Journal of Sea Research 137 (2018) 1–8

Contents lists available at ScienceDirect

Journal of Sea Research

journal homepage: www.elsevier.com/locate/seares

Influence on phytoplankton of different developmental stages of mesoscale eddies off eastern Australia

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ARTICLE INFO

Keywords:
Oceanic eddies
Phytoplankton
Surface temperature
Divergence
East Australian Coastal Ocean

ABSTRACT

The influence of oceanic mesoscale eddies on their internal phytoplankton levels varies at different developmental stages. Based on 12 years of satellite ocean color observations, we investigated the variability of phytoplankton inside 4564 anticyclonic eddies and 3675 cyclonic eddies off eastern Australia in different development stages using the method of composited average analysis. The results indicated that the lowest level of chlorophyll was observed in the forth (decay) development stage for anticyclonic eddies, which was associated with the warmest SST, largest eddies amplitude, rotation speeds, angular velocities and surface water convergence. It is indicated that downwelling induced by anticyclonic eddies dominates the chlorophyll variations. Because the convergence induced by the ageostrophic velocity components occurred throughout the eddy's development stage, relaxation of the density perturbations (upwelling) associated with eddy decay was not observed in this study. Chlorophyll concentration near the center of cyclonic eddies decreased from the first to the middle stage, and then increased to the largest levels at the last stage. Although vertical motions induced by the ageostrophic velocity components varied from divergence to convergence during the development of an eddy, a higher eddy-ambient water exchange occurred and dominated the increases in total divergence and chlorophyll concentration in the last stage.

1. Introduction

Mesoscale eddies are ubiquitous and play an important role in phytoplankton distribution. Phytoplankton variability and distribution in relation to mesoscale eddies is still hotly debated (McGillicuddy et al., 2007, 2008; Mahadevan et al., 2008). Phytoplankton levels may change with variations in the dynamic processes and environments of eddies. It has been found that when surface stratification is stronger and cyclonic eddies are more intense, the export of particulate organic carbon to the deep ocean is higher than during the rest of the year (Alonso-González et al., 2013). Eddies can sustain phytoplankton growth over nutrient-poor surface waters in the subtropical gyres that extend over mid-latitudes (McGillicuddy and Robinson, 1997). Conversely, Chelton et al. (2011a) suggested that the swirling velocities that surround eddy cores can induce the horizontal advection of chlorophyll. In contrast, Gruber et al. (2011) showed that high eddy activity levels tend to be associated with low biological production levels because eddies cause the diffusion and advection of nutrients along density surfaces, leading to the onshore advection of thick blobs of less-dense water and offshore advection of thick blobs of dense water.

Another way of understanding the eddy-induced phytoplankton variations is to think of the life cycles (development stages) and associated variations in eddy properties (including eddy amplitude, scale, rotation and translation speed, nonlinearity and angular velocity). Mesoscale eddies can trap and transport water masses within their interiors, and they usually persist for months over distances of hundreds of kilometers. Mesoscale eddies initially provide horizontal and vertical transfer of heat and nutrients; and then as they mature, they trap the initial water mass and move away; eventually, the eddies die and release their anomalous properties to a new environment (Williams, 2011). Phytoplankton levels and communities may change during the eddy life cycle (Condie and Condie, 2016). Furthermore, throughout the entire developmental stage of an eddy, continuous variations of phytoplankton levels may be generated from variations in eddy amplitude, scale, translation speed, linear rotation velocity, nonlinear degree and rotational angular velocity. The variations in these eddy properties change the distributions and levels of phytoplankton by affecting the upwelling displacement and horizontal scale of swirling eddies. For example, changes in eddy amplitude, which are usually associated with the vertical displacement of the isopycnic surfaces,

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https://doi.org/10.1016/j.seares.2018.03.004
Received 22 March 2017; Received in revised form 13 March 2018; Accepted 15 March 2018
Available online 26 March 2018

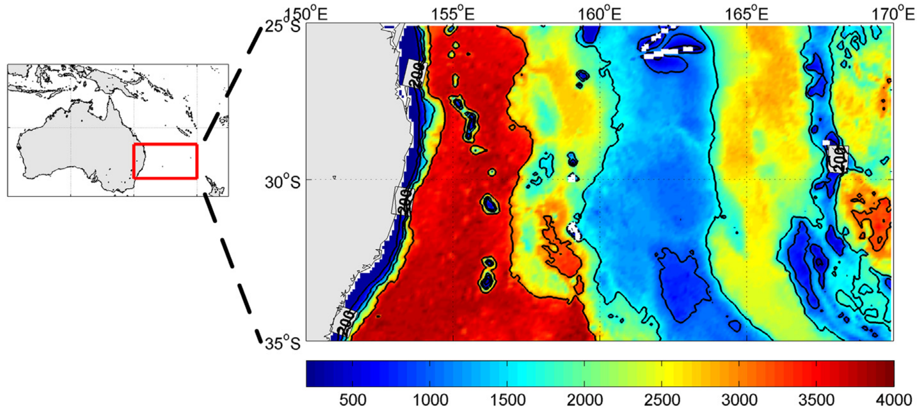

Fig. 1. Bathymetry map of the study area; only 200 m contours are shown.

likely compensate for or reduce the nutrients in the well-illuminated upper ocean, resulting in increases or decreases in phytoplankton biomass (McGillicuddy and Robinson, 1997; Siegel et al., 1999, 2011). Eddy vorticity, which is defined as twice the rotational angular velocity, is closely related to both the variability of the mixed layer depth and temperature distributions (Smith et al., 1996).

The east coast of Australia is located in the southwest Pacific Ocean. The main dynamic features off the east coast of Australia include South Equatorial Current (SEC) inflow, bifurcation, the East Australian Current (EAC) and its separation, the Tasman Front and New Zealand eddies (Ridgway and Dunn, 2003). South Pacific waters are transported in the westward-flowing SEC from the subtropical gyre center toward the southwest Pacific Ocean. A branch of the SEC reaches the east coast of Australia, and is transported southward and enters the Tasman Sea, forming the EAC (Ganachaud et al., 2013). The EAC flows along the eastern coast of Australia, staying close to the continental shelf (Wood et al., 2016). The spatial structure of the mean flow is influential down to the mesoscale (Ridgway and Dunn, 2003). The east coast of Australia is characterized by highly variable sea surface height (SSH) (Qiu and Chen, 2004) and is a highly variable system with a large number of mesoscale eddies that dominate the flow. Ridgway and Dunn (2003) evaluated four quasi-permanent eddies off the east coast of Australia, including the Norfolk Eddy, North Cape Eddy, and two eddies associated with the EAC flow within the Tasman Abyssal basin. Many researchers have studied the eddies associated with the EAC flow (located to the west of 158°E) and identified that the saddle point connects the two eddies at 29°S, and the EAC separation point is located at approximately 32–34°S (Ridgway and Dunn, 2003; Tilburg et al., 2001). South of the separation point, the EAC becomes unstable and dissipates as an eddy system. Studies on eddy frequencies and dynamics (Brassington et al., 2011; Oke and Griffin, 2011), eddy temporal variations (Qiu and Chen, 2004), and the relationships between mesoscale eddies and the currents and topography (Mata et al., 2006; Ridgway and Dunn, 2003) have been mainly focused on the mesoscale eddies that are associated with the EAC meander and the Tasman Front.

Nutrient supply is an important and limiting factor of the abundance of phytoplankton off eastern Australia (Syahailatua, 2005). Nutrient levels can be influenced by mesoscale eddies, coastal upwelling, topography and winds, all of which can stimulate phytoplankton blooms (Ridgway and Dunn, 2003; Roughan and Middleton, 2002). Cyclonic eddies can affect phytoplankton biomass, biodiversity and productivity. Higher phytoplankton biomasses have been observed inside the cold eddies (Hassler et al., 2011). Within eddies, a vertical supply of nutrients occurs, which increases the phytoplankton biomass. Moreover, cyclonic eddies near the EAC can retain the assemblages of their origin and transport the water mass from the continental slope to the shelf (Tranter et al., 1986; Hassler et al., 2011). The phytoplankton concentrations in EAC anticyclonic eddies have been found to be elevated and higher than the original concentrations (when they had formed). This finding differs from the results that anticyclonic eddies depress the pycnoclines, push nutrient-depleted water out of the well-illuminated surface layers and form oligotrophic conditions. Most previous studies of the biological response in mesoscale eddies mainly focused on the mesoscale eddies associated with the EAC meander and the Tasman Front. Phytoplankton variability that was induced by mesoscale eddies has mainly been found in previous studies in one or several specific cases (Baird et al., 2011). However, except for the eddies that were associated with large-scale ocean currents, mesoscale eddies are ubiquitous in the study area. The statistics of these mesoscale eddies are beneficial to the identification of their common impacts on the distributions and variations of phytoplankton. For these mesoscale eddies, phytoplankton distributions in relation to the different developmental stages of eddies are still unclear.

This paper is organized as follows. In Section 2, we define five development stages of eddies according to the eddies trajectory, describe the eddy properties and compositely averaged analysis used for the statistics of all mesoscale eddies at five developmental stages. In Section 3, to identify the common features of the biological responses in all mesoscale eddies and determine phytoplankton distributions in relation to the different developmental stages of eddies, statistics on the phytoplankton levels inside eddies at five normalized developmental stages were collected for all of the identified eddies with a lifetime greater than five weeks. Eddy properties in different developmental stages are also presented to analyze their relationships with the variability in phytoplankton levels. A conclusion of this study is presented in Section 4.

2. Materials and methods

The study area is located off eastern Australia (25°S–35°S, 150°E–170°E) and covers an area of 2.05 million km^2 (Fig. 1). The bathymetry shows a longitudinal pattern and is dominated by several ridges that radiate northwards (Ridgway and Dunn, 2003). Daily 9 km Sea-viewing Wide Field-of-view Sensor (SeaWiFS) chlorophyll products were obtained from the National Aeronautics and Space Administration's (NASA's) Ocean Color website (https://www.oceancolour.org/) for the period from August 1997 to December 2010. These products were generated using the Garver–Siegel–Maritorena (GSM) algorithm (Maritorena et al., 2002, 2010). The chlorophyll products were log10 transformed and interpolated to a 0.25° × 0.25° grid with a time step of 7 days. Weekly sea surface temperature (SST) data from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) for the period from December 1997 to December 2010 were obtained from the Asia-Pacific Data-Research Center. Chlorophyll and SST data were low-pass filtered temporally using a loess smoothing filter with a half-power cutoff of 30 days to remove the anomalous values. The data were then