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ABSTRACT

Typhoon-enhanced primary production (PP) in the ocean has long been neglected, as it is a big challenge to estimate such PP due to the lack of ocean color data obscured by clouds and rainfall that accompany typhoons and complicated biological responses. In this study, we developed a statistical approach, based on all the typhoons passing though the South China Sea (SCS) and the Western North Pacific Subtropical Ocean (WNPSO) during 2003 and 2012. We then estimated the annual and interannual carbon fixation induced by typhoons in the SCS and the WNPSO. The annual mean carbon fixation due to typhoons in the whole SCS was estimated to be approximately 2.716 ± 0.304 Mt (1 Mt$=10^{12}$ g), equivalent to 5–15% of the new PP of the SCS. This suggests that typhoons contribute to the biological carbon fixation in the SCS. In terms of the WNPSO, the annual mean carbon fixation due to typhoons was only about 2.112 ± 0.640 Mt, although the area is much larger and super typhoons occur more frequently. The main reason for the smaller value in the WNPSO is that the cold nutrient-rich water is more difficult to be brought to the upper layer to support the growth of phytoplankton due to thicker mixed layer depth and deeper nutricline depth in the WNPSO in comparison with those in the SCS. In addition, typhoon-enhanced PP tended to be higher in the El Niño years in the WNPSO due to increased occurrence of super typhoons, while it was lower in the La Niña years. However, no obvious relationship with El Niño-Southern Oscillation (ENSO) was found in the SCS during the study period.

1. Introduction

Typhoons (also referred to as hurricanes or tropical cyclones) can enhance primary production (PP) in open oceans and coastal waters (e.g., Lin et al., 2003, Lin, 2012; Babin et al., 2004; Siswanto et al., 2007, 2009; Zheng et al., 2010a; Hung et al., 2010, Hung and Gong, 2011; Mei. et al., 2015). In the oligotrophic open ocean, vertical mixing and upwelling induced by typhoons (Price, 1981; Chen et al., 2003) can bring nutrients from a deep layer to the surface layer to support the growth of phytoplankton. Lin et al. (2003) reported that the contribution of typhoons to the annual new PP of the South China Sea (SCS) may be as much as 20–30%. In coastal waters, nutrients can also come from terrestrial input as river discharges increase due to heavy rainfall during typhoon passages (Hung et al., 2013). As a result, excessive nutrients brought by typhoons may be responsible for enhanced eutrophication in coastal waters, which may further trigger excessive algal blooms or red tides, causing hypoxia and other environmental problems (e.g., Zhou et al., 2012; Ernawaty et al., 2014). Therefore, the biogeochemical effects of typhoons on marine ecosystems cannot be neglected in open oceans and coastal waters.

How to quantify these biogeochemical changes (such as nutrients, PP) induced by typhoons, however, remains a big challenge. The reason is the difficulty in obtaining ship measurements due to bad weathers. Further, ocean color data are most likely unavailable as satellite observations are often obscured by clouds and rainfall that accompany typhoons. Since satellites can not measure nutrient concentrations at present, we have focused on PP in this study. The Vertically Generalized Production Model developed by Behrenfeld and Falkowski (1997) is often used to estimate PP enhancement (Lin et al., 2003, Lin, 2012; Mei. et al., 2015). However, this method can only be applied to the cases

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when ocean color data are available. Others developed empirical algorithms, such as the algorithm by Siswanto et al. (2007), which relates typhoon-enhanced PP to the parameters of the maximum sustained wind speed, typhoon translation speed, and ocean depth in the outer shelf of the East China Sea. Although the aforementioned studies attempted to give quantitative results of typhoon-induced PP, the uncertainty was great as most of these results were evaluated based on a single typhoon event (Lin et al., 2003) or on a few limited cases (Siswanto et al., 2007; Lin, 2012). Also, the estimation method might be not applicable to other regions, as noted by Siswanto et al. (2007).

In this study, we investigate all the typhoons passing through the SCS and Western North Pacific Subtropical Ocean (WNPSO) with the most active typhoons in the world during 2003 and 2012. We develop a statistical approach, which can be used to estimate typhoon-induced PP enhancement even if the ocean color data is not available in some typhoon cases. Then, we investigate the interannual variations of the annual production induced by all typhoons in the SCS and WNPSO during 2003 and 2012 based on the newly developed algorithm. The contributions of all typhoons to PP are assessed in the SCS and WNPSO, respectively. Finally, we attempt to identify the possible factors that control the ocean biological responses to typhoons in the SCS and WNPSO.

2. Data and methods

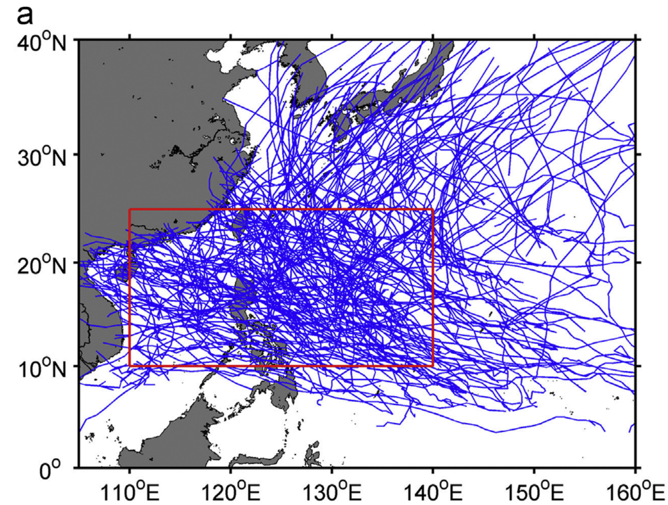
2.1. Study area

The tracks of all typhoons (TS–C5, according to the Saffir–Simpson Scale) passing through the Western North Pacific during 2003 and 2012 are shown in Fig. 1a. The most frequently visited area of 10°N–25°N, 110°E-140°E (red rectangle in Fig. 1a and b) is chosen as our study area, which covers most of the SCS and the WNPSO, where most frequent, intense typhoons among the world's oceans are found (Lin et al., 2003, Lin, 2012; Camargo and Sobel, 2005; Chen et al., 2012).

The study area is then subdivided into small sub-regions of 5° by 5°. There are six bins (S1–S6) in the SCS and 11 bins (W1–W11) in the WNPSO (Fig. 1b). The number in the parentheses represents the total number of typhoons passing through each bin during 2003 and 2012. It is found that S4 and N6 (marked in red in Fig. 1b) are the sub-regions with the most frequently visited typhoons in the SCS and WNPSO, with the total numbers of 36 and 41, respectively. For these two sub-regions of S4 and N6, the annual carbon fixation induced by typhoons is evaluated.

2.2. Data

Due to the inherently intense cloud cover and rainfall during a typhoon, we have to use MODIS 8-day composite level-3 chlorophyll-*a* (Chl-*a*) data to investigate ocean biological responses due to the passages of these typhoons. The data were obtained from the NASA ocean color website (http://oceancolor.gsfc.nasa.gov/), which has a spatial resolution of 9 km. Net primary production (NPP) data with the same resolution of Chl-*a* data were provided by the Ocean Productivity website (http://www.science.oregonstate.edu/ocean. productivity/), which were calculated by using the VGPM (Behrenfeld and Falkowski, 1997). Daily composite sea surface temperature (SST) data with a spatial resolution of 0.25° from TMI and AMSR-E were used to investigate surface cooling induced by typhoons (Price, 1981; Sakaida et al., 1998; Cione and Uhlhorn, 2003; Tsai et al., 2008). Unlike the ocean color data, the microwave SST data were seldom influenced by cloud cover and rainfall (Wentz et al., 2000). The data were downloaded from the Remote Sensing Systems (http://www.remss.com/).



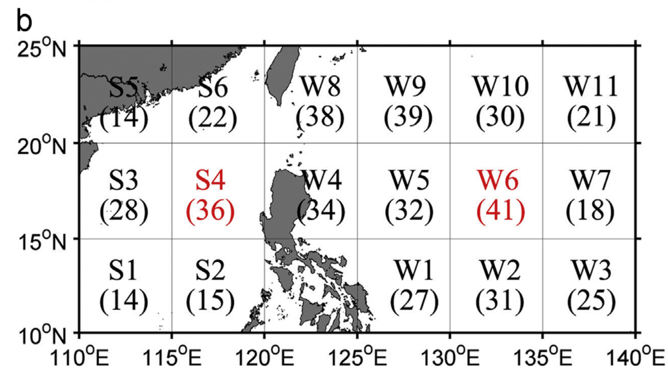


Fig. 1. (a) The tracks of all typhoons (TS–C5, according to the Saffir–Simpson Scale) passing through the Western North Pacific during 2003 and 2012. (b) The sub-regions of size 5° × 5°. There are six sub-regions (S1–S6) in the SCS and 11 sub-regions (W1–W11) in the WNPSO. The number in the parentheses represents the total number of typhoons passing through the sub-region. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

Climatological monthly mixed layer depth (MLD) and annual mean nitrate data were obtained from the World Ocean Atlas 2009 (http://www.nodc.noaa.gov/OC5/ WOA09/pr_woa09.html) (Garcia et al., 2010), which is a set of objectively analyzed climatological fields of in situ temperature, nitrate, and other fields at standard depths. The spatial resolutions of MLD and nitrate data are 2° and 1°, respectively. In this paper, the MLD data in February, May, August, and November are used to represent water stratification in winter, spring, summer, and fall of the Northern Hemisphere, respectively. In order to illustrate the nutrient distribution in the upper layer, the annual mean nitrate data at depths of 0, 30, 50, and 100 m were selected. The Multivariate ENSO Index (MEI; Wolter and Timlin, 2011) was downloaded from the website (http://www.esrl.noaa.gov/psd/ people/ klaus.wolter/ MEI/table.html) and used to investigate the relationship between typhoon frequency and ENSO cycle (Siswanto et al., 2007). During the study period of 2003–2012, there were three El Niño events (2004, 2006 and 2009) and two La Niña events (2007 and 2010).

The typhoon track data used in this study were downloaded from the Unisys Weather Web site (http://weather.unisys.com/hurricane), which is based on the best hurricane track data from the Joint Typhoon Warning Center (JTWC). The data include typhoon center position in latitude and longitude, time (in UTC), maximum sustained wind speed and typhoon scale according to the Saffir–Simpson scale every 6 h. The average maximum sustained wind speed and translation speed along the typhoon track are used to study their relationships with typhoon-enhanced PP.

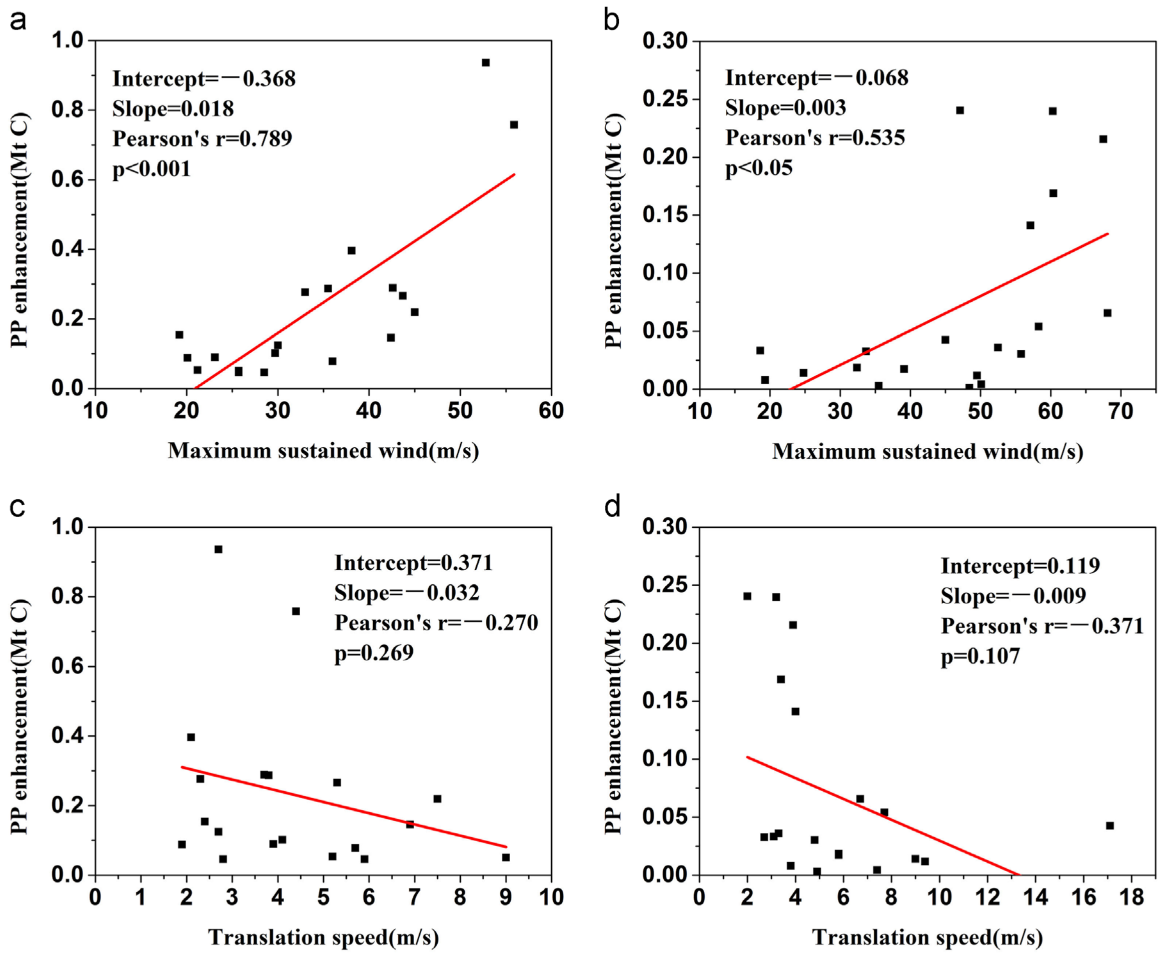


Fig. 2. (a,b) Correlations of PP enhancement and maximum sustained wind in S4 and W6, respectively. (c,d) Correlations of PP enhancement and translation speed in S4 and W6, respectively.

2.3. A statistical approach

The maximum sustained wind and translation speed have been shown to be the major factors affecting typhoon-induced ocean responses (Siswanto et al., 2007; Mei. et al., (2015)). In order to estimate typhoon-induced PP enhancements, we first consider the relationships between PP enhancement and these two factors. The PP enhancements were significantly correlated with the maximum sustained wind speed in both S4 (r=0.789, $p < 0.001$) and W6 (r=0.535, $p < 0.05$) (Fig. 2a and b). Althoughit seems that PP enhancement was negatively correlated with translation speed, the relationship was not statistically significant in both sub-regions ($p > 0.1$) (Fig. 2c and d). The above results reveal the dominance of maximum sustained wind speed in determining PP enhancement in our study area. Thus, we will estimate typhoon-induced PP enhancement by only considering typhoon intensity.

If the Chl-*a* data in the study area were not missing before and after the passages of these typhoons, the overall PP enhancement could be easily obtained by the sum of the PP enhancement induced by each typhoon. However, the missing data is not avoidable. Therefore, we establish a statistical approach in this study to estimate typhoon-enhanced PP when the data is not available. First, we calculate the 8-day-averaged PP of the two sub-regions of S4 and W6 before and after the passages of typhoons. Then, we partition the typhoons to different scales according to the Saffir–Simpson Scale and calculate the average PP enhancements of typhoons with different scales. Note that the typhoon scale here means the maximum scale when it passed through the sub-region rather than the maximum scale during its lifetime. Finally, we construct the annual total PP enhancement E using

$$E = \sum \Delta Npp_i \times A_i \times D + \sum N_{c_j} \times \Delta Tpp\_AVG_{c_j} \quad (1)$$

where $\Delta Npp_i$is the averaged PP enhancement of the bloom area when the Chl-*a* data is available, A_i is the bloom area which is defined to be the area of the averaged PP enhancement over 50 mg C/m^2/d in this paper, D is assumed to be eight days in this paper because of the temporal resolution of the data we used, c_j represents the typhoon scale, N_{c_j} is the number of typhoons with scale c_j passing through the sub-region when the Chl-*a* data is missing, $\Delta Tpp\_AVG_{c_j}$ is the averaged total 8-day PP enhancement induced by the typhoons of scale c_i with available Chl-*a* data after their passages. As typhoons could also induce surface cooling and increase Chl-*a* concentration, the corresponding averaged ΔSST and ΔChl-*a* are also given in this paper.

To ensure the reliability of these results, two criterions are applied. First, the typhoon is excluded if the MODIS 8-day Chl-*a* data were severely affected by clouds or rainfall after its passage. Second, if two typhoons passed through the sub-region within eight days, we classify them as one event because the temporal resolution of the PP data used is eight days. Therefore, although there were 36 typhoons passing through S4 during 2003 and 2012, the MODIS Chl-*a* data were available only for 19 events after excluding 14 typhoons due to the unavailability of Chl-*a* data after their passages and classifying three pairs of typhoons (Cimaron/Chebi, Nalgae/Nesat and Imbudo/Koni) as three events according to the second criterion (Table 1). Similarly, only 20 events were

Table 1
The typhoons passing through S4 during 2003 and 2012. The typhoons are arranged by descending order based on typhoon scale, and listed after applying the two principles in Section 2.3.

No.	Time	Typhoon name	Typhoon scale*	Translation speed (m/s)	Maximum wind speed (m/s)	ΔSST (°C)	ΔChl-*a* (mg/m^3)	Bloom area (m^2)	Daily averaged PP (mg C/m^2/d)	Total 8-day production (Mt C)
1	2006.05	Chanchu	C4	4.4	55.9	−3.84	0.159	2.34e+11	405.23	0.758
2	2010.10	Megi	C4	2.7	52.8	−3.27	0.507	2.26e+11	517.01	0.936
3	2012.12	Bopha	C3	3.7	42.6	−1.54	0.083	2.30e+11	157.07	0.289
4**	2006.11	Cimaron/ Chebi	C3/C1	2.1/5.5	38.1/39.6	−1.33	0.032	2.55e+11	193.96	0.396
5**	2011.09	Nalgae / Nesat	C3/C2	3.8/5.1	35.5/38.0	−2.78	0.110	1.88e+11	190.82	0.287
6**	2003.07	Imbudo/ Koni	C2/C1	7.5/3.6	45.0/24.4	−2.42	0.055	2.46e+11	111.05	0.219
7	2004.12	Nanmadol	C2	5.3	43.7	−0.74	0.136	1.66e+11	200.16	0.267
8	2009.05	#2	C2	6.9	42.4	−0.32	0.083	1.53e+11	119.08	0.146
9	2003.08	Krovanh	C1	5.7	36.0	−1.34	0.068	1.01e+11	96.42	0.078
10	2004.06	Conson	C1	2.8	28.5	−0.82	0.036	5.60e+10	103.24	0.046
11	2007.11	Peipah	C1	2.3	33.0	−0.75	0.113	1.90e+11	182.24	0.277
12	2008.05	#5	C1	2.7	30.0	−0.52	0.058	1.26e+11	123.18	0.124
13	2003.05	Linfa	TS	1.9	20.1	−1.09	0.036	9.62e+10	114.72	0.088
14	2008.06	#7	TS	4.1	29.7	−1.47	0.040	1.23e+11	103.33	0.102
15	2008.11	#24	TS	3.9	23.1	−1.06	0.031	1.16e+11	96.43	0.089
16	2009.06	#3	TS	2.4	19.2	−1.34	0.081	1.27e+11	151.37	0.154
17	2009.09	#16	TS	5.2	21.2	−0.97	0.050	7.45e+10	89.22	0.053
18	2010.07	Conson	TS	5.9	25.7	−0.67	0.028	6.84e+10	84.68	0.046
19	2011.07	Nock_ten	TS	9.0	25.7	−0.97	0.030	7.63e+10	83.2	0.051

* The typhoon scale is the maximum scale when it passed through S4 rather than the maximum scale during its lifetime.
** These two typhoons passed through S4 within eight days; so they are classified as one event.

Table 2
The typhoons passing through W6 during 2003 and 2012. The typhoons are arranged by the descending order based on typhoon scale, and listed after applying the two principles in Section 2.3.

No.	Time	Typhoon name	Typhoon scale*	Translation speed (m/s)	Maximum wind speed (m/s)	ΔSST (°C)	ΔChl-*a* (mg/m^3)	Bloom area (m^2)	Daily averaged PP (mg C/m^2/d)	Total 8-day production (Mt C)
1	2003.11	Lupit	C5	3.9	67.5	−2.37	0.069	2.07e+11	129.91	0.215
2	2003.10	Ketsana	C4	2.0	47.1	−2.96	0.093	1.74e+11	172.33	0.241
3	2004.04	Sudal	C4	3.2	60.3	−1.87	0.051	2.35e+11	127.38	0.240
4**	2004.10	Tokage/ Nock_ten	C4/C3	4.0	57.1	−2.52	0.069	1.26e+11	139.76	0.141
5	2005.04	Sonca	C4	4.8	55.8	−0.40	0.027	4.96e+10	76.43	0.030
6	2008.05	#3	C4	6.7	68.1	−1.86	0.018	1.04e+11	78.92	0.066
7	2008.05	#6	C4	3.3	52.5	−1.32	0.034	4.52e+10	99.63	0.036
8	2009.05	#1	C4	7.7	58.3	−1.23	0.017	8.57e+10	78.71	0.054
9	2009.10	#22	C4	3.4	60.4	−1.83	0.052	1.79e+11	118.19	0.169
10	2007.05	Yutu	C3	4.9	48.4	−0.75	0.001	2.94e+9	58.45	0.001
11	2007.07	Man_yi	C3	9.4	49.5	−1.79	0.018	2.30e+10	64.45	0.012
12	2010.10	Megi	C3	7.4	50.1	−0.61	0.013	8.22e+9	65.87	0.004
13	2003.08	Dujuan	C2	5.8	39.1	−0.63	0.024	3.05e+10	71.03	0.017
14	2006.07	Kaemi	C2	17.1	45.0	−0.26	0.023	6.62e+10	80.28	0.042
15	2006.09	Shanshan	C2	2.7	33.7	−1.02	0.027	5.25e+10	77.74	0.033
16	2005.09	Khanun	C1	5.8	32.4	−0.45	0.033	3.12e+10	72.81	0.019
17	2011.09	Nalgae	C1	4.9	35.5	−0.27	0.013	6.24e+9	64.20	0.003
18	2004.05	Omais	TS	3.1	18.6	−1.87	0.022	5.22e+10	79.93	0.033
19	2008.08	#13	TS	9.0	24.8	−0.46	0.020	2.65e+10	65.95	0.014
20	2010.05	Omais	TS	3.8	19.3	−0.02	0.017	1.68e+10	58.98	0.008

* The typhoon scale means the maximum scale when it passed through W6 rather than the maximum scale from its generation to its landfall.
** These two typhoons passed through W6 within eight days; so they are classified as one event.

available for W6 after excluding the 19 typhoons according to the first criterion and classifying one pair of typhoons (Tokage/ Nock_ten) as one event according to the second criterion (Table 2). The averaged total PP enhancements of typhoons with different scales were derived using all the selected typhoons in S4 and W6, respectively. Then, the annual total PP enhancements were calculated using Eq. (1) and all the selected typhoons passing through S4 and W6 during each year of 2003–2012.

3. Results and discussion

3.1. Typhoon-induced PP enhancement in the SCS

The typhoons passing through S4 in the SCS during 2003 and 2012 are shown in Table 1. They are arranged by the descending order based on the typhoon scale. Table 1 shows that the maximum scale of typhoons passing through S4 was Category 4 (C4). If we define the typhoon with a scale C4 or C5 as a super typhoon, there were two super typhoons, Chanchu in May 2006 and Megi in

October 2010. Both of them lingered in S4 for almost three days and caused the averaged SST to decrease by more than 3 °C. At the same time, the total 8-day PP enhancement which is calculated based on the bloom area and the daily averaged PP triggered by typhoons is also shown in Table 1. The total 8-day PP enhancement reached 0.758 Mt C (1 Mt$=10^{12}$ g) of Chanchu and 0.936 Mt C of Megi although the increments of the average Chl-*a* concentration between them were quite different (Table 1). In fact, these two cases were investigated before (Fu et al., 2009; Chen et al., 2012) as they were among the most intense typhoons reaching the SCS during the last decade. Fu et al. (2009) found that the maximum drop of SST was up to 7 °C and the averaged Chl-*a* concentration increased over 20%. Chen et al. (2012) investigated the large phytoplankton bloom induced by Typhoon Megi in October 2010 and reported the maximum Chl-*a* concentration increased about 30 times along the typhoon track in the SCS after the typhoon passage in comparison with the climatology. However, they mainly focused on the changes of SST and Chl-*a* concentration. In this study, we are mainly concerned about the PP enhancement induced by typhoons. The averaged total PP enhancement of super typhoons was 0.847 ± 0.126 Mt C (Table 3). In addition, although the total PP enhancement varied greatly from typhoon to typhoon as it was influenced by many factors (Zheng et al., 2008, 2010b; Lin, 2012), it tended to change with the typhoon intensity based on our statistical results (Table 1). It seems that the stronger the typhoon was, the higher the PP enhancement was. The averaged total PP enhancement was about 0.342 ± 0.076 Mt C for the typhoons of C3, namely, Cimaron/Chebi in November 2006, Nalgae/Nesat in October 2011, Bopha in December 2012. Similarly, the averaged total PP enhancements for C2, C1 and TS were 0.230 ± 0.063, 0.131 ± 0.102 and 0.083 ± 0.038 Mt C, respectively (Table 3).

The annual contribution of typhoons to the total PP in S4 could be derived using Eq. (1). Since there were two C4 typhoons, one C3 typhoon, one C1 typhoon and one tropical storm passing through S4 in 2006, the total production of typhoon Chanchu in May 2006 and typhoons Cimaron/Chebi in November were 0.758 and 0.396 Mt C, respectively (Table 1). The unknown production induced by the other two typhoons was using the respective averaged production of each typhoon scale as shown in Table 3. Therefore, the total carbon fixation for S4 in 2006 was estimated to be 2.084 ± 0.164 Mt, as shown in Fig. 3 (the similar process was applied to derive the total production induced by typhoons in other years). Note that the error is given by the sum of the standard deviation of averaged PP enhancement when the PP data are not available after the passages of some typhoon cases. However, the carbon fixations were less than 1 Mt in all other years during 2003 and 2012. The least carbon fixation was only 0.167 ± 0.076 Mt in 2005. Low carbon fixation also occurred in the years of 2004 and 2007, with values of 0.313 and 0.277 Mt, respectively. The corresponding typhoons passing though S4 were no more than two in 2004, 2005 and 2007, while there were five typhoons in 2006. Although the number of typhoons in 2009 was the same as that in 2006, the estimated carbon fixation was only 0.437 ± 0.038 Mt in 2009. The main reason was that the typhoon intensity was much

Table 3
Averaged total PP enhancement and its standard deviation based on typhoons with different scales in S4.

Typhoon Scale	ΔAVG_TPP (Mt C)	Standard Deviation (Mt C)
C4	0.847	0.126
C3	0.342	0.076
C2	0.230	0.063
C1	0.131	0.102
TS	0.083	0.038

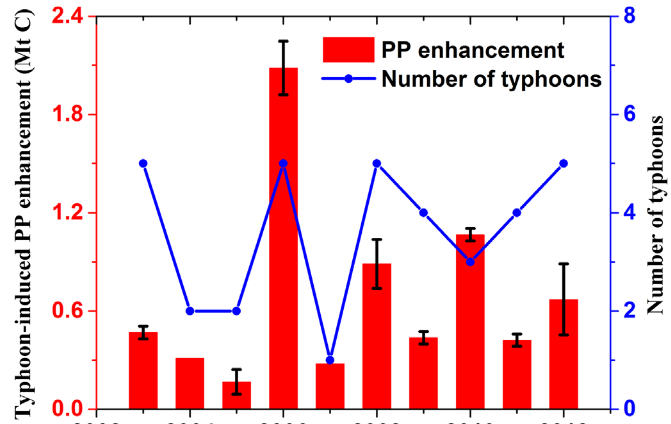


Fig. 3. Typhoon-induced PP enhancement (Mt C) in S4 during 2003–2012. The blue dot indicates the number of typhoons passing through S4 each year.

weaker in 2009 than in 2006 and that there were three tropical storms in 2009. From the above results, we can see that the interannual variation of the carbon fixation induced by typhoons was large. We attributed this large variation to both intensity and number of typhoons in S4. Siswanto et al. (2007) correlated the typhoon-induced PP enhancement to the Southern Oscillation Index (SOI) and found an inverse relationship between them. However, the relationship between the carbon fixation induced by typhoons and ENSO cycle was not obvious in S4 during our study period.

Based on the interannual results, the annual mean PP induced by typhoons in S4 was 0.679 ± 0.076 Mt C. Thus, the carbon fixation resulting from typhoons was estimated to be about 2.716 ± 0.304 Mt in the entire SCS in accordance with the proportion of the typhoons in the other areas of SCS (almost three times of S4, in Fig. 1b). Lin et al. (2003) first reported that the carbon fixation induced by Typhoon Kai-Tak in July 2000 was 0.8 Mt, or 2–4% of the annual new production in the SCS. Thus, they concluded that the contribution of all typhoons to the annual new production in the SCS might be as much as 20–30%. However, our result was much lower, only about 5–15%. One of the most obvious reasons was that the result of Lin et al. (2003) was based on one single strong typhoon Kai-Tak and the assumed condition that an average of 14 strong typhoons passing over the SCS annually. Our result is probably more reasonable as we used the actual typhoons passing through the SCS and considered each typhoon's intensity individually.

3.2. Typhoon-induced PP enhancement in the WNPSO

The typhoons passing through W6 in the WNPSO during 2003 and 2012 are shown in Table 2. They are also arranged by the descending order based on the typhoon intensity. There were nine super typhoons passing through W6 during the study period. Typhoon Lupit in November 2003 was the only Category 5 typhoon, which induced the averaged SST reduction of 2.37 °C, the 8-day averaged Chl-*a* concentration and PP enhancement of 0.069 mg/m^3 and 129.91 mg C/m^2/d (Table 2), respectively. However, the most significant SST cooling and Chl-*a* response were induced by Category 4 Typhoon Ketsana in October 2003, with the averaged SST reduction of 2.96 °C and the averaged Chl-*a* increase of 0.093 mg/m^3 (Table 2). Lin (2012) suggested that the possible reason was that the transit time of Typhoon Ketsana was much longer than that of Typhoon Lupit. Unlike in S4, the physical and biological responses to the Category 4 typhoons in W6 varied

Table 4
Averaged total PP enhancement and its standard deviation based on typhoons with different scales in W6.

Typhoon scale	ΔAVG_TPP (Mt C)	Standard Deviation (Mt C)
C4-C5	0.132	0.088
TS-C3	0.017	0.014

greatly. The averaged SST cooling ranged from 0.40 to 2.96 °C, the averaged change for Chl-*a* was 0.017–0.093 mg/m^3 and that for total 8-day PP enhancement was 0.030–0.241 Mt C. If Category 4 Typhoon Sonca in April 2005 and #6 in May 2008 with PP enhancement lower than 0.040 Mt C were excluded, all other Category 4 typhoons caused larger PP enhancements in comparison with weak typhoons from TS to C3. Since there was only one C5 typhoon in the results, in order to reduce uncertainty we classified C5 and C4 typhoons in the WNPSO as one class. Therefore, the averaged PP enhancement for super typhoons in W6 was about 0.132 ± 0.088 Mt C (Table 4). However, the influence was very weak by typhoons with intensity below C4 and the PP enhancement was no more than 0.040 Mt C. Therefore, we classified the typhoons from TS to C3 as one class and the averaged PP enhancement for this class was estimated to be 0.017 ± 0.014 Mt C (Table 4).

Similarly, the annual contribution of typhoons to the total PP in W6 was also derived using Eq. (1). The maximum carbon fixation was 0.747 ± 0.231 Mt in 2004, while the minimum was only 0.029 ± 0.014 Mt in 2010, as shown in Fig. 4. As super typhoons had major contributions to the total typhoon-induced PP enhancement in W6 from the above analysis, the interannual variation in this sub-region was mainly related to the number of super typhoons (Fig. 4). Previous studies revealed that super typhoons tended to be more frequent in El Niño years than in La Niña years in the Western North Pacific (Camargo and Sobel, 2005; Lee et al., 2012). Siswanto et al. (2007) reported an inverse relationship between typhoon-induced PP enhancement to the Southern Oscillation Index (SOI), which was due to the tendency of typhoons to be more frequent and intense during the ENSO warm phase. Fig. 5 shows that the highest number of Category 5 typhoons occurred in 1997, which was the strongest El Niño year in the last two decades. Similarly, 2004 was a moderate El Niño year with four super typhoons, which induced the maximum carbon fixation in W6 during 2003–2012. As there were no super typhoons passing though W6 in the La Niña years of 2007 and 2010, the carbon fixation was less than 0.1 Mt per year. Therefore, ENSO cycles obviously affected the typhoon-enhanced PP in the WNPSO.

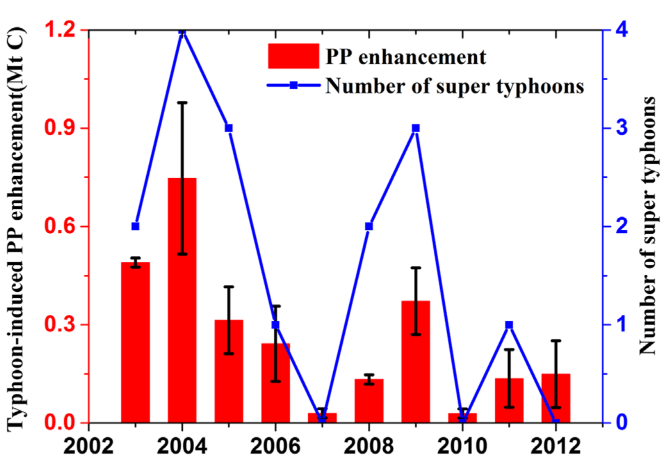


Fig. 4. Typhoon-induced PP enhancement (Mt C) in W6 during 2003–2012. The blue dot indicates the number of super typhoons passing through W6 each year.

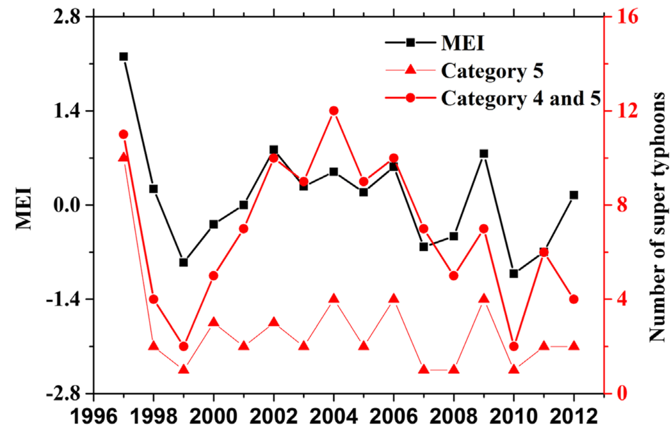


Fig. 5. Relationship between MEI (left *y*-axis) and the number of super typhoons (right *y*-axis) in the WSNPO during 1997–2012.

Based on the interannual results, the annual mean PP induced by typhoons in W6 was about 0.264 ± 0.080 Mt C. Thus, the carbon fixation resulting from typhoons was about 2.112 ± 0.640 Mt in the entire WNPSO in accordance with the proportion of the typhoons in the other areas of the WNPSO (almost seven times of W6, in Fig. 1b). Lin (2012) estimated that the total carbon fixation was 3.27 Mt in 2003 in the WNPSO of 15°–25°N, 127°E-180°. Considering that the area of her study region is about 1.5 times of ours, her estimation and ours can be considered to be consistent.

3.3. Comparison between SCS and WNPSO

From the results given in Sections 3.1 and 3.2, we can see that typhoons' effects on SCS's PP could not be neglected and the contribution of all typhoons to SCS's annual new production might be as much as 5–15%. However, the contribution of all typhoons to the WNPSO's might be small as the annual carbon fixation was only 2.112 ± 0.640 Mt although the area is almost twice of that of the SCS. According to previous studies, the ocean's response to a typhoon is determined by many factors: typhoon's intensity, translation speed, typhoon-induced Ekman upwelling, and ocean's precondition (Zheng et al., 2008, Zheng et al., 2010a,b; Lin, 2012). As our results were based on the statistics of all typhoons rather than on one case, the ocean precondition (e.g., nutricline depth and MLD) should be the main contributors, which determine whether the nutrients in the deep layer could be brought to the upper layer to sustain the growth of phytoplankton. Fig. 6 shows the climatological annual mean nitrate concentration at depths of 0, 30, 50, and 100 m. In the surface layer, the nitrate concentrations are less than 0.5 μM in the SCS except in the coastal regions while the concentrations are less than 0.2 μM in the WNPSO (Fig. 6a), one of the well-known ocean deserts. Therefore, the biological productions in the upper layer of these two regions are mainly limited by the availability of nutrients. However, the nitrate concentrations significantly increased with the deepening of water depth in the SCS (Fig. 6b–d). The concentration was almost twice (1–2 μM) at 50 m compared with that in the surface layer, and was more than 10 μM at 100 m. In contrast, there was almost no change with nitrate concentrations in the WNPSO (Fig. 6b–d). Even if the depth reached 100 m, the nitrate concentration was still less than 1 μM. Although typhoons can induce vertical mixing and upwelling, bringing nutrient-rich water from the deep layer into the euphotic zone (Price, 1981), the nutrients in the SCS could obviously be brought to the surface layer more easily than in the WNPSO. The climatological monthly averaged MLDs in February, May, August, and November, are shown in Fig. 7. The MLD in the

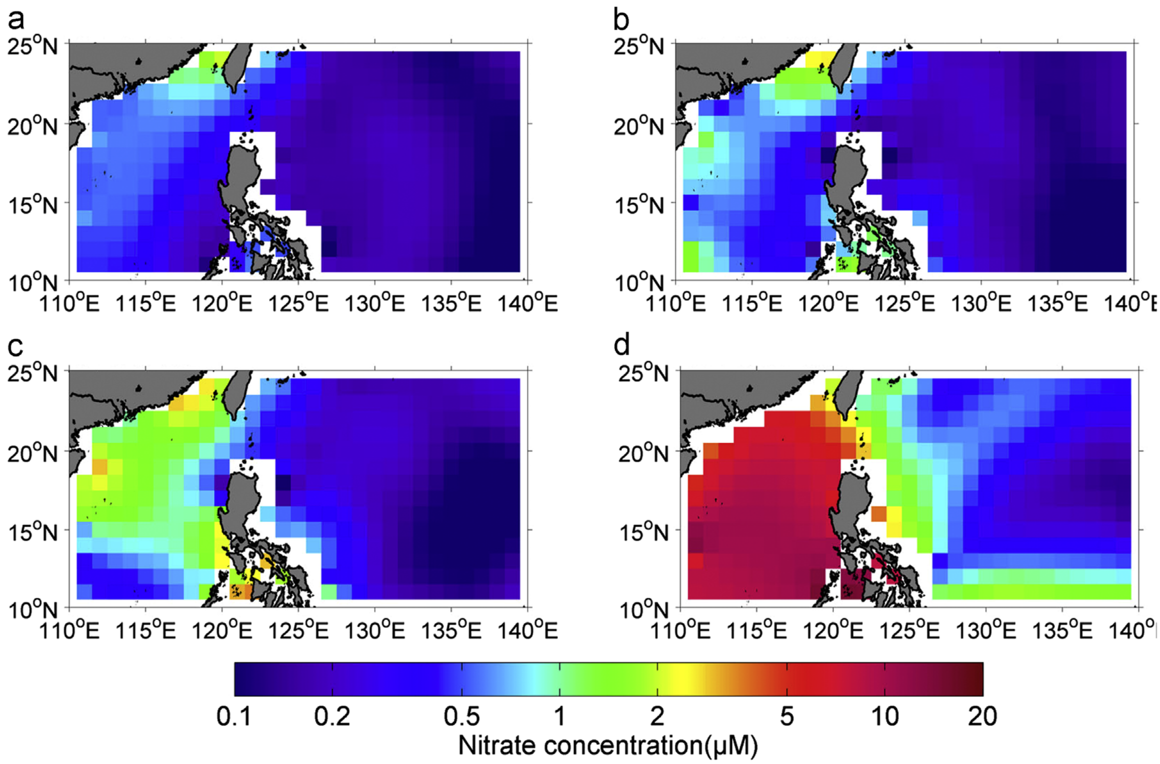


Fig. 6. Climatological annual mean nitrate concentration (μM) at depth of (a) 0 m, (b) 30 m, (c) 50 m, and (d) 100 m.

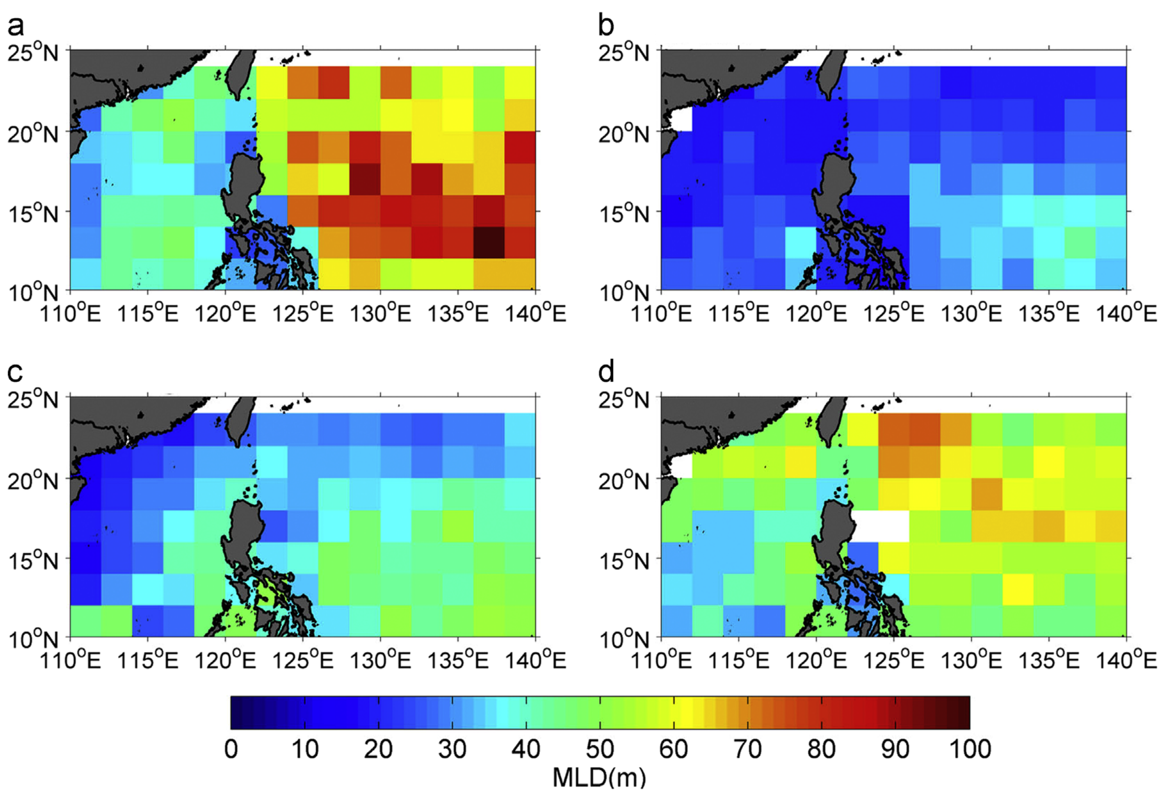


Fig. 7. Climatological monthly averaged mixed layer depth (m) in (a) February, (b) May, (c) August, and (d) November.

SCS is less than 40 m and is always shallower than that in the WNPSO in any season. In fall and winter, the MLD in the WNPSO even reaches 60–100 m. This again suggests that the cold, nutrient-rich water is more difficult to be brought to the upper layer in the WNPSO than in the SCS. Therefore, the deep MLD and nutricline depth determined that the annual carbon fixation by all typhoons in the WNPSO was smaller than that in the SCS during our study period.

4. Summary and conclusions

A statistical approach was developed to estimate the annual and interannual typhoon-enhanced PP in the SCS and WNPSO, respectively, during 2003–2012. The annual mean carbon fixation in the whole SCS was estimated to be approximately 2.716 ± 0.304 Mt, equivalent to 5–15% of the new PP of the SCS, while it was only about 2.112 ± 0.640 Mt in the WNPSO, although the typhoon intensity was stronger in the latter and the area is larger in comparison. The results suggest that frequently visited typhoons contributed greatly to PP in the SCS. However, the effect in the WNPSO might be weak. The main reason is that the cold nutrient-rich water was more difficult to be brought to the upper layer to support the growth of phytoplankton due to the deep MLD and nutricline depth in the WNPSO than in the SCS. Although we have focused on the SCS and WNPSO in this study, the biogeochemical effects of typhoons on coastal marine ecosystems in all China seas are worth studying in the future research.

Our statistical approach can be applied to all typhoons even if the PP data are not available in some typhoon cases due to cloud or rainfall, allowing us to determine the annual contribution of typhoons to the local or global carbon cycle easily. This method does not rely on any physical mechanism or empirical relationship as in Siswanto et al. (2007) with typhoon features (intensity, translation speed, size, etc.) and ocean pre-existing conditions (negative sea surface height anomaly, etc.). The effects of mesoscale eddies on PP enhancement have not been separated from the actual mixing event that occurred following the passage of each typhoon although eddies can be intensified or generated in some typhoon cases in the study area (Chow et al., 2008; Sun et al., 2014). In addition, the subsurface chlorophyll maximum can be carried to the surface layer via vertical advection and mixing and result in the overestimation of PP enhancement. Hence, the accuracy of PP enhancement estimation needs to be further improved.

We identified an obvious relationship between the enhanced PP induced by typhoons and ENSO cycles in the WNPSO. The carbon fixation tended to be higher in the El Niño years and lower in the La Niña years, which is mainly due to the more frequent super typhoons in the El Niño years than in the La Niña years. However, no obvious relationship between typhoon-enhanced PP and ENSO cycle was found in the SCS. Global warming has been predicted to decrease phytoplankton productivity in the tropical and subtropical oceans as increasing stratification would limit nutrient supplies (Irwin and Oliver, 2009). However, the frequent, intensified typhoons under global warming may complicate this prediction as they can produce transient shoaling of the thermocline/nutricline into the euphotic zone, and increase PP.

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