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Research papers

Estimation of typhoon-enhanced primary production in the South China Sea: A comparison with the Western North Pacific

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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.

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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/).

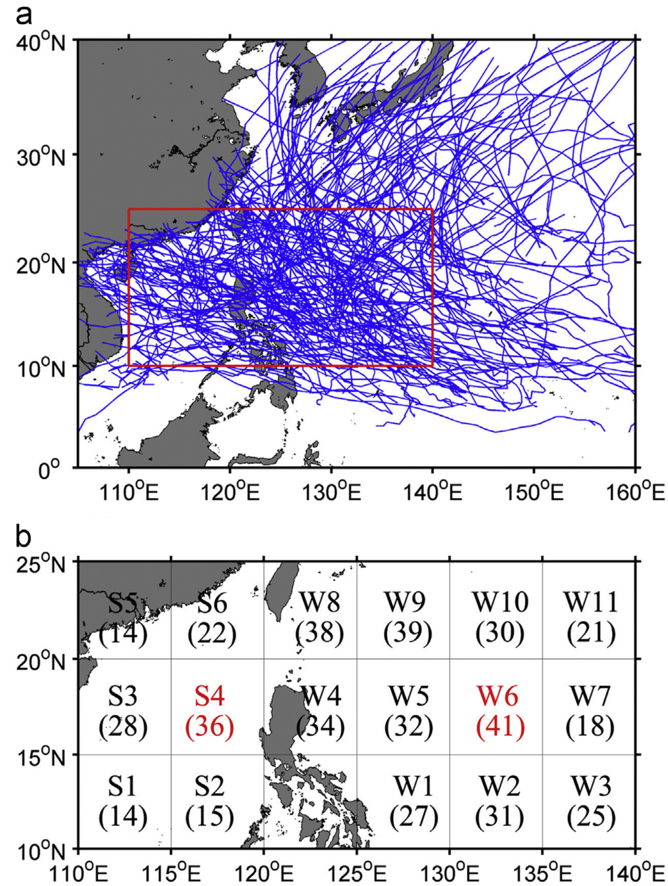

Fig. 1. (a) The tracks of all typhoons (TS–C5, according to the Saffir–Simpson Scale) passing through the Western North Pacific during 2003 and 2012. (b) The sub-regions of size 5° × 5°. There are six sub-regions (S1–S6) in the SCS and 11 sub-regions (W1–W11) in the WNPSO. The number in the parentheses 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.

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