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Impact of nonlinear mesoscale eddy on phytoplankton distribution in the northern South China Sea

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ABSTRACT

Approximately thirteen years of mean sea level anomaly (MSLA) and chlorophyll (Chl) data in the northern South China Sea (NSCS) were analysed to investigate the influence of a nonlinear, mesoscale eddy on ecological and biogeochemical processes. Over two thousand mesoscale eddies were identified and tracked using a new sea surface height-based method and approximately 40% of these eddies were nonlinear. A westward co-propagation of Chl and MSLA signals at a speed of approximately 0.07 m s^{-1} was found to correspond well with the variability of Chl within cyclonic and anticyclonic eddies. The covariability relationships were different depending on the season. The results of a lagged cross correlation between MSLA and Chl, as well as Chl composite averaging within mesoscale eddies, showed that eddy advection dominates the Chl dipole structure within mesoscale eddies. This mechanism was further confirmed by the significant correlations of the west-to-east Chl difference with background Chl gradient ($R = 0.32$ for cyclonic eddies and $R = -0.20$ for anticyclonic eddies) and eddy scale ($R = 0.33$ for cyclonic eddies and $R = -0.21$ for anticyclonic eddies). Moreover, the strong correlation (0.44) between the in-to-out Chl difference and amplitude for the cyclonic eddy implied that eddy pumping contributes to the high Chl levels near the centre of cyclonic eddy.

1. Introduction

Understanding the influence of oceanic physical processes on the spatial heterogeneity and temporal variability of phytoplankton is of prime importance in understanding physical–biological interactions. Mesoscale eddies are responsible for a major portion of ocean circulation energy, which has a substantial effect on nutrients and phytoplankton movement and distribution.

Mesoscale eddies are ubiquitous in the northern South China Sea (NSCS). They are frequently generated in the northeastern SCS, and most propagate westward and incline a little to the south near the continental slope. Studies of the NSCS mesoscale eddy have mainly focused on the eddy's temporal–spatial variability (Wang et al., 2000, 2003; Wu and Chiang, 2007), eddy genesis and evolution (D. Wang et al., 2008; G. Wang et al., 2008; Zhuang et al., 2010) and the relationship between mesoscale eddies and the Kuroshio (Jia and Liu, 2004).

However, phytoplankton variability due to eddy movement has been sparsely researched. Recent research has indicated that the eddy-induced pumping of nutrients results in higher chlorophyll (Chl) levels within the cyclonic eddy centre in the South China Sea. The cyclonic eddy pumps deeper, nutrient-rich, cold water up into the euphotic zone, and the nutrients stimulate phytoplankton growth (Xiu and Chai, 2011). However, the way in which the anticyclonic eddies affect the Chl pattern in the NSCS remains uncertain. The biological change associated with anticyclonic eddies presents with distinct characteristics in other regions. Some studies have found that the nutrient-rich water transported upwards along the up-bowed isopycnals and the high levels of Chl occur in the periphery of anticyclonic eddies due to upwelling in the periphery (Kahru et al., 2007b; Mizobata et al., 2002; Petihakis et al., 2012). McGillicuddy and Robinson (1997) indicated that there were no ecosystem responses in the anticyclonic eddies. Several researchers have found that high biomass occurs in the centre of anticyclonic eddies in some regions (Moore et al., 2007; Paterson et al., 2008). In the NSCS, Lin et al. (2010) found an anticyclonic eddy that carried coastal, high-nutrient water into the oligotrophic region of the NSCS, leading to high levels of phytoplankton. Ning et al. (2008) found that downwelling caused by a depressed pycnocline led to high temperature, low salinity, impoverished nutrients and reduced Chl concentrations in the euphotic zone of two anticyclonic eddy centres, and they hypothesised that baroclinic instability modulated by topography led to the formation of two anticyclonic eddies in the NSCS. These studies on the NSCS only focused on one or several specific eddy cases (Chen et al., 2007; Huang et al., 2010; Lin et al., 2010). However, mesoscale eddies induce distinct Chl distribution due to unique eddy genesis and evolution, biological backgrounds or interactions with other dynamic processes. The way in which most anticyclonic eddies affect Chl distribution over a longer time period needs to be further examined.

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Furthermore, the effects of other influencing mechanisms remain unclear in the NSCS. Recently, four dominant mechanisms of eddy-driven phytoplankton variability (eddy pumping, eddy-Ekman pumping, eddy advection of meridional property gradients around an eddy and submesoscale pumping) were identified by Siegel et al. (2011). Distinguishing between these mechanisms is very important because each one has a different impact on the spatial patterns of phytoplankton. Eddy advection could be an important vehicle in biomass modulation in many areas with significant meridional property gradients (Chelton et al., 2011b). A large meridional gradient in background Chl (Chl before removal of the seasonal, large-scale variability) in the NSCS coincides with the region of westward propagation of eddies that are generated from the western Luzon Island and the Luzon Strait (Fig. 1), as well as planetary waves (also known as Rossby waves). The superposition of multiple Rossby waves shows eddy-like features from altimetry observations, which makes it difficult to differentiate between eddies and Rossby waves (McGillicuddy, 2011). However, Rossby waves and eddies have different degrees of nonlinearity. Nonlinear eddies retain fluid inside them, and therefore, they transport heat, salt and passive tracers (Chaigneau and Pizarro, 2005; Danabasoglu et al., 1994), but linear Rossby waves do not retain fluid. This difference is very important in recognising the dynamic mechanism for the temporal–spatial variability of phytoplankton.

This paper mainly addresses the spatial variability of Chl in relation to the westward propagation of the mean sea level anomaly (MSLA) in the NSCS. In particular, we examine how nonlinear eddies drive Chl variability in the NSCS.

2. Data and method

The study area for the mesoscale eddy analysis covered the area from 15°N–23°N and 110°E–120°E. The MSLA and geostrophic velocity data that we used cover approximately thirteen years (August 1997–December 2010) and were extracted from the Delayed-Time Reference Series provided by Archiving, Validation and Interpretation of Satellite Data in Oceanography (AVISO). The data were gridded to 1/4° × 1/4° with a time step of 7 days. The MSLA data were high-pass filtered spatially with half-power filter cutoffs of 20° longitude by 10° latitude over the global ocean. This spatial high-pass filtering attenuates MSLA variability associated with any large-scale Rossby waves and removes steric

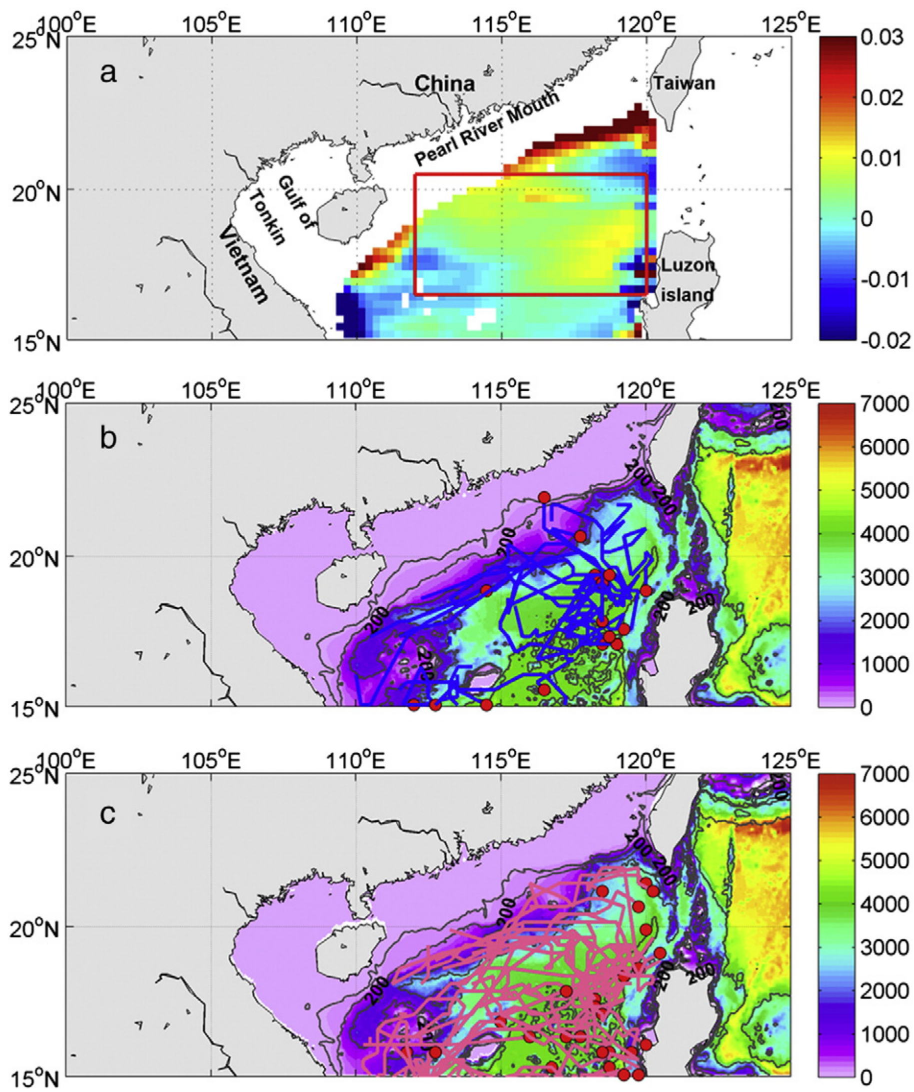

Fig. 1. The distribution of the meridional gradient of surface Chl and the trajectories of eddies with lifetimes > 16 weeks from August 1997 to December 2010 in the NSCS. (a) Meridional gradient of multi-annual mean Log_{10}(Chl), where positive (negative) meridional gradients indicate Chl decreases (increases) from north to south. The red box indicates high Chl meridional gradient regions; (b) The trajectories of cyclonic eddies overlaid upon the bathymetry of the NSCS, with only the 200 m contours shown. The solid red points represent the genesis position of cyclonic eddies, and the lines represent the tracks of cyclonic eddies; (c) the same representation as (b) is shown, but with the trajectories of anticyclonic eddies.