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Coupling of the spatial–temporal distributions of nutrients and physical conditions in the southern Yellow Sea

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ABSTRACT

This study investigated the coupling of the spatial–temporal variations in nutrient distributions and physical conditions in the southern Yellow Sea (SYS) using data compiled from annual-cycle surveys conducted in 2006–2007 as well as satellite-derived sea-surface temperature (SST) images. The influence of physical dynamics on the distribution and transport of nutrients varied spatially and seasonally in the SYS. The Changjiang Diluted Water (CDW) plume (in summertime), the Subei Coastal Water (SCW) (year-round), and the Lubei Coastal Current (LCC) (in wintertime) served as important sources of nutrients in the inshore area in a dynamic environment. The saline Taiwan Warm Current (TWC) might transport nutrients to the northeast region of the Changjiang Estuary in the summer, and this nutrient source began to increase from spring to summer and decrease when autumn arrived. Three types of nutrient fronts, i.e., estuarine, offshore, and coastal, were identified. A circular nutrient front caused by cross-shelf transport of SCW in the southeast shelf bank area in the winter and spring was observed. The southeastward flow of western coastal cold water in the SYS might be an important conduit for cross-shelf nutrient exchange between the SYS and the East China Sea (ECS). The tongue-shaped low-nutrient region in the western study area in the wintertime was driven by the interaction of the southward Yellow Sea Western Coastal Current (YSWCC) and the biological activity. The vertically variable SCM (subsurface Chl-a maximum) in the central SYS was controlled by coupled physical–chemical processes that involved stratification and associated nutricline. The average nutrient fluxes into the euphotic zone due to upwelling near the frontal zone of the Yellow Sea Cold Water Mass (YSCWM) in the summer are estimated here for the first time: $1.4 \pm 0.9 \times 10^3$ μmol/m^2/d, $0.1 \pm 0.1 \times 10^3$ μmol/m^2/d, and $2.0 \pm 1.3 \times 10^3$ μmol/m^2/d for DIN, PO_4–P, and SiO_3–Si, respectively. The depletion of nutrients in the central SYS and the upwelled transport in the boundary of the YSCWM resulted in a spatial transfer of the high Chl-a zone, varying generally from the central SYS to the boundary of the YSCWM from spring to summer, and the nutrient flux associated with this upwelling could contribute significantly to local primary production. This study deepens our understanding of the mechanisms influencing the distribution and transport of nutrients in the SYS.

1. Introduction

The southern Yellow Sea (SYS) is a semi-enclosed marginal sea bordered by the Chinese mainland to the west and the Korean Peninsula to the east, and there is a deep trough (>70 m) that extends generally northwestward in the central area (Fig. 1). In the winter, the current system over the continental shelf is primarily characterized by a southward movement of coastal water (Uda, 1934, 1936) and a northwestward inshore intrusion of the Yellow Sea Warm Current (YSWC) (Teague and Jacobs, 2000; Lie et al., 2009; Yu et al., 2010; Yuan and Hsueh, 2010; Lin et al., 2011). In contrast, in the summer, the Yellow Sea Cold Water Mass (YSCWM) (Ho et al., 1959; Takahashi and Yanagi, 1995; Zhang et al., 2008) and the northeastward expansion of the Changjiang Diluted Water (CDW) (Beardsley et al., 1985; Chang and Isobe, 2003) characterize the SYS current system; meanwhile, the front of the Taiwan Warm Current (TWC) (Guan, 1994) can reach the southeastern area of the SYS in the summer.

Nutrients are the material basis of marine biogeochemical cycles and, thus, play an important role in marine primary productivity and phytoplankton growth (Tyrrell, 1999). The SYS is a highly productive region with several commercially important fisheries (Tang and Su, 2000; Lin et al., 2005); moreover, a highly characteristic phytoplankton composition has been observed in the SYS (Huang et al., 2006; Fu et al., 2009a). As nutrients strongly influence phytoplankton growth and,

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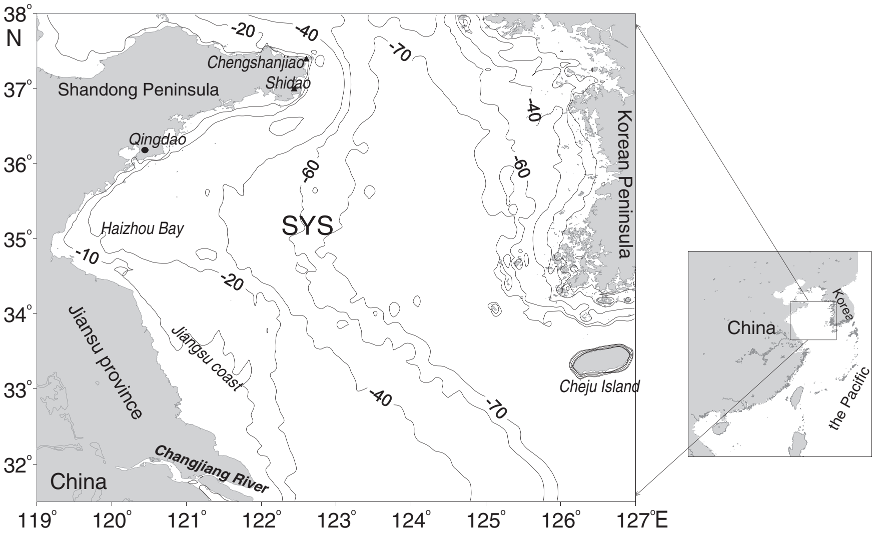

Fig. 1. Geography and depth (m) isobaths of the SYS.

consequently, food web dynamics, the study of the spatial–temporal variations in nutrient distributions in the SYS and of the underlying mechanisms is important for understanding this marine ecosystem. Several studies, primarily conducted since the 1980s, have investigated nutrient conditions in the SYS. Many of these studies have been conducted by oceanographers from China and Korea and have provided information regarding nutrient transport (Wang et al., 1999; Wang, 1999), nutrient limitation (Lin et al., 2002; Wang et al., 2003; Gao et al., 2004; Sun et al., 2008), and seasonal variations in nutrient distributions along a 35°N transect (121°–125°E) (Wang, 2000). Moreover, various aspects of the dynamics and budgets of nutrients in the SYS have also been described (Chung et al., 1991; Bashkin et al., 2002; Wang et al., 2002; Tian et al., 2003, 2005; Liu et al., 2003; Jin et al., 2013). However, these studies on nutrient distribution primarily focused on small locally important areas within the SYS or the central area. Using nutrient data originating primarily from marine atlases (Wang, 1991; KORDI, 1987, 1993) and other sources (Chen, 1996; Lee et al, 1998; Wang, 2000; Wang et al, 2003), Chen (2009) produced several nutrient maps and identified the nutrient fronts associated with physical fronts in the Bohai, Yellow and East China Seas. Based on these modified surface maps, Chen (2008) provided a comprehensive description of nutrient distributions in those areas. However, there have been few studies of the coupling of nutrient conditions and physical processes over a large scale in the SYS based on data from annual-cycle investigations with intensive sampling (Wang et al., 1999; Liu et al., 2003; Sun et al., 2008; Chen, 2009; Jin et al., 2013). Furthermore, there has been a lack of research on the horizontal transport of nutrients under the influence of individual physical forces in the SYS, and on the upwelled transport of nutrients in the boundary area of the YSCWM where a tidal upwelling occurs (Zhao, 1987; Lü et al., 2010) in summer.

We previously investigated the general patterns of nutrient distribution regarding seasonality (Wei et al., 2010a,b,c, 2011b) in the SYS using data from investigations conducted during 2006–2007. This paper focuses primarily on the coupling of spatial–temporal variations in nutrient distributions and physical–biological conditions in the SYS. We present research in the following four categories: 1) the physical conditions, including the current structure and the classification of water bodies, are described in more detail, and the seasonal cycle of nutrient distributions is reconstructed; 2) based on field observations, statistical analyses, and the incorporation of remote-sensing data, the impacts of different water masses on nutrient transport and nutrient fronts are investigated, and the hydrodynamic mechanisms associated with nutrient fronts on the southeast shelf bank in the SYS in the wintertime and their implications for cross-shelf nutrient transport are individually identified; 3) the interactions among related physical–biogeochemical parameters in the western and central SYS are examined; and 4) the effects of upwelled water around the boundary of the YSCWM on the vertical transport of nutrients and on subsequent phytoplankton growth are further portrayed as they exist under stratified conditions during the summer. Our investigation of these issues provides a detailed understanding of the mechanisms regulating nutrient conditions in the SYS and represents a substantial expansion of previous work. Our findings also provide a scientific foundation for the accurate modeling of nutrient cycling and studies of ecosystem dynamics in the SYS.

2. Materials and methods

The temperature, salinity, and nutrient data in this study were compiled from reports by Wei et al. (2010a,b,c, 2011b) and one additional study (Ge et al., 2010). The data were collected in the spring (Apr. 4–26, 2007), summer (Jul. 14–Aug. 3, 2006), autumn (Oct. 6–Nov. 5, 2007), and winter (Jan. 8–Feb. 4, 2007). The station locations, sampling resolution and the collection of temperature, salinity, nitrate (NO_3–N), nitrite (NO_2–N), ammonia (NH_4–N), phosphate (PO_4–P), and silicate (SiO_3–Si) data in each season have been described elsewhere (Wei et al., 2010a,b,c, 2011b). Dissolved inorganic nitrogen (DIN) was calculated as the total of NO_3–N, NO_2–N, and NH_4–N. The Chl-a data and primary productivity data used in this study are derived from Fu et al. (2009a) and Sun et al. (2012), respectively. Specifically, water samples of nutrients were analyzed by spectrophotometry after filtration through 0.45 μm cellulose acetate fiber filters (which were pretreated by combusting at 50 °C for 5 h). NO_3–N and NO_2–N were determined by the standard pink azo dye method and NH_4–N by the hypobromate oxidation-pink azo dye method; PO_4–P and SiO_3–Si were determined by the standard molybdenum blue method, respectively. All the methods and procedures were in accordance with that recommended by Parsons et al. (1984) and calibrated with standard substances (state second level standard substances of China). The precisions for determining NO_3–N, NO_2–N, NH_4–N, PO_4–P, and SiO_3–Si were ± 0.3, ± 0.02 ± 0.1, ± 0.02, and ± 0.2 μmol/L, respectively. Samples for Chl-a were filtered through GF/F filters and then quickly frozen at -20 °C in dark until analysis in laboratory; Chl-a was extracted in 90% v/v acetone and measured using a Turner Designs TD-700 fluorometer (Parsons et al., 1984). Primary productivity was measured by using the isotopic (^{14}C) tracer method established by Steemann Nielsen (1952).