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The asymmetric distribution of phytoplankton in anticyclonic eddies in the western South China Sea

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ABSTRACT

An anticyclonic eddy's periphery is characterized by large horizontal density gradients, strain and vertical velocity. In this paper we document the asymmetric distribution of phytoplankton around the periphery of anticyclonic eddies in the western South China Sea based on 432 eddies detected from satellite data. The high level of phytoplankton occurs consistently at the northwestern periphery of eddies, with a maximum positive chlorophyll anomaly greater than 0.01 mg m^{-3}. The asymmetric distribution of phytoplankton primarily tags the non-uniform surface velocity field varying from 0.15 m s^{-1} to 0.3 m s^{-1} along the eddy's periphery. The coastal boundary and off-coast jet may be the primary cause of the non-uniform flow. Associated with the non-uniform flow speed, the combined effects of the velocity convergence and steepened northwestern part of the eddies act to sharpen the density fronts and tend to result in an ageostrophic secondary circulation at the northwestern edge of the eddy. The upward component of the ageostrophic secondary circulation can enhance the nutrient flux into the euphotic layer, thereby increasing phytoplankton productivity. Anticyclonic eddy-induced ageostrophic secondary circulation appears to be an important mechanism for increasing phytoplankton productivity in the oligotrophic waters of the South China Sea.

1. Introduction

Satellite-derived phytoplankton patterns are frequently associated with mesoscale eddy dynamics. The physical mechanisms responsible for phytoplankton variability in relation to mesoscale eddies is still hotly debated (McGillicuddy et al., 2007, 2008; Mahadevan et al., 2008). The main mechanisms of eddy-driven phytoplankton variability include eddy-induced variability of nutrients or light availability (e.g., eddy pumping, eddy-wind interactions and eddy impacts on the mixed-layer depth) and direct horizontal transport by eddies (e.g., eddy stirring and eddy trapping) (Siegel et al., 2011; McGillicuddy, 2016). A significant difference between these two mechanisms is that the former can change phytoplankton productivity by regulating the vertical distribution of growth-regulating factors (e.g., nutrients and light), while the latter can only advect water masses around the eddy and is not expected to have a biogeochemical impact (Siegel et al., 2011). Biological activities related to anticyclonic eddies appear to be much more complicated than those found in their cyclonic counterparts (Eden and Dietze, 2009). The peripheries of eddies, which are characterized by large horizontal density gradients, strain and vertical velocity, exhibit complex biological processes. In contrast to the dipole and monopole anomalies of chlorophyll in the center of eddies, a ring-shaped pattern has been observed around the peripheries of eddies (Kahru et al., 2007), particularly anticyclones. One possible mechanism for the ring-shaped pattern is that nutrient-rich water is transported upward along the up-bowed isopycnals in the peripheries of eddies (Mizobata et al., 2002; Kahru et al., 2007). A submesoscale process at the peripheries of eddies is also expected to generate an upwelling and elevate chlorophyll levels (Zhou et al., 2013). Submesoscale fronts arise dynamically through advective interactions involving mesoscale currents (Lévy et al., 2012). They have major implications for phytoplankton productivity because the timescales on which they transport nutrients are similar to the rate of phytoplankton growth (Mahadevan, 2016).

A strong submesoscale vertical velocity can transport nutrients to the euphotic zone. In light-limited regions, the reduction of vertical mixing at submesoscale fronts can increase the residence time of photosynthetic organisms in the well-lit euphotic layer and promote primary production (Lévy et al., 2012; Mahadevan, 2016). Eddy pumping-induced deepening of the mixed layer in anticyclonic eddies

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pushes the nutricline further out of the euphotic zone and limits nutrients available for photosynthesis (McGillicuddy et al., 1998; Siegel et al., 1999). On the other hand, the wind-driven Ekman current interacts with the anticyclonic eddy and generates a divergence inside the eddy, resulting in a high phytoplankton biomass (Martin and Richards, 2001). During their formation, anticyclonic eddies tend to create a deeper mixed layer, producing positive chlorophyll anomalies in a nutrient-limited regime and negative chlorophyll anomalies in a light-limited regime (McGillicuddy, 2016). The chlorophyll anomalies driven by eddy pumping, eddy-wind interactions and eddy-induced variability of the mixed layer depth appear as a monopole structure in the center of the eddies. In contrast to the monopole structure, eddy stirring is a dominant mechanism for the dipole structure of the phytoplankton distribution (high and low biomass on the opposite halves of an eddy) in the areas with strong chlorophyll gradients (Chelton et al., 2011a).

In the South China Sea (SCS), mesoscale eddies mainly propagate along two major bands in the northern SCS and western SCS. Previous studies have shown that the main eddy mechanisms affecting phytoplankton include eddy pumping, wind/eddy interactions, and direct horizontal transport in the SCS. An eddy pumping-induced low chlorophyll concentration was frequently observed in the center of anticyclonic eddies (Ning et al., 2008; Xiu and Chai, 2010). Wind/eddy interactions induce a shape change in the anticyclonic eddy, and eddy-Ekman pumping may increase to induce a high concentration of chlorophyll when the shape extension of the anticyclonic eddy is parallel to the wind direction in the SCS (Li et al., 2014). An anticyclonic eddy formed near the coastal area of the northern SCS can trap high-chlorophyll water and transport it to the oligotrophic region of the northern SCS (Lin et al., 2010). Anticyclonic eddy advection of the chlorophyll background gradient also induces a chlorophyll difference in the western and eastern sides of eddies (Liu et al., 2013). In contrast to the northern SCS, there is no meridional gradient of chlorophyll in the western SCS. The distribution of phytoplankton related to most anticyclonic eddies, especially the detailed patterns of phytoplankton around the periphery of anticyclonic eddies, remains unclear.

2. Data and methods

The South China Sea (SCS) is the largest marginal basin connected to the western Pacific Ocean, with a total area of 3.5 million km^2 and an average depth greater than 3 000 m (0°–25°N, 100°–125°E, Fig. 1(a)). The western SCS (5–18°N, 105–115°E) is a very dynamic region for physical and biological oceanographic processes. The wind direction in the western SCS reverses seasonally, with a northeasterly monsoon in winter and a southwesterly monsoon in summer. During the northeasterly monsoon, the surface current moves southward along the coast of Vietnam and moves in the opposite direction during the southwesterly monsoon (Fig. 1(b) and (c)) (Hwang and Chen, 2000). Ekman transport driven by the southwesterly monsoon induces a strong seasonal upwelling off the southeastern coast of Vietnam in summer (Kuo et al., 2000). The upwelled cold, nutrient-rich water with high-phytoplankton levels spreads eastward offshore (Tang et al., 2004), forming a high chlorophyll concentration filament at approximately 12°N (Fig. 1(f) and (g)). The local orographic wind drives the offshore current separation (Xie et al., 2003, 2007). Under the influences of solar insolation and land-sea interactions, a northwest-southeast gradient of sea surface temperatures occurs in winter (Fig. 1(d)). In summer, driven by the southwesterly monsoon, the upwelled cold water is horizontally transported northward and eastward (Fig. 1(e)). The western SCS is oligotrophic, with limited nitrogen and phosphorus within the euphotic layer instead of being light limited (Chen et al., 2003; Wu et al., 2003). The nutrient levels in deep water are higher than in the surface layer (Wang and Tang, 2014).

Daily 9 km Sea-viewing Wide Field-of-view Sensor (SeaWiFS) global chlorophyll products were obtained from the National Aeronautics and Space Administration (NASA) for the period August 1997 to December 2010. These products were generated using the Garver-Siegel-Maritorena (GSM) algorithm (Maritorena et al., 2002, 2010). The chlorophyll product was log10 transformed and interpolated to a 1/4°×1/4° grid with a temporal resolution of 7 days. The data were temporally low-pass filtered, using a loess smoothing filter with a half-power cutoff of 30 days to minimize the influences of data gaps and cloud contamination. Then, the data were spatially low-pass filtered (2°×2°) to remove sudden local phytoplankton bloom events. The remaining data gaps were interpolated using Kriging interpolation. The data were then high-pass filtered in space at 6°×6° and a time of 500 days to attenuate both the large-scale variability and temporal variability that exceeds the mesoscale eddy lifetime (Chelton et al., 2011a). After reprocessing, the chlorophyll (hereafter Chl) anomaly (log10 transformed) was obtained for the study area. A composite analysis was performed on the Chl anomaly. In the subsequent analysis, the data collected in the first and last 37 weeks were removed to eliminate the effects of temporal filtering on either end of the data period. Thus, the period for the processed data used in the analysis is from May 1998 to March 2010.

The Moderate Resolution Imaging Spectroradiometer (MODIS) monthly Sea Surface Temperature (SST) data were obtained from the ocean color website for the period July 2002 to March 2010. The World Ocean Atlas 2009 (WOA09) data from the National Oceanographic Data Center of National Oceanic and Atmospheric Administration (Locarnini et al., 2010) were used in our calculations. The Quick Scatterometer (QuikSCAT) wind data were obtained from the Asia-Pacific Data-Research Center for the period January 1999 to December 2009. Backward Finite-Size Lyapunov Exponents (FSLE) is a useful tool for identifying frontogenetically active regions (Calil and Richards, 2010), which can be obtained from the Center of Topography of the Oceans and the Hydrosphere (CTOH) for the period December 2000 to April 2009. It is defined as $\lambda = \log(\delta_\tau/\delta_0)/\tau$, where δ_0 is the initial separation distance and δ_τ is the final separation distance after time τ. The initial separation distance is 0.04° and the final deformation after time τ is 0.6°.

Mean sea level anomaly (MSLA) and geostrophic velocity data from August 1997 to December 2010 were obtained from the Delayed-Time Reference Series provided by Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO). The data were gridded to 1/4°×1/4° with a time step of 7 days. Spatial high-pass filtering with half-power cutoffs of 20° longitude by 10° latitude was used to attenuate the MSLA variability generated by any large-scale Rossby waves and steric heating and cooling effects (Chelton et al., 2011b). The MSLA data used in this study were from May 1998 to March 2010, matching the time period of the chlorophyll data. The process performed on the chlorophyll and MSLA data was almost same as the method given by Chelton et al. (2011a), except that they filled in the small number of remaining gaps of chlorophyll by bilinear interpolation, whereas we used Kriging interpolation to fill in the remaining data gaps. Each anticyclonic eddy was identified and tracked using a new sea surface height-based method proposed by Chelton et al. (2011b). The method worked as follows: the MSLA field was partitioned starting from a MSLA threshold of −100 cm and proceeded upwards in increments of 1 cm until achieving a closed MSLA contour that satisfied the following criteria: (1) The MSLA value of all of the pixels in the closed MSLA contour were above the MSLA threshold; (2) at least 8 pixels (0.25° per pixel) and fewer than 1000 pixels were enclosed by the closed contour of MSLA; (3) there was at least one local MSLA maximum; (4) the amplitude of the eddy was at least 1 cm; and (5) the maximum distance between any pairs of points within the closed MSLA contour must be less than a specified maximum to exclude the irregular shaped eddies. The specified maximum was obtained according to the method given by Chelton et al. (2011b). Eddies with their centroids located over coastal areas with depths < 200 m were removed. The trajectories of antic-