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Seasonally chemical hydrology and ecological responses in frontal zone of the central southern Yellow Sea

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ABSTRACT

Based on annual-cycle survey data collected in 2006–2007 in the southern Yellow Sea (SYS) and analyses on the seasonally chemical hydrologic characteristics of the boundary front of the Yellow Sea Cold Water Mass (YSCWM) and Yellow Sea Warm Current (YSWC), the seasonal variations in upwelling along the frontal zone were determined, and the ecological impacts of the front were investigated. During the generation and dissipation of the YSCWM, the implied upwelling along its western front exhibited seasonal variation. The upwelling first shifted westward from the deep-water region to its westernmost point in summer then returned eastward. The intensity of the upwelling gradually increased from spring to summer and decreased in autumn. In spring, the existence of cold water west of the YSWC was not conducive to the reproduction of phytoplankton. Additionally, the front to the east of this cold water mass also made the western boundary of the phytoplankton bloom region in the central SYS more obvious, forming a prominent chlorophyll a (Chl-a) front. During the entire stratified season (summer and autumn), the upwelling in the frontal zone of the YSCWM played an essential role in maintaining the relatively high concentrations of Chl-a. In winter, the front that formed at the intersection of the YSWC and coastal cold water was also favorable for the formation of the high-Chl-a region. The distribution of anchovy biomass was closely related to the seasonal variations in the position of the frontal zone. In winter and spring, the tongue-shaped warm water and front associated with the intrusion of the YSWC into the SYS had a significant impact on anchovy. During the stratified season in summer and autumn, the development of a front near the boundary of the YSCWM was an important physical driving mechanism for the dense distribution of anchovy. This work enhanced the study of the seasonal relationships between the physical, chemical and biological processes in the frontal zone of the central SYS and deepened our understanding of the ecological significance of this front.

1. Introduction

As the interface between oceanic current systems or water masses with different properties, oceanic fronts are one of the main physical factors closely related to ecologically dynamic processes. Circulation in a frontal zone is relatively complicated, and upwelling and convergence areas are often present (James, 1978; Roughan and Middleton, 2002) and can deliver abundant nutrients for the growth of phytoplankton. Additionally, the complementary environmental factors provided by the intersection of water masses can also promote the reproduction of phytoplankton (Salvide, 1976), which is favorable for the feeding and reproduction of zooplankton and fish. Fishing grounds are often located in frontal areas with relatively high production; therefore, fronts are of great ecological significance (Tang and Su, 2000; Chen et al., 2003).

The Yellow Sea (YS) is a semi-enclosed marginal sea, with an average water depth of 44 m. There is a north–south oriented trough (>70 m) in the central area, and the bathymetric contours on both sides of the trough are generally parallel to the coastline. The line connecting Chengshantou on the Shandong Peninsula of China and Chang San-got in Korea divides the YS into two parts, the northern Yellow Sea (NYS) and the southern Yellow Sea (SYS) (Fig. 1). The Yellow Sea Warm Current (YSWC) invades from the southeast to the north in winter (Teague and Jacobs, 2000; Lie et al., 2009; Yu et al., 2010) and the Yellow Sea Cold Water Mass (YSCWM) is entrenched at the bottom in summer (Ho et al., 1959; Yu et al., 2006; Zhang et al., 2008). These water masses represent the two most important physical oceanographic features in the central YS. In addition, a southward coastal flow is present in winter along the eastern and western sides of the YS (Uda, 1934, 1936) and corresponds to the northward YSWC in the central

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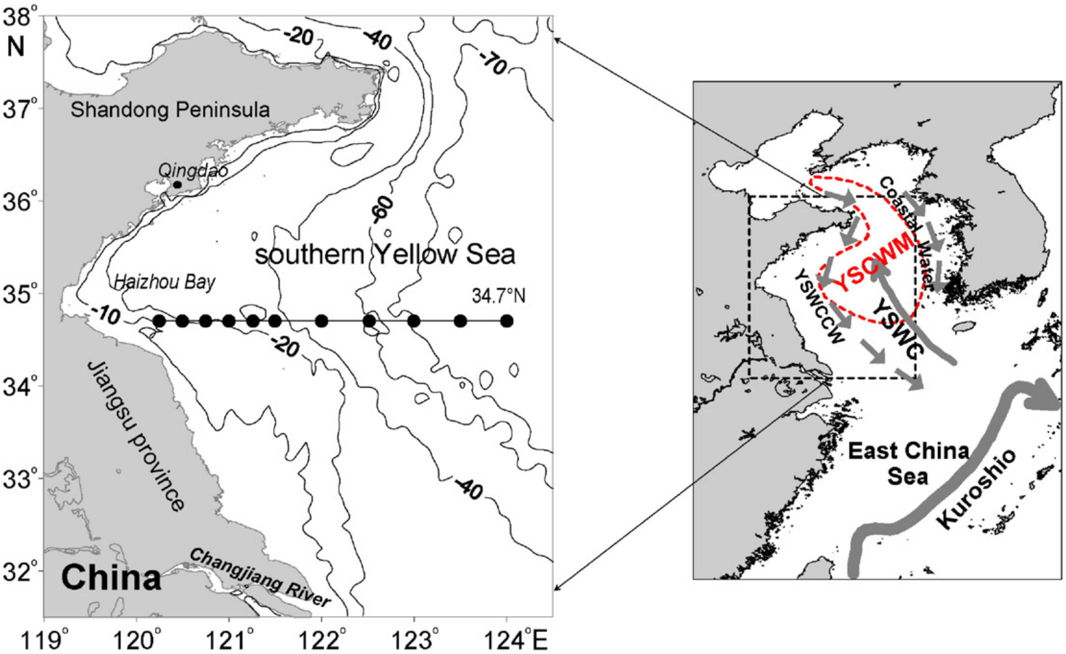

Fig. 1. Map of the study area, which shows the geographic site locations along the cross-shelf transect of 34.7°N with depth (m) isobaths in the SYS and related circulation components (note: YSWC represents Yellow Sea Warm Current in winter and spring; YSWCCW represents Yellow Sea Western Coastal Cold Water in winter and spring; the area surrounded by the enclosed dashed red line represents the general range of the YSCWM in summer).

sea area. Under the impact of these current fields, an oceanic front with distinctive features is always present at the boundary of the YSWC in winter and at the boundary of the YSCWM in summer (Chen, 2009). Previous studies indicate that the YSCWM and YSWC grow and dissipate alternately; the YSWC is strongest in winter, whereas the YSCWM is strongest in summer. The residual water of the YSWC retained from the winter and spring provides important background conditions for the formation of the YSCWM (Ho et al., 1959; Yu et al., 2006). Influenced by the succession process of the YSCWM and YSWC, the front at the boundary can also exhibit certain seasonal variations, and the variation in the position of the front can to some extent control the mixing and exchange between the coast and the central area of the YS. Moreover, some studies have shown that there is also an upwelling in the boundary frontal zone of the YSCWM in summer (Xia and Guo, 1983; Lie, 1986; Zhao, 1987; Lü et al., 2010; Wei et al., 2016) that can induce dense distributions of phytoplankton and significant subsurface chlorophyll a (Chl-a) maximum (SCM) phenomenon (Fu et al., 2009b). As one of the critical species in the YS ecosystem (Tang and Su, 2000), the migration and distribution of anchovy are also closely connected to the generation and dissipation of the YSCWM and YSWC (Ma, 1989; Zhu and Iversen, 1990; Chen et al., 1997; Jin et al., 2005; Li et al., 2007b; Huang et al., 2010). Additionally, *Calanus sinicus* and anchovy eggs can form dense distributions near the frontal zone of the YSCWM (Liu, 2002; Wei et al., 2003; Zhou et al., 2008; Wang et al., 2013), which is an oversummering site for *C. sinicus* (Wang et al., 2003; Pu et al., 2004). A certain association exists between the position of the frontal zone around the YSCWM and fish catches in the warm season (Su, 1986; Zhu and Iversen, 1990; Wan et al., 2002, 2008). Therefore, the hydrological characteristics of the boundary frontal zone of the YSWC and YSCWM and its seasonal variations have a significant impact on the primary production process and fishery resources.

Studies on the YS oceanic front have been conducted previously, mainly using in situ observational data (Tang and Zheng, 1990; Zhao, 1987; Chen, 2009), satellite remote sensing data (Zheng and Klemas, 1982; Hickox et al., 2000; Huang et al., 2010), and numerical simulation methods (Lie, 1989; Wei and Yang, 1993; Qi and Su, 1998; Liu et al., 2003; Liu, 2003; Lü et al., 2010). The ecological effects of the frontal zone in the YS have also been partially examined (Liu, 2002; Wei et al., 2003; Li et al., 2007a; Zhou et al., 2008; Fu et al., 2009b; Wei et al., 2016). However, the seasonal variations and coupling of the typical hydrological, chemical, and biological characteristics in the boundary frontal zone during the generation and dissipation of the YSCWM and YSWC have not been well understood. In this paper, observational data on various environmental factors and anchovy biomass are used to explore the seasonally chemical hydrology in the frontal zone of the central SYS and determine the seasonal variations in frontal upwelling. Consequently, some ecological impacts associated with this front and the physical–biogeochemical coupling mechanisms were examined.

2. Materials and methods

The data were collected during four surveys in the SYS in spring (Apr. 4–26, 2007), summer (Jul. 14–Aug. 3, 2006), autumn (Oct. 6–Nov. 5, 2007), and winter (Jan. 8–Feb. 4, 2007). These cruises were supported by the special project “Comprehensive Investigation and Assessment of Coastal Seas in China”. The surveyed area was located at 32°20′–36°40′N and west of 124°00′E, as previously shown by Fu et al. (2009a) and Wei et al. (2010). The station locations, sampling resolution and analytical methods for the various parameters (temperature, salinity, density, nutrients and Chl-a) used in this paper have been described elsewhere (Fu et al., 2009a; Wei et al., 2010; Ge et al., 2010). In particular, to examine the coupling between physical, chemical, and biological processes in the frontal zone of the central SYS, the data from the typical cross-shelf transect of 34.7°N (Fig. 1) were also selected from the original database. To determine the thermocline and pycnocline in the surveyed area during the summer, a quasi-step function approximation method (Ge et al., 2003) was adopted to fit the vertical profiles of temperature and density.

The anchovy biomass data used in this paper were obtained via the following procedures: a bottom trawl was used (screen mesh of 836 mesh × 20 cm; screen heights varying from 6.1 m to 8.3 m according to the water depth and warp length; net mouth width ranging between 24.5 m and 25.9 m) to trawl the fishery resources at 23 stations during the four surveys in the SYS. The trawl was dragged for 1 h at