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Effects of typhoon events on chlorophyll and carbon fixation in different regions of the East China Sea

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ABSTRACT

Typhoons play an important role in the regulation of phytoplankton biomass and carbon fixation in the ocean. Data from the moderate-resolution imaging spectroradiometer (MODIS) on 35 typhoon events during 2002–2011 are analyzed to examine the effects of typhoon events on variations in sea surface temperature (SST), chlorophyll-a (Chl-*a*), and depth-integrated primary productivity (IPP) in the East China Sea (ECS). For all 35 typhoon cases, the average SST drops by 0.1 °C in the typhoon influenced regions, and the maximal decrease is 2.2 °C. During the same period, average Chl-*a* increases by 0.1 mg m^{-3}, with the maximal increase reaching up to 1 mg m^{-3}, and average IPP increases by 32.9 mg C $m^{-2}\cdot d^{-1}$, with the largest increase being 221 mg C $m^{-2}\cdot d^{-1}$. The IPP are significantly correlated with SST and Chl-*a* data, and the correlations become stronger after typhoon passage. On average, nearly one-third of the ECS is affected by typhoons during the 10 year period, and the resident time of the typhoons in the area reach to 38.2 h. Effects of the typhoon events on SST, Chl-*a*, and IPP manifest differently in the three key sea areas, namely, the coastal water (depths <50 m), continental shelf (depths 50–200 m), and open sea (depths >200 m) regions in the ECS. Specifically, stronger responses are observed in shallow water than in deeper depths. The comparisons between the pre- and post-typhoon periods show that IPP in the post-typhoon period increases by 19.7% and 12.2% in the coastal and continental shelf regions, respectively, but it decreases by 9.4% in the open sea region. Overall, our results reveal that there is a close coupling between Chl-*a*, SST, and IPP in shallow areas and that typhoon events can have strong effects on carbon fixation in coastal regions.

1. Introduction

As one of the most powerful meteorological activities on earth, typhoon events often induce large changes in natural habitats. The patterns and trajectories of typhoon events are important factors that mediate effects on ocean environments (Sun, 2007). Typhoon energy penetrates into the ocean, which can cause strong entrainment and mixing (Shang et al., 2008; Pan and Sun, 2013; Zhao et al., 2015). The changes in physical processes then lead to nutrient and phytoplankton responses in the water column, which depend on the translation speed and intensity of typhoon events (Zhao et al., 2008). Typhoon events are also known to affect the biogeochemical processes of nutrient and carbon cycling (Frank et al., 2015).

The East China Sea (ECS) is located in the northwest Pacific Ocean and is one of the largest marginal seas in the world (Li et al., 2009). The ECS covers an area of more than 77 × 10^4 km^2 and is subjected to frequent typhoon activity. During typhoon events, the kinetic energy of typhoon wind is transmitted into the water column and changes in hydrologic conditions occur (heat, salinity, temperature, etc.) (Lin and Jeng, 2000; Chang et al., 2008a). Studies have shown that decreases in the sea surface temperature (SST) can lead to subsequent changes in nutrient concentrations and the uptake of nutrients by phytoplankton, which ultimately affects chlorophyll-a (Chl-*a*) and depth-integrated primary productivity (IPP) (Lin and Wu, 2007). In the early 1980s, Price (1981) studied the response of SST to hurricanes and found that entrainment was the main factor in the SST decrease and that the influenced area had

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a characteristic bias to the right of the cyclone's direction of travel. In May 2006, typhoon “Pearl” caused the average SST to decrease by 2.2 °C in the South China Sea (SCS), as reported by Jiang et al. (2008). Zhu and Zhang (2006) used model and satellite data to analyze the relationship between the cooling of SST and the intensity of typhoons and found that every 20 hPa change of air pressure in a typhoon's center could induce a 1 °C variation of SST. Increases in Chl-*a* concentrations are usually associated with such decreases in SST. One mechanism involves Ekman pumping, which can increase during typhoon events, and enhances the upwelling of nutrients from the deep ocean to the euphotic zone and stimulates the growth of phytoplankton as detected by Chl-*a* (Babin et al., 2004). Typhoon “Saomai” in 2006 resulted in an average of a 2.4-fold increase in surface Chl-*a* and even a 10-fold increase in some areas after the passage of the typhoon (Fu et al., 2008). High Chl-*a* levels resulting from a typhoon event can last for 2–3 weeks (Babin et al., 2004). Elevated Chl-*a* occurs not only at the surface, but also in the interior above the thermocline, as observed by Hung et al. (2010). Specifically, they found that the depth of the euphotic zone became shallower after typhoon “Fengwong” and that the in situ measured subsurface Chl-*a* concentration was 50% higher than surface moderate-resolution imaging spectroradiometer (MODIS) data.

Climate extremes have impacts on the carbon cycle (Reichstein et al., 2013), and the variation in carbon fixation is often related to Chl-*a* (Lin, 2012). In July 2007, typhoon “Kai-tak” remained in the South China Sea for 3 days, where it increased Chl-*a* by nearly 30 times and 0.8 million tons (Mt) of extra carbon was estimated to have been fixed compared to the pre-typhoon period. This value represents 2%–4% of the annual primary productivity in the SCS (Lin et al., 2003a). A tropical cyclone event was demonstrated to have increased the water column primary productivity from 490 mg C $m^{-2}\cdot d^{-1}$ to 820–980 mg C $m^{-2}\cdot d^{-1}$ in the Bay of Bengal during May 2003 (Smitha et al., 2006). Water column integrated primary production reached the highest level 3 days after typhoon “Mawar” moved across Sagami Bay of Japan, and the levels remained elevated for 9 days (Tsuchiya et al., 2013). Zhao et al. (2008) used SeaWiFS data and the vertically generalized production model (VGPM) (Behrenfeld et al., 2005, 2006) to study the effects of two typhoon events in the SCS and found an increase in IPP, which accounted for almost 3.5% of the annual IPP in the typhoon influenced area.

Most studies of typhoon effects on phytoplankton have focused on just one or two events. However, examinations of multiple typhoon events over longer periods such as 10 years, particularly analyses of the effects in different depth regions of the ECS are still lacking. The objectives of this study are as follows: to examine the effects of all typhoons during 2002–2011 passing over the ECS on variations of SST, Chl-*a*, and IPP by using MODIS data during the pre/post typhoon periods; to compare the effects between different water depth regions; and to estimate carbon fixation in typhoon influenced areas.

2. Materials and methods

2.1. Data sources

The ECS (21°–42°N, 114°–133°E) is often impacted by multiple typhoon events each year. Typhoon track data were derived from the Joint Typhoon Warning Center (JTWC) (http://www.usno.navy.mil/JTWC). The maximum wind velocity, typhoon wind circle radius, and moving speed data were obtained from the Japan National Institute of Informatics (NII) (http://agora.ex.nii.ac.jp/digital-typhoon). In order to express the large wind events more clearly, the word “typhoon” is used to discuss events with intensities of a tropical storm and above. The phrase “pre-typhoon” stands for the 8-day period before typhoon transit, while the phrase “post-typhoon” stands for the 8-day period after typhoon transit over the influenced area.

The Chl-*a*, SST, diffuse attenuation coefficient (Kd490), and photosynthetically active radiation (PAR) data were obtained from the National Aeronautics and Space Administration (NASA) (https://oceancolor.gsfc.nasa.gov). The Aqua/Terra satellites carrying MODIS provide these data. After processing, the data conform to L3 class products, which have a 4 km spatial resolution. We use the 8-day composite data to perform the calculations and evaluate the pre- and post-typhoon periods.

2.2. Estimation of depth-integrated primary productivity

We revised the VGPM algorithm (Behrenfeld and Falkowski, 1997a, 1997b) to obtain estimations of IPP. Parameters in the model can be acquired from satellite remote sensing data, and the simplified specific expression used is as follows:

$$PP_{eu} = 0.66125 \times P^{b}_{opt} \times \left[\frac{E_0}{E_0 + 4.1}\right] \times Z_{eu} \times Chl \times DL \tag{1}$$

Related parameters are shown in Table 1.

The maximum photosynthetic rate is as follows:

$$P^{B}_{opt} = \begin{cases} 1.13, & T < -1^{\circ}\mathrm{C} \\ 4.00, & T > 28.5^{\circ}\mathrm{C} \\ fT, & -1^{\circ}\mathrm{C} \le T \le 28.5^{\circ}\mathrm{C} \end{cases} \tag{2}$$

When the SST stays between −1 °C and 28.5 °C, f(T) is:

$$P^{B}_{opt} = -3.27 \times 10^{-8}T^{7} + 3.4132 \times 10^{-6}T^{6} - 1.348 \times 10^{-4}T^{5} + 2.462 \times 10^{-3}T^{4} - 0.0205T^{3} + 0.0617T^{2} + 0.2749T + 1.2956 \tag{3}$$

The practical euphotic depth was calculated by the equation from Li et al. (2003b), which is appropriate for the ECS:

$$\mathrm{Z_{eu}} = \frac{3.512}{Kd490} \tag{4}$$

2.3. Data validation

Because of the great destructive force of typhoons, it is almost impossible to acquire large areas of cruise data during or around typhoon events. Besides, coastal waters in many areas of the ECS belong to case 2 waters (waters optical properties are significantly influenced by other matters such as mineral particles and colored

Table 1
Explanation of related parameters in the VGPM model.

Variables	Definition	Unit
PP_{eu}	Daily depth-integrated carbon fixation quantity	mg C $m^{-2}\cdot d^{-1}$
P^{b}_{opt}	Maximum photosynthetic rate	mg C mg $Chl^{-1}\cdot h^{-1}$
E_0	Photosynthetically active radiation	Ein $m^{-2}\cdot d^{-1}$
Kd490	Diffuse attenuation coefficient	–
Z_{eu}	Euphotic depth	m
Chl	Chl-*a* concentration measured from revised satellite data	mg m^{-3}
DL	Daylight hours	h