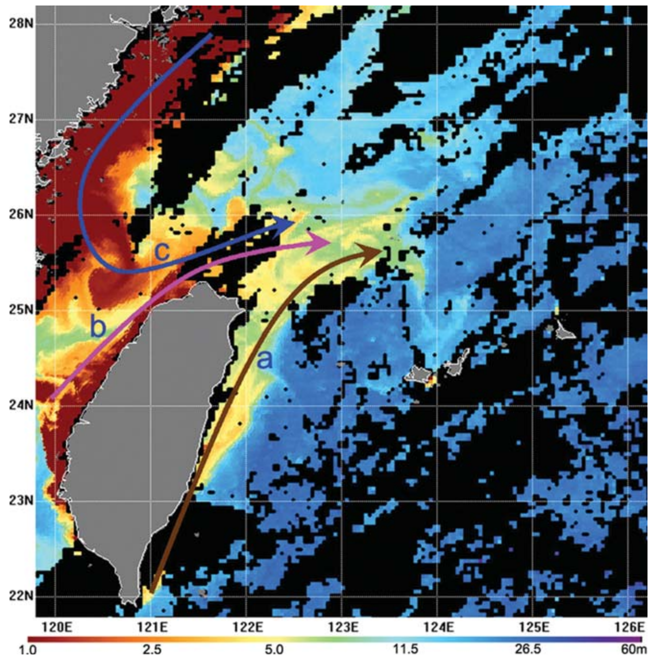

Figure 4. Schematic map of the three sources of turbid waters transported to the region off northeastern Taiwan triggered by Morakot. Shading indicates satellite-derived water transparency on 14 August 2009. (a) From the east coast of Taiwan, (b) from the west coast of Taiwan, and (c) from the coast of mainland China.

and cross the strait, and some of them can be transported further to the region off northeast of Taiwan. Such a cross-strait transport can still be clearly observed from the water transparency images obtained during 12–14 August, as shown in Figures 3b–3d, though it was 3–5 days after typhoon landing.

In summary, there are three sources for turbid waters transported to the region off northeast of Taiwan triggered by typhoon—one is from the eastern coast of Taiwan, another is from the western coast of Taiwan, and the other is from the coast of mainland China, as shown schematically in Figure 4. Carried by the Kuroshio, these turbid waters could be transported northeastward to the southern Okinawa Trough along the western edge of the Kuroshio further. Interestingly, some even crossed the Kuroshio, perhaps by eddy diffusion, as suggested by the feature resembling an eddy at (124°E, 25°N) in Figure 4.

3.2. Phytoplankton Blooms Caused by the Typhoon Morakot

In addition to the particulate material transported to the southern Okinawa Trough, nutrients might also be transported to the Kuroshio main stream, because nutrient concentrations in the outflowing water off northeastern Taiwan are increased during typhoon events [*Shiah et al*., 2000]. Combined with the upwelling off northeast of Taiwan, the supply of nutrients to the oligotrophic surface layer of the Kuroshio may have increased primary productivity and new production in the Kuroshio adjacent to the ECS shelf.

Figure 5 shows the 8 day composite chlorophyll concentration pre-Typhoon and post-Typhoon Morakot, which was retrieved by MODIS. Before the passage of Morakot, the chlorophyll concentration in the region off northeast of Taiwan was <0.5 μg/l, as shown in Figure 5a, even in the upwelling area associated with the Kuroshio subsurface water. However, after the passage of Morakot, the chlorophyll concentration was significantly increased even in regions south of the upwelling center normally found off northeastern Taiwan (Figure 5b). This high chlorophyll concentration region extended from the Taiwan Strait to the east and spreading northeastward for about 300 km along the Kuroshio path, likely reflecting the nutrient contribution from runoff or coastal waters. Even 2 weeks after the landing of Morakot (Figure 5c), the chlorophyll concentration in the region off northeastern Taiwan was still higher than the value before Morakot.

In highly turbid coastal waters, MODIS may overestimate the chlorophyll concentration due to the influences by terrestrial particulates and dissolved organic matters [*He et al*., 2013a]. For a period of typhoon visiting, it is especially difficult to validate the satellite-derived *Chl*. Since the underway *Chl* was measured by fluorescence sensor on the CTD instead of laboratory analysis, the measured *Chl* itself may contain uncertainty which prohibits us to make the validation of the satellite-derived *Chl*. Yet by assuming that the trend of the underway *Chl* is reliable, we can examine the consistency of the *Chl* trends between the satellite retrieval and underway measurement, as shown in Figure 6. Although the satellite-derived *Chl* is smaller than the underway *Chl*, the trend of satellite *Chl* retrieved by Aqua/MODIS on 19 August 2009 is consistent well with the underway *Chl*, indicating the reliability of the trends of the satellite-derived *Chl*. In addition, the *Chl* is highly dynamic after the passage of typhoon

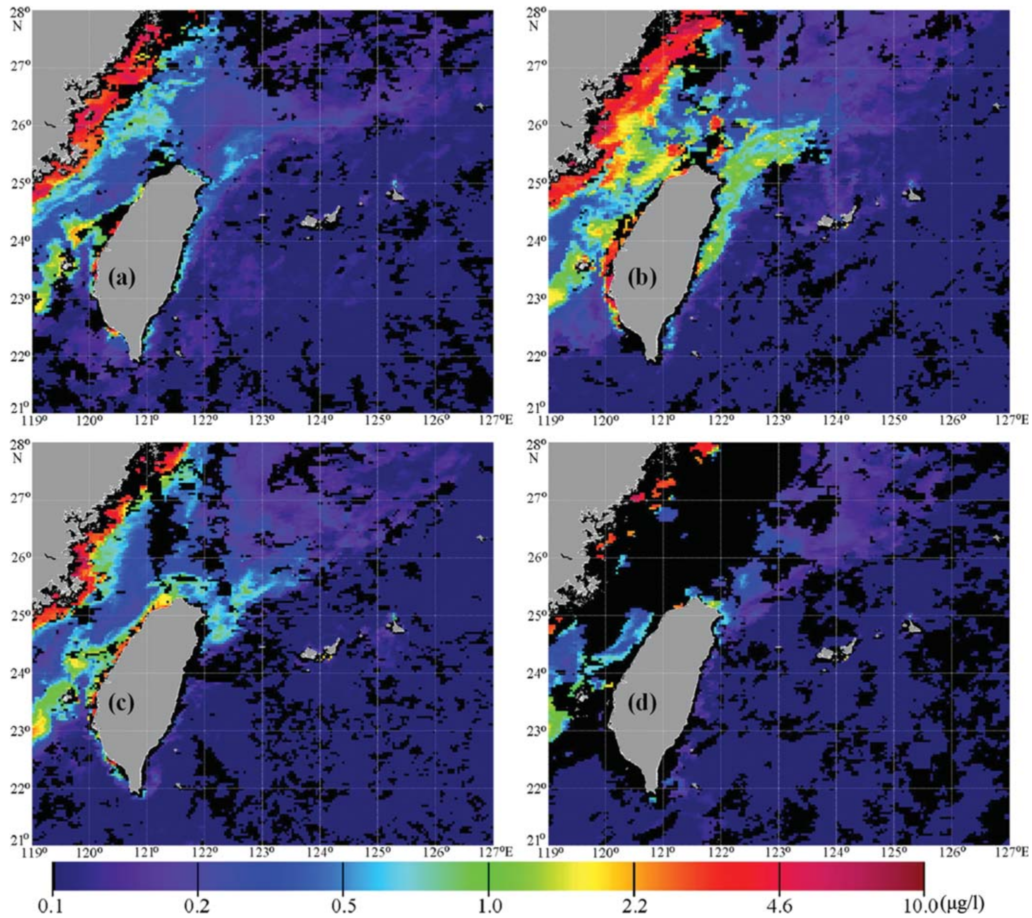

Figure 5. Satellite-retrieved 8 day composite chlorophyll concentrations pre and post-Typhoon Morakot in 2009. (a) 28 July to 4 August, pre-Morakot; (b) 13–20 August, post-Morakot; (c) 21–28 August, post-Morakot; (d) 29 August to 5 September, post-Morakot.

as revealed by the large difference of the satellite-derived *Chl* between the 2 adjacent days (Figure 6). Such high dynamic was supported by the in situ *Chl* at a fix station off northern coast of Taiwan measured by *Jan et al.* [2013], which showed the quick changes of the *Chl* with gradually increasing to 1.9 mg/m^3 on 14 August after Morakot passed, reaching a maximal level (~3.7 mg/m^3) on 18 August, and rapidly decreasing to 0.8 mg/m^3 on 19 August. Such high dynamic should explain the different patterns between Figures 5b and 2c, since Figure 5b is the 8 day composite value while Figure 2c is an instantaneous value.

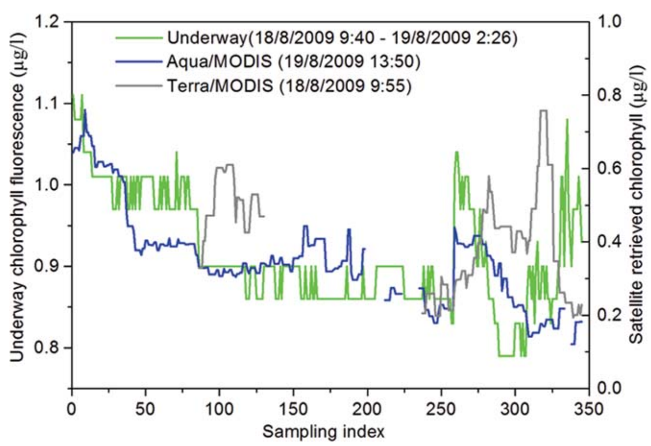

Figure 6. Comparison of the *Chl* trends between satellite retrieval and underway measurement. The sampling index represents the number of the valid samples of the underway measurement from the west to the east along the KP section (Figure 2c). The observation times are referred to the local standard time.

4. Discussion

4.1. Turbid Water off Northeast of Taiwan Contributed by Terrestrial Material Transport

It might be argued that the turbid water off northeast of

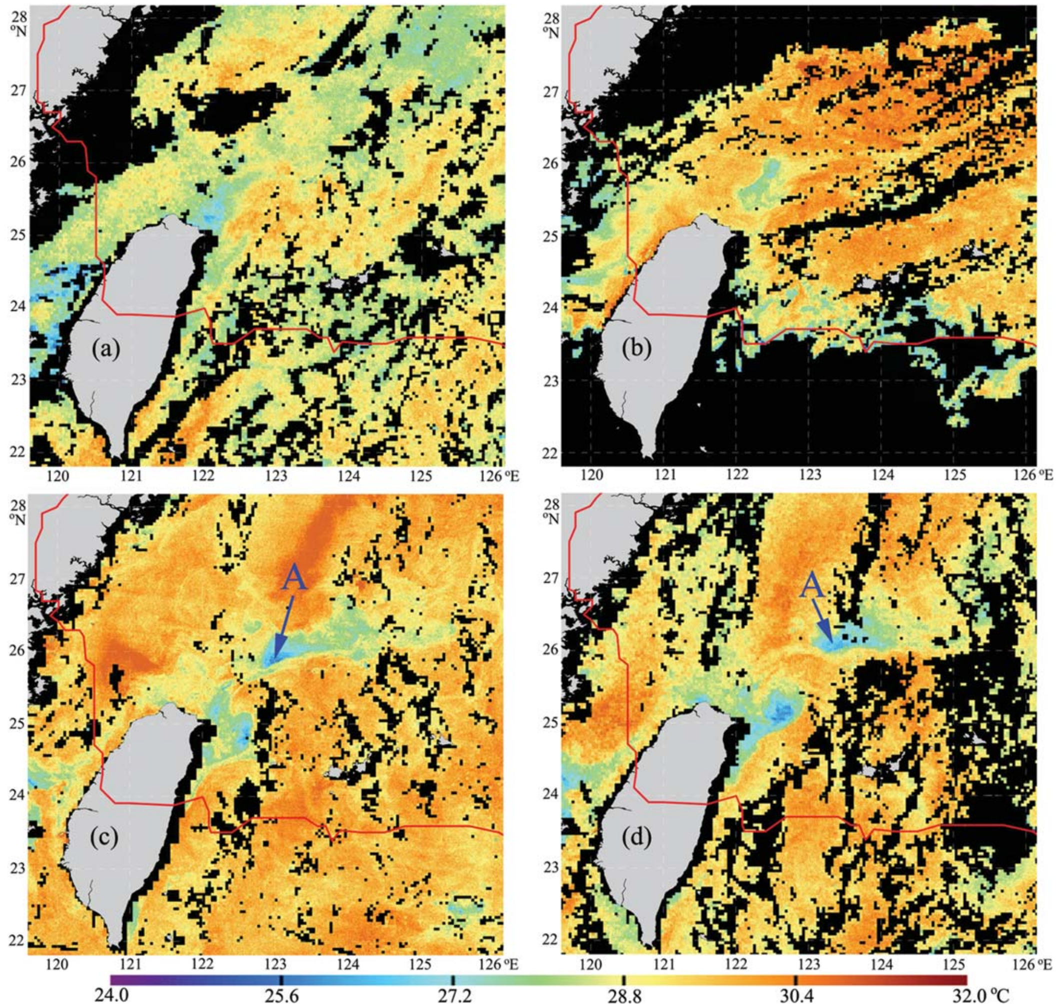

Figure 7. Satellite-retrieved daily sea surface temperature images pre and post-Morakot in 2009. The black regions are covered by clouds. The red solid line from east to west is the track of the Morakot. (a) 8:49 on 8 July, pre-Morakot; (b) 9:29 on 1 August, pre-Morakot; (c) 9:11 on 19 August, post-Morakot; (d) 8:48 on 20 August, post-Morakot.

Taiwan could have been caused by upwelling-induced phytoplankton blooms instead of terrestrial material, since phytoplankton can also reduce the water transparency through light absorption and scattering. It is well known that the subsurface Kuroshio waters upwell onto the ECS year round when the Kuroshio impinges on the continental shelf northeast of Taiwan [*Liu*, 1983; *Wong et al*., 1989; *Su et al*., 1990; *Liu et al*., 1992; *Wong et al*., 2000; *Wu et al*., 2008b; *Chen*, 2011]. Moreover, a typhoon can push the Kuroshio axis toward the shelf and thus enhance the upwelling of the Kuroshio subsurface water [*Chang et al*., 2008; *Morimoto et al*., 2009]. Based on numerical simulation, *Tsai et al*. [2008, 2013] found that typhoon provided an environment favorable for the Kuroshio intrusion onto the shelf, and the upwelling region off northeast Taiwan became colder and saltier. Similarly, the present study shows that the passage of Morakot significantly enhanced upwelling and enlarged the area of cold water off northeastern Taiwan (Figure 7). The enhanced upwelling could supply abundant nutrients and induce a phytoplankton bloom [*Tang et al*., 2002; *Lin et al*., 2003a; *Lin*, 2012], and further reduce the water transparency. However, the upwelling induced phytoplankton bloom alone could not have reduced the water transparency to <5 m off northeastern Taiwan as shown in Figure 3. Based on in situ measurement, *Jan et al*. [2013] found that the surface *Chl* reached a maximal level of 3.7 μg/l after Morakot. The satellite-derived 8 day composite *Chl* off northeastern Taiwan also showed that the *Chl* were generally <2 μg/l after Morakot's passage (Figure 5b). If there are no terrestrial particles, the water transparency should be larger than 10.6 m (corresponding to *Chl* of 3.7 μg/l) as retrieved by equation (1). Thus, the <5 m *SDD* off northeastern Taiwan after Morakot's passage (Figure 3) indicates the transportation of the terrestrial material to this region.

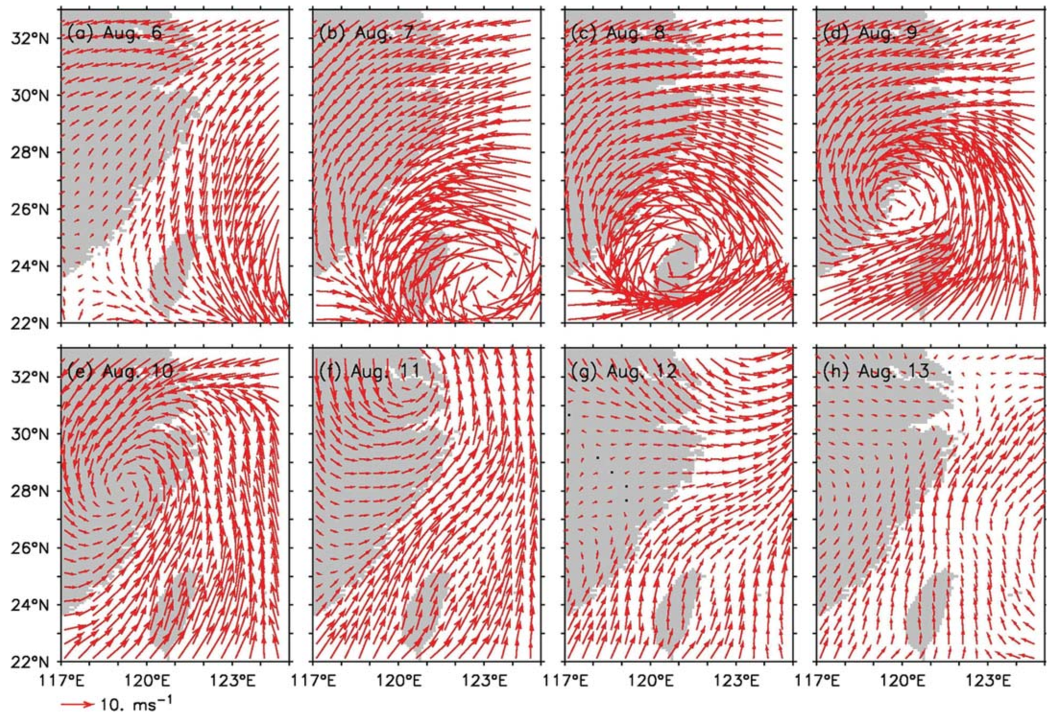

Figure 8. Daily wind fields at 10 m above sea surface during Typhoon Morakot in 2009. The subimages of Figures 8a–8h are from 6 to 13 August, respectively.

In addition, unlike the water transparency affected by multiple factors, salinity is a more direct index for identifying the fresh water associated with terrestrial material. As is well known, the upwelled Kuroshio subsurface water has higher salinity and lower temperature compared with the surrounding waters. Both the satellite-retrieved SST (Figure 7) and the underway measured temperature (Figure 2b) showed cold surface water off northeastern Taiwan after Morakot's passage, as expected. If the cold surface water was only the result of upwelling of Kuroshio subsurface water, the salinity should be higher than that of the surrounding water. However, the underway measured salinity 10 days after the passage of Morakot was still as low as 32.9 off northeastern Taiwan (Figure 2a), indicating the input of runoff or coastal water. In fact, based on the hydrographic survey off the northeastern coast of Taiwan roughly 1 week after Morakot, *Jan et al*. [2013] also observed an Ω-shaped freshwater pulse about 50 km wide off the northern tip of Taiwan. It is interesting to see the water mass with both low salinity and low temperature off the northeastern Taiwan, which might be the result of mixing between the low salinity freshwater and low temperature upwelling waters. Based on the in situ measurement about two and a half weeks after Morakot, *Jan et al*. [2013] pointed out that the major freshwater pulse left the sea off the northern and northeastern coasts of Taiwan, which might have been mixed with upwelling waters and carried by the Kuroshio to the northeast.

Moreover, the translation speed of the cold surface water off northeastern Taiwan is about 0.8 m/s, as deduced by the movement of the cold core "A" within the two adjacent days SST obtained on 19 and 20 August (Figures 7c–7d). This speed is similar with the averaged velocity of 0.77 m/s for the Kuroshio in that region measured by the high-frequency ocean surface radar system after Typhoon Hai-Tang in 2005 [*Morimoto et al*., 2009]. Such a fast motion indicates the cold water tends to drift northeastward along the western flank of the Kuroshio, and is not the manifestation of the upwelling spreading.

4.2. Cross-Strait Transport of Terrestrial Material From the Coast of Mainland China Triggered by Morakot

Figures 8 and 9 show the daily wind fields at 10 m above the sea surface and the model-simulated flow fields at a depth of 20 m during the period of Morakot (6–13 August 2009), respectively. With Morakot located around Taiwan on 6 August, the wind in the Taiwan Strait blew to the south (Figure 8a); however, the flow was still northward in the whole Taiwan Strait due to the weak wind and its short duration

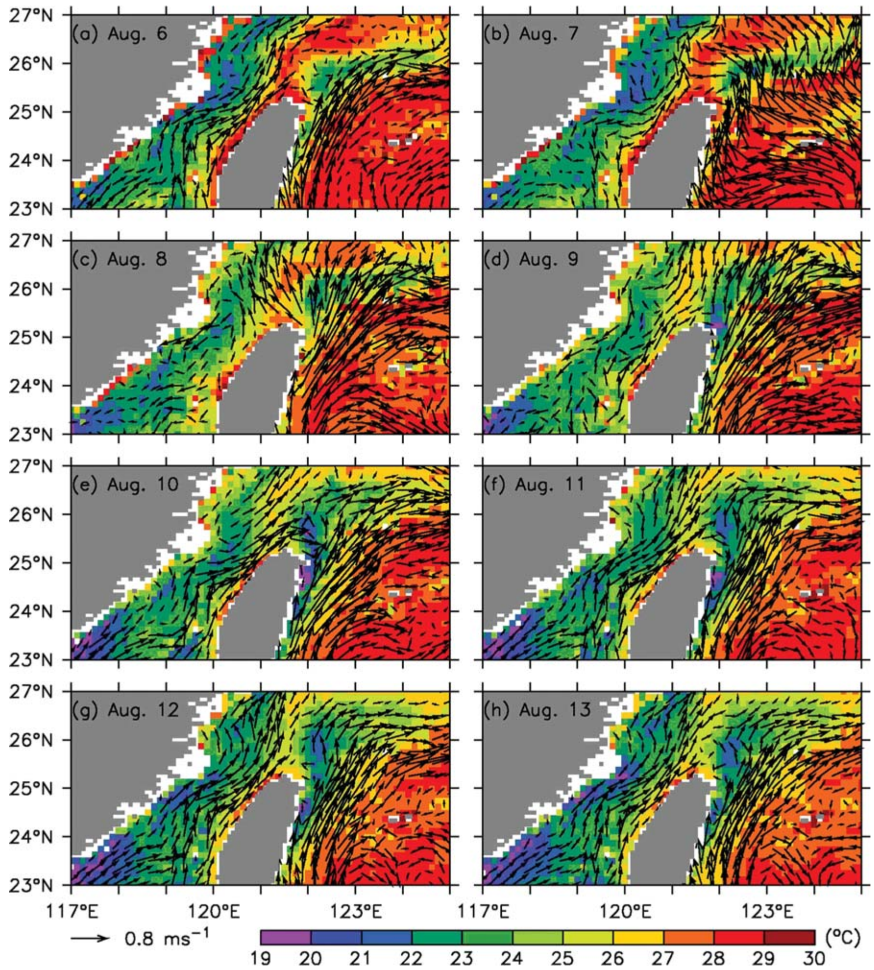

Figure 9. Model-simulated daily flow fields at the 20 m depth during Typhoon Morakot in 2009. Shading indicates water temperature at 20 m depth. The subimages of Figures 8a–8h are from 6 to 13 August, respectively.

(Figure 9a). One day later, the southward wind strengthened (Figures 8b and 8c), and turned the flow to the south (Figures 9b and 9c). The southward flow carried turbid waters and associated terrestrial material from the Zhejiang-Fujian coasts north of the Taiwan Strait to the central Taiwan Strait. On 9 August, the southward flow was still strong in the western Taiwan Strait (Figure 9d), although the wind direction had turned to the northeast (Figure 8d). As the typhoon moved further north after 10 August, the northward flows rebounded and predominated over the whole Taiwan Strait (Figures 9e–9h). Correspondingly, the southward terrestrial materials transported from the Zhejiang-Fujian coasts during 7–8 August were blocked and transported to the north again. Carried by the northeastward flow in the northern Taiwan Strait as shown in Figures 9e–9h, these terrestrial materials crossed the strait and could be transported farther to the region northeast of Taiwan. Overall, the model results are consistent with the satellite observed cross-strait transport as shown in Figure 3.

Trajectories of particles released lend further support for the cross-strait transportation of materials that is directly observed by satellite as shown in Figure 3. Figure 10a shows the trajectories of particles released between 120.0°E and 120.5°E along 26°N on 5–9 August. After released, particles first moved southward carried by the southward typhoon-induced flows, indicating that the particles from the Zhejiang-Fujian coasts entered the central Taiwan Strait. These particles arrived in the central Taiwan Strait could be further transported to the region off the northeastern Taiwan by the northeastward current after the typhoon leaves. Figure 10b shows the simulated trajectories of particles released between 119.5°E and 120°E along 24.5°N on 7–9 August. After released, particles first moved southward, and then turned to the north 1–3 days later. The particles released after 10 August moved northward directly. This outcome indicates that the

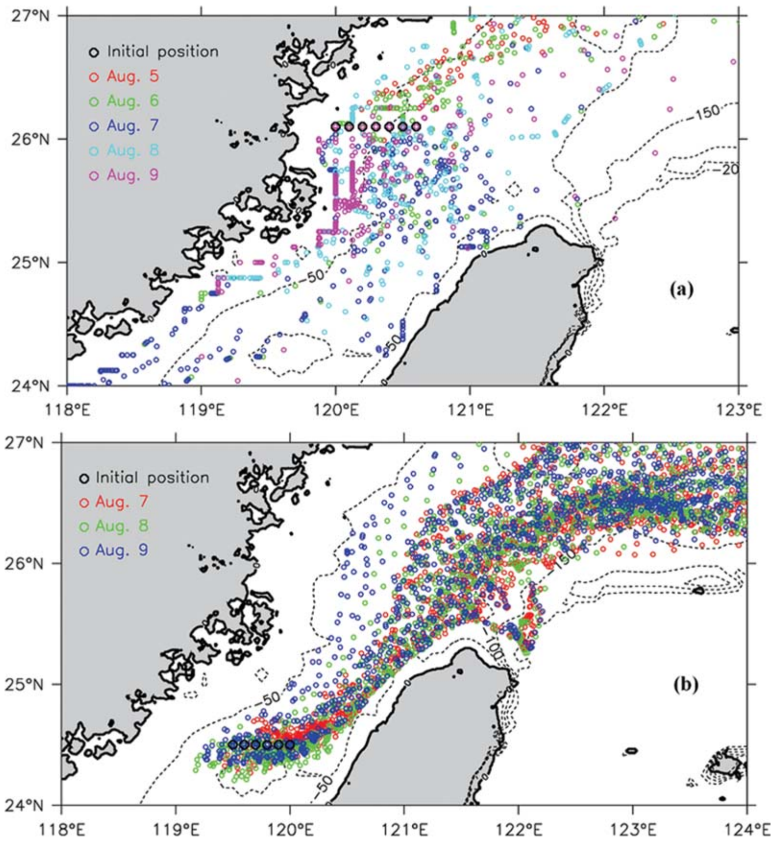

Figure 10. Model-simulated trajectories of particles released (a) between 120°E and 120.5°E along 26°N on 5–9 August and (b) between 119.5°E and 120°E along 24.5°N on 7–9 August.

particles were blocked in the central Taiwan Strait during 7–9 August when the flows were forced southward by Morakot. Afterward, most particles flowed directly to the ECS shelf, but some of them arrived at the region off northeastern Taiwan, implying that the cross-strait transported material from the coast of mainland China is one of the sources for the terrestrial material transported to the region off northeastern Taiwan during typhoon events. During the transportation, the sand and coarse silt particles should deposit rapidly after the passage of Morakot, yet the clay and fine silt particles and dissolved nutrients can remain in suspension and be transported to a long distance. In the east coasts of the Australia, *Bainbridge et al*. [2012] found that fine sediment particles could be carried to a distance at least 100 km within the river plume 10 days after the flood peak.

Concerning cross flows in the Taiwan Strait, it is a typical feature that the southward China Coastal Current can turn in the Taiwan Strait to join the poleward-flowing Taiwan Coastal Current in winter. The associated cross flows are observed from hydrographic data [*Jan et al*., 2002] as well as model simulations [*Wu et al*., 2007]. In fact, biological data also suggest a cross-strait drift of Calanu sinicus (Copepoda, Crustacea) by the surface currents, some 100–200 km across the Taiwan Strait in winter-early spring [e.g., *Hwang et al*., 2006]. Dynamically, the cross flows in winter are caused by the northeaster monsoon wind relaxation. The northeast monsoon piles up waters downwind and the consequent Rossby adjustment drives the cross flows after the wind relaxes. In the present study, the typhoon in summer serves as the role of northeaster monsoon during wintertime. After Morakot's departure, the storm moves farther north and the northerly wind relaxes, which generates a cross flow to join the northward-flowing Taiwan Coastal Current. In addition to substantial support from satellite observations (this study), the posttyphoon appearance of the cross flow suggested by our model is also consistent with theoretical expectations.

4.3. Transportation of the Terrestrial Material to the Southern Okinawa Trough Caused by Morakot

Based on the trajectories of the Surface Velocity Program (SVP) drifters released in the northern Taiwan Strait and off the northern coast of Taiwan about 1 week after Morakot (13–17 August 2009), *Jan et al*. [2013] found that the drifters associated with the freshwater pulse off the northern coast of Taiwan drifted into the Kuroshio, and suggested that the majority of the typhoon triggered freshwater pulse off the northern coast of Taiwan moved anticyclonically along the northern coast of Taiwan and then was carried by the Kuroshio to the northeast as time evolved. In addition, they reported that 1 month after Morakot, Japanese fishermen caught Taiwanese freshwater grouper, which is usually farmed along the western coast of Taiwan, in the waters around Okinawa. Carried by the Kuroshio, the typhoon-induced terrestrial materials off

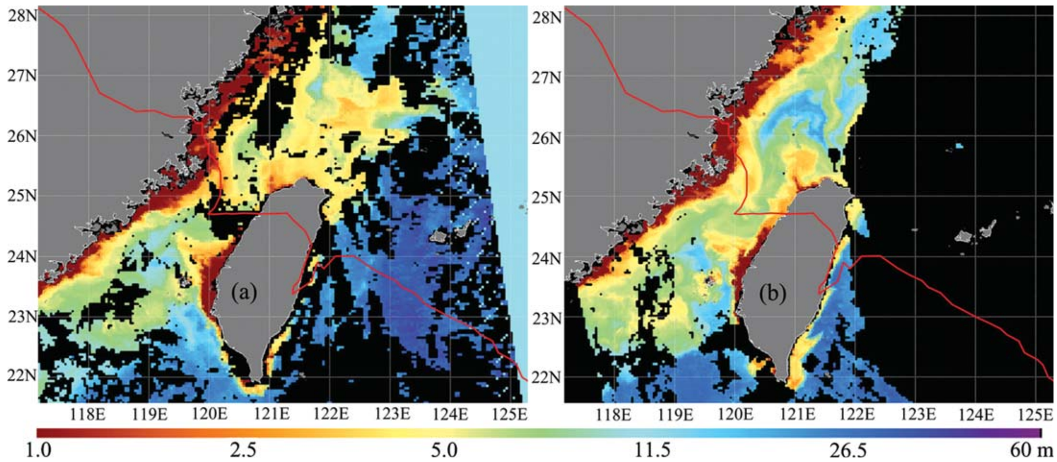

Figure 11. Satellite-derived daily water transparency images after the passage of the Typhoon HaiTang in July 2005. (a) 13:40 on 23 July 2005; (b) 13:28 on 25 July 2005. The black regions are covered by clouds or sun glints. The red solid line from east to west is the track of the HaiTang.

northeastern Taiwan turbid waters could be transported north-eastward along the west slope of the southern Okinawa Trough. Although these terrestrial materials in the surface layer are hardly across the strong and broad Kuroshio Current, the particles may settle under the effect of gravity during the journey. These deposited particles on the slope can be further transported to the trough basin by gravitational forcing under long-time scale [*Fan et al*., 2004], perhaps mainly through the submarine canyon conduits [*Liu et al*., 2006]. In fact, the observed sedimentation rates in the southern Okinawa Trough reach 0.10–0.95 cm yr^{-1} [*Chung and Chang*, 1995], which is >10 times larger than those observed in the northern and central troughs (<0.01–0.08 cm yr^{-1}) [*Ikehara*, 1995]. This is consistent with the satellite observation herein that typhoon-triggered terrestrial material enters the Okinawa Trough.

Based on the biomarkers in surface sediments lying on the bottom of the shelf along two transects in the ECS, one from northeast of the Changjiang estuary southward along the coast, the other from the mouth of the Changjiang River and reaches the western edge of the Okinawa Trough (along the so-called PN line), *Zhu et al*. [2008] concluded that part of the terrestrial material transported southward along the Chinese coast turning eastward, passing the northern tip of Taiwan, and then turning around and joining the northwardly flowing Kuroshio, and finally depositing near the shelf break. These conclusions are consistent with our results drawn from Figure 3.

The discussion of the flux of the terrestrial material transported off northeastern Taiwan is somewhat speculative since satellite remote sensing can only observe the surface layer water. Based on the cruise data about 1 week after the passage of Typhoon Morakot, *Jan et al*. [2013] found that the estimated volume transport of the freshwater pulse (with salinity <33) off the northern coast of Taiwan was 0.3×10^6 m^3/s. If we assume a mean *SPM* of 3.0 mg/l (corresponding to SD of 5 m under *Chl* of 3.7 μg/l which is the maximum *Chl* observed by the cruise data of *Jan et al*. [2013]), then the estimated flux of the terrestrial particles transported off northeastern Taiwan is about 0.54 Mt within 1 week. Since there are on average 3.7 typhoons passing across or near Taiwan every year [*Huang et al*., 2011], the total transportation flux per year triggered by typhoons could be up to 2.0 Mt, which is about 27% of the total SPM discharge (~7.5 Mt) of the Minjiang River, the largest river inputting the southern ECS (Figure 2) [*Liu et al*., 2009].

4.4. Can Other Typhoon-Triggered Terrestrial Material Transport as Morakot?

Typhoon HaiTang in July 2005 has a similar track with Morakot across the Taiwan Strait (Figure 11). It was a strong typhoon with maximum wind speed of 60 m/s, and crossed the Taiwan Strait from its landfall on the east of Taiwan Island on 18 July 2005 [*Chang et al*., 2008]. HaiTang had significant impacts on the oceanic environment in the southern ECS, such as enhancing the upwelling of the Kuroshio subsurface water and phytoplankton bloom [*Chang et al*., 2008; *Morimoto et al*., 2009]. From the cloudless satellite-derived water transparency just after the passage of HaiTang (Figure 11), we can see the similar distribution of the turbid waters around the Taiwan Island and along the coast of Mainland China with that of Morakot. Although

HaiTang is much more powerful than Morakot, the area of turbid waters triggered by HaiTang is much smaller than that of Morakot, as inferred from the satellite-derived water transparency images on 23 July, 2005 and 14 August 2009 with both of them corresponding to 5 days after the passage of typhoons. The smaller areas of turbid waters along the both sides of the Taiwan Island might be caused by the less rainfall of HaiTang as compared to Morakot which brought huge runoff with record-breaking rainfall of 2900 mm over 3 days in the southern Taiwan and triggered high sediment discharge in Taiwanese rivers. Nevertheless, the turbid waters off northeast of Taiwan triggered by HaiTang can still be seen clearly, which might be further carried by the Kuroshio and transported north-eastward along the west slope of the southern Okinawa Trough.

In addition, similar cross-strait transportation of turbid water was found in the northern Taiwan Strait from the coast of mainland of China during the passage of HaiTang. Yet as compared with Morakot, the cross-strait transportation induced by HaiTang is weaker. The difference may be due to the translation speed of typhoon and its cross-strait time. HaiTang spent about 30 h to cross the Taiwan Strait, while it took about 40 h for Morakot. Although Morakot was a relatively weak typhoon, its very slow translation speed ($\sim$10 km/h) across the Taiwan Strait and the associated southward winds were strong enough to halt and even reverse the prevailing northward surface current in the Taiwan Strait, which induced the episodic cross-strait transport.

5. Conclusions

Based on the unique advantage of satellite remote sensing with daily observing capacity, the terrestrial materials transported by Typhoon Morakot-induced winds to the region off northeast of Taiwan were identified by a time series of satellite-derived water transparency images. Three sources were identified: one is from the eastern coast of Taiwan, another is from the western coast of Taiwan, and the other is from the coast of mainland China. During Morakot's passage, terrestrial material from the coast of mainland China could cross the Taiwan Strait and be further transported to region off northeast of Taiwan. Also, terrestrial material from both sides of Taiwanese coasts was transported to northeast of Taiwan carried by the northward flows. Furthermore, these terrestrial materials off northeastern Taiwan could then be transported northeastward to the southern Okinawa Trough along the western edge of the Kuroshio, which could be another source of mud in the Okinawa Trough. In addition, nutrients might also be transported to the Kuroshio main stream, and significant phytoplankton blooms were observed along the Kuroshio's path for about 300 km off northeastern Taiwan.

Presently, exact estimating the fluxes of terrestrial material transported to the Okinawa Trough due to typhoon events is difficult because satellite data can only reflect surface conditions. Also, quantifying the percentages of terrestrial material transported to the Okinawa Trough from the three sources triggered by typhoon events is especially important for the study of biogeochemical processes in the ECS. More in situ observations and modeling simulation should be carried out in the future to quantify these fluxes.

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