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Marine phytoplankton biomass responses to typhoon events in the South China Sea based on physical-biogeochemical model

Gang Pan[a,*], Fei Chai[b], DanLing Tang[a], Dongxiao Wang[a,*]

[a] State Key Laboratory of Tropical Oceanography (LTO), South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, 510301, China
[b] School of Marine Sciences, University of Maine, Orono, ME 04469, USA

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ABSTRACT

Most previous studies confirmed that marine phytoplankton biomass can increased dramatically and then formed blooms along the typhoon track after typhoon passage. However, many events of no significant responses to typhoons were neglected. In order to figure out the most important factor for bloom formation, a coupled physical-biogeochemical model was used to study the biogeochemical phytoplankton responses to all 79 typhoon events that affected the South China Sea (SCS) during 2000–2009. The major factors investigated included typhoon intensity and translation speed, Chlorophyll a concentration (Chl-a) and vertical nitrate transport in the euphotic zone before and after typhoon passage. The results revealed that phytoplankton blooms were triggered after 43 typhoon events, but no significant blooms were found after 36 other typhoons. Of the 43 typhoon events that triggered blooms, 24 were in the open ocean and 19 were on the coast. Subsurface blooms were detected after five typhoon events that did not trigger surface blooms. Over half of the typhoons that affect the oligotrophic SCS can trigger phytoplankton blooms, and contribute to the marine primary productivity. The mechanism of the above results were surveyed, we found that (1) an increased nitrate concentration is the basic and key precondition for phytoplankton blooming in the oligotrophic SCS; (2) typhoon intensity, and translation speed control the upward flux of nitrates together, and translation speed has more effect than intensity; (3) uplifted nitrates could trigger phytoplankton bloom, and Chl-a levels reached a peak 3 days later than nitrate levels; (4) mesoscale eddies and the nutricline depth before a typhoon's arrival also affects bloom genesis; and (5) the composition of phytoplankton functional groups in the coast was adjusted by typhoon, which have more complex mechanism of bloom formation than that in the open ocean. In summary, the physical driving force that modulates blooms is vertical nutrient transportation in the SCS.

1. Introduction

Typhoons (also referred to as tropical cyclones, or hurricanes) are powerful sea surface dynamical processes that are generated in tropical oceans. It is well known that the vertical mixing and upwelling induced by typhoons can uplift the deeper chlorophyll to the surface, and bring nutrient-rich deeper water up into the upper euphotic zone (Price, 1981; Shang et al., 2008; Zheng and Tang, 2007). The uplifted nutrients can trigger phytoplankton blooms (as measured by Chlorophyll a concentration, Chl-a) and increase marine new productivity, particularly in oligotrophic tropical oceans (Lin et al., 2003; Shang et al., 2008; Ye et al., 2013; Zhao et al., 2008). Most previous studies on biogeochemical phytoplankton responses to typhoons focused on positive event, in which obvious phytoplankton blooms were observed by satellite remote sensing (Babin et al., 2004; Lin, 2012; Subrahmanyam et al., 2002; Walker et al., 2005) and field observation (Naik et al., 2008; Shiah et al., 2000; Zhang et al., 2014). There are separate typhoon events, case by case. Many events of no significant responses to typhoons were neglected. Lin (2012) systematically checked phytoplankton blooms induced by all 11 typhoon events in the part of pacific ocean (15–25°N, 127–180°E) in 2003, and found that only two (18%) phytoplankton blooms occurred (Lin, 2012).

The South China Sea (SCS) is the largest marginal ocean of the pacific ocean, and a third of the typhoons generated in the North-West Pacific Ocean (NWPO) affect the SCS, with about 8 typhoons per year (Mendelsohn et al., 2012; Wang et al., 2007; Zhao et al., 2008) (Fig. 1). Typhoon plays an important role in enhancing phytoplankton biomass and primary productivity in oligotrophic SCS (Lin et al., 2003; Shang et al., 2008; Zhao et al., 2008; Zheng and Tang,

* Corresponding authors.
E-mail addresses: gpan@scsio.ac.cn (G. Pan), dxwang@scsio.ac.cn (D. Wang).

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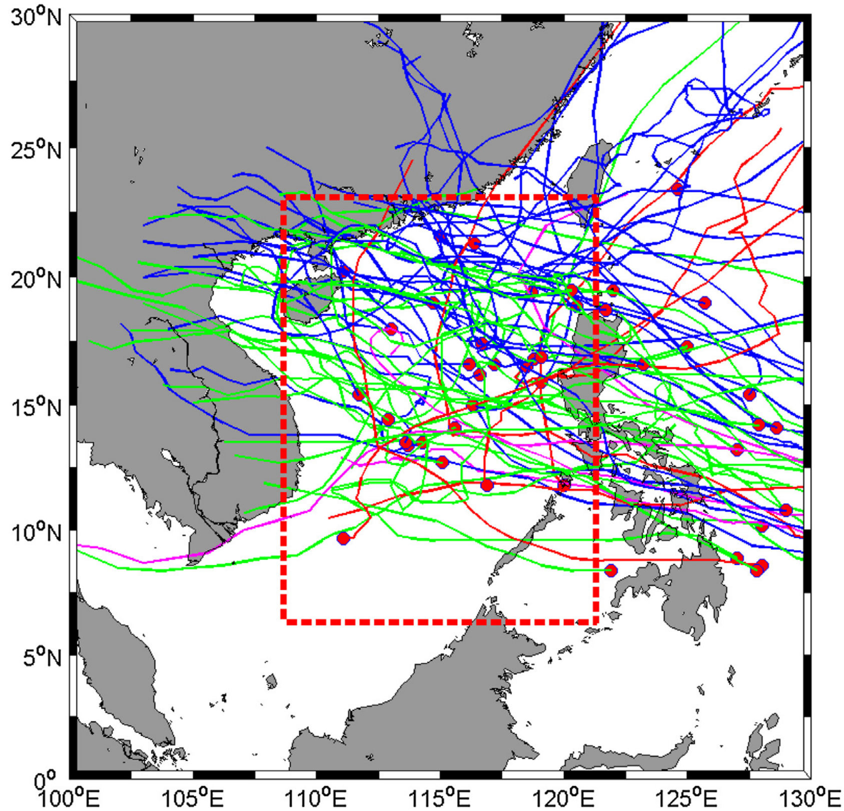

Fig. 1. Tracks of typhoon observed between 2000 and 2009, which affected the South China Sea and adjacent ocean. Red dashed box (6°–24°N, 108°–122°E) indicates the study area. Red solid circles present the place of typhoon genesis; red, blue, green, and magenta lines are typhoon tracks in spring (MAM), summer (JJA), autumn (SON), and winter (DJF), respectively. Gray patch means land. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2007). However, few phytoplankton blooms triggered by typhoon have been detected. The factor that is the most important for bloom formation is unknown. Checking the typhoon events systematically is a good method to figure out the key factor.

In general, marine phytoplankton blooms along the typhoon's track after its passage can be observed by satellite remote sensing (Babin et al., 2004; Lin, 2012; Subrahmanyam et al., 2002; Walker et al., 2005) and field observations (Naik et al., 2008; Shiah et al., 2000; Zhang et al., 2014). However, visible/infrared satellite sensors [i.e., Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) and Moderate Resolution Imaging Spectroradiometer (MODIS)] are sensitive to cloud cover; therefore, they do not provide a clear spatial or temporal indication of typhoon-induced responses. Field observations of pre- and post-typhoon phytoplankton biomasses are few, because of the dangers inherent in fieldwork associated with typhoon events. Therefore, a reliable technique is needed.

Physical-biogeochemical models that link physics and ecosystem components with phytoplankton growth are useful tools with which to fill the gaps in space and time in field and satellite observations. Therefore, physical-biogeochemical models, once their performance has been evaluated by available observations, provide an alternative means of investigating the overall response of the upper ocean to typhoons (Chai et al., 2009; Gierach et al., 2009; Hung et al., 2010; Shibano et al., 2011). However, only a few individual typhoons' passages have been investigated in terms of Chl-a and nutrient responses by combining biogeochemical processes with physical models, such as Katrina in 2005 in the Gulf of Mexico (Gierach et al., 2009), and Keith in 1997 in the NWPO (Shibano et al., 2011).

Until now, to our knowledge, the contributions of all typhoon events over several years have never been systematically quantified. The purpose of this study was to simulate phytoplankton and nutrient responses to typhoon events, characterize blooms after a typhoon's passage, determine the factors that affect bloom genesis, and elucidate the mechanisms involved. A coupled three-dimensional physical-biogeochemical model (i.e. the Regional Ocean Modeling System (ROMS)–Carbon, $Si(OH)_4$, Nitrogen Ecosystem (CoSiNE) model, ROMS–CoSiNE model) was used.

2. Methods

2.1. Study area

The SCS has a total area of about 3.5 million km^2. Its bottom topography is characterized by a basin with a maximum depth of 5000 m at the center, wide continental shelves in the north and south, and steep slopes in the east and west (Chai et al., 2009; Tang et al., 2004). It has tropical oligotrophic surface waters, with a shallow mixed layer and nutricline depths (Gong et al., 1992; Wang et al., 2012; Wong et al., 2007). The NWPO has the highest density of typhoons in the world, both in number and intensity (Mendelsohn et al., 2012; Wang et al., 2007).

The distribution of small phytoplankton (<5 μm in diameter) in the SCS is highly uniform. The annual mean depth-integrated phytoplankton concentration in the entire basin is estimated to be ~35 mmol m^{-2}. Diatoms mainly exist in the central and southern basins, and high concentrations are found from western Luzon Island to eastern Vietnam. The annual average total phytoplanktonic carbon content is similar to that of diatoms, i.e., diatoms account for the majority of the biomass (Ma et al., 2013). The main