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A coupled physical–biological modeling study of the offshore phytoplankton bloom in the Taiwan Strait in winter

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ABSTRACT

In-situ observations find that offshore phytoplankton blooms occur occasionally in the north-central Taiwan Strait (TWS) in winter, but the formation mechanisms behind are not yet understood. We simulate the offshore bloom scenario in the winter of 1998 with a coupled physical–biological numerical model. Model results illustrate that when the northeasterly wind is relaxed, a cross-strait current is induced, which carries diluted Min-Zhe Coastal Water (MZCW) offshore, extending into the upper layer of the western TWS. Vertical mixing is weakened in the western TWS due to intensified stratification formed by the location of fresh MZCW over saline water. Consequently, the vertical diffusion of chlorophyll decreases, and the bloom occurs in the upper layer of the western TWS. Additionally, the cross-strait current carries the high chlorophyll concentration from near-shore to offshore regions, forming a maximal offshore chlorophyll concentration. We propose that the relaxation of the northeasterly wind acts as a trigger for the winter bloom occurrence in the TWS through complicated physical processes, i.e., the diluted MZCW extending offshore, the stratification intensifying and mixing weakening, forming distinctive characteristics of winter blooms in the TWS.

1. Introduction

The Taiwan Strait (TWS) connects the East China Sea and South China Sea and is located in the western Pacific (Fig. 1). The circulation structure of the TWS is controlled strongly by the Asian monsoon (Hu et al., 2010). A strong northeasterly wind prevails in the region during winter (December to February), with a mean speed of approximately 10.2 m s^{-1} (Hu et al., 2010); the corresponding general circulation structure is shown in Fig. 1. The strong wind drives the cold, fresh and nutrient-rich Min-Zhe Coastal Water (MZCW), which flows into the strait along the Chinese coast. Meanwhile, the South Mixing Water (SMW), which is composed of warmer and higher salinity Kuroshio branch water and South China Sea subsurface water, intrudes into the strait from the southeastern canyon, i.e., the Penghu Channel (Hu et al., 2010; Jan et al., 2002; Wang and Chern, 1988).

The MZCW provides sufficient nutrients for phytoplankton growth in the TWS. However, the phytoplankton biomass in the TWS is relatively low in winter, with a mean chlorophyll concentration of less than 1.0 mg m^{-3} (Zhang, 2001; Zhang and Huang, 2000). Winter mean chlorophyll data detected of the Moderate Resolution Imaging Spectroradiometer (MODIS) (Fig. 2) over 10 years (2002–2012) indicate that the surface chlorophyll concentration is approximately 1.0–2.0 mg m^{-3} in the central TWS. However, anomalously high chlorophyll concentrations (approximately 2.5–3.0 mg m^{-3}) compared to the climatological winter status were found in the north-central TWS from the transect observations in the winters of 1998 (Zhang and Huang, 2000; Naik and Chen, 2008) (indicated by the red shadows in Fig. 2). These anomalously high chlorophyll concentrations are labeled as the winter offshore bloom in the TWS.

Mixing is typically intensive in the TWS during winter due to strong wind speeds. The occurrence of the offshore bloom is beyond our understanding under such kinetic conditions. Because of the severe sea state in winter, there are limited cruise data to explain the existence of the offshore bloom. Furthermore, the satellite chlorophyll data are scarce due to large cloud cover. Hence, the mechanisms driving bloom occurrence are not yet understood.

We use a coupled physical–biological model to study a winter offshore bloom scenario in 1998. The model description and evaluation are given in Section 2. In Section 3, the modeled biological and physical results illustrate a weakened mixing effect on bloom production due to a relaxation of the northeasterly wind. In Section 4, an analytical model further confirms the mixing effect on bloom production. Subsequently, we emphasize that an intensified stratification plays a dominant role in reducing mixing. Moreover, the effect of advection on maximal offshore chlorophyll formation is discussed. Finally, the physical and biological processes that induce bloom are summarized in Section 5.

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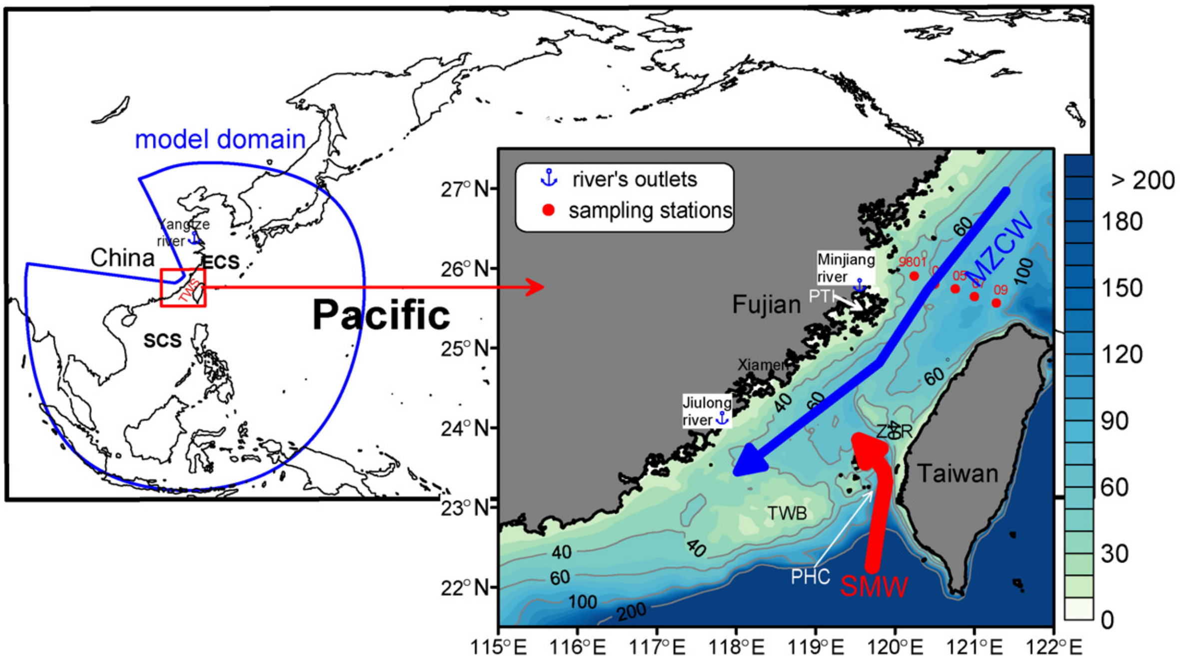

Fig. 1. Model domain and bathymetry (with isobaths shown) of the Taiwan Strait, which is indicated by the red box (inset). The red dots mark the cruise sampling stations (9801–9809) in 1998. The blue anchor symbol indicates river's outlet. The thick arrowed lines indicate the main circulation in the strait in winter: MZCW for the Min-Zhe Coastal Water (blue), SMW for South Mixing Water (red), ECS: East China Sea, SCS: South China Sea, TWS: Taiwan Strait, PTI for Pingtan Island, PHC for the Penghu Channel, ZYR for Zhangyun Ridge, and TWB for the Taiwan Bank.

2. Model description and evaluation

2.1. Physical model

The physical model used in this study is the Regional Ocean Model System (Shchepetkin and McWilliams, 2005), which is a primitive equation model under hydrostatic and Boussinesq assumptions. The model has a curvilinear-orthogonal grid in the horizontal direction, and the grid size varies from 40 km at the open boundary to 1.5 km in the TWS. The model domain covers the northwestern Pacific from 93.13°E to 147.68°E and from 8.54°S to 44.9°N (see the inset in Fig. 1).

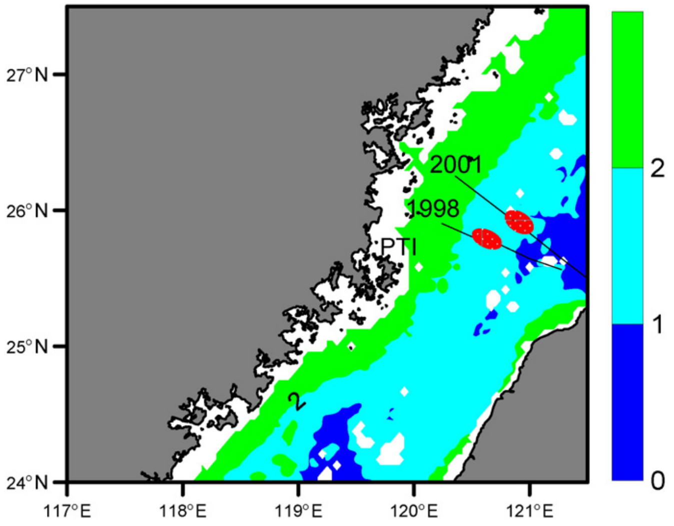

Fig. 2. Climatological mean chlorophyll in winter (December–February) (unit: mg m^{-3}) derived from MODIS 1992–2012 daily data. The red shadows indicate the anomalous offshore blooms (2–3 mg m^{-3}) observed in 1998 and 2001, respectively. The black lines show the observation sections.

The water column is vertically divided into 30 layers following the S-coordinate scheme (Song and Haidvogel, 1994), with an enhanced resolution in the euphotic zone. The average depth is approximately 60 m in the TWS, and the vertical resolution ranges from 0.1 to 5 m from surface to bottom. The vertical mixing coefficient is calculated using the Mellor and Yamada 2.5-turbulence closure model (Mellor, 2001; Mellor and Yamada, 1982). The model bathymetry is interpolated from 2-minute global relief data and combined with the digitized depth data along the Chinese coast published by China's Maritime Safety Administration.

2.2. Biological model

A nitrogen-based nutrient–phytoplankton–zooplankton–detritus model (Fennel et al., 2006) is coupled with the physical model. The model schematic is shown in Fig. 3. Separating new and regenerative productivity processes and considering the aggregate effect of detritus, the model contains seven state variables: nitrate (NO_3), ammonium (NH_4), phytoplankton (PHYTO), chlorophyll (CHLO), zooplankton (ZOOP), small detritus (SDET), and large detritus (LDET). The relationship between chlorophyll and phytoplankton biomass is calculated using the method of Geider et al. (1996, 1997), which considers the change in chlorophyll content per phytoplankton cell relative to changes in light and nutrient conditions. NO_3 and NH_4 support new and regenerated productivities, respectively. The model also considers the inhibition of NO_3 uptake by NH_4. The detritus is divided into large and small components according to size. The mortality of phytoplankton and inefficient ingestion by zooplankton generate small detritus. Small detritus can aggregate with the phytoplankton to form large detritus in the model. A fraction of the detritus is mineralized into NH_4 in the water column, with the remaining fraction sinking toward the seabed.

In this study, we adopt the simplified scheme of coupling pelagic and benthic systems, as proposed by Soetaert et al. (2000), where the organic matter that reaches the bottom of the domain is immediately remineralized into NH_4 and added to the water composition in this region. The advantage of this scheme is that it ensures mass conservation in both