Continental Shelf Research 30 (2010) 620–632

Contents lists available at ScienceDirect

Continental Shelf Research

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

Upwelling and surface cold patches in the Yellow Sea in summer: Effects of tidal mixing on the vertical circulation

Xingang Lü [a,b], Fangli Qiao [a,b,*], Changshui Xia [a,b], Guansuo Wang [a,b], Yeli Yuan [a,b]

[a] The First Institute of Oceanography, State Oceanic Administration (SOA), 6 Xianxialing Road, Hi-Tech Industrial Park, Qingdao 266061, PR China
[b] Key laboratory of Marine Science and Numerical Modeling (MASNUM), SOA, 6 Xianxialing Road, Hi-Tech Industrial Park, Qingdao 266061, PR China

ARTICLE INFO

Article history:
Received 21 December 2008
Received in revised form
28 June 2009
Accepted 3 September 2009
Available online 15 September 2009

Topical issue on "Tides in Marginal Seas" (in memory of Professor Alexei V. Nekrasov). The issue is published with support of the North Pacific Marine Science Organization (PICES).

Keywords:
Upwelling
Surface cold patch
Tidal mixing
Secondary circulation
Numerical modeling
Mechanism
The Yellow Sea

ABSTRACT

A three-dimensional, prognostic, wave–tide–circulation coupled numerical model is developed to study the effects of tidal mixing on the summertime vertical circulation in the Yellow Sea (YS). The distribution and mechanisms of upwelling are investigated by numerical means. Validated by historical tide gauge data, satellite sea surface temperature (SST) data, and cruise observation data, the model shows satisfactory performances in reproducing the dominant tidal system and three-dimensional sea temperature structure. Model results suggest that strong tidal mixing plays an important role in the formation of the vertical circulation in the YS. The Yellow Sea Cold Water Mass (YSCWM) is fringed by typical tidal mixing fronts (TMFs), which separate the cold, stratified water at the offshore side from the warm, well-mixed, shallow water at the other side. Considerable baroclinic gradient across the TMF makes the frontal zone the spot where the most active vertical circulation occurs; a secondary circulation is triggered with a distinct upwelling branch occurring mainly on the mixed side of the front. The numerical model produces systematic upwelling belts surrounding the YSCWM, and the upwelling is essentially induced by the TMF over sloping topography. The relative importance of tidal mixing and wind forcing for upwelling is further examined in numerical experiments. The southerly wind enhances the upwelling off the western coasts, but its overall influences in the whole YS are less important than tidal mixing. As shown by both satellite data and numerical modeling, the summertime SST field in the YS is featured by the stable existence of several site-selective surface cold patches (SCPs), most of which scatter in the waters off convex coastlines. One of the SCPs is found off Subei Bank, and the others are located off the eastern tip of Shandong Peninsula and off the three tips of Korean Peninsula. Two processes give rise to the SCP: on the one hand, TMF-induced upwelling supplies cold water from the deep layer; on the other hand, tidal mixing itself can stir the bottom water upward and homogenize the water column vertically. In the waters around the tips of peninsula in the YS, the tidal currents are extraordinarily strong, which provides a possible explanation for the site-selectivity of the SCPs.

1. Introduction

The Yellow Sea (YS), semi-enclosed by China and Korean Peninsula, is one of the western Pacific marginal shallow seas. The water depth in the YS is only 44 m on average, with a maximum about 100 m in the central trough, which extends northwestward into the Bohai Sea. The seaward connection to the East China Sea (ECS) covers a broad shelf along a line from the northern side of Yangtze River mouth to Cheju Island. The YS is divided into northern and southern YS (SYS) by a line between Chengshanjiao in Shandong Peninsula and Jangsan point in Korean Peninsula. The bathymetry along the western coasts (China side) in the SYS is characterized by a wide shallow water, Subei Bank (Fig. 1).

In warm seasons, the whole Yellow Sea is occupied by a basin-scale water mass of low temperature lying under the seasonal thermocline. Early documentation on this giant water volume, known as the Yellow Sea Cold Water Mass (YSCWM), dates back to the work of Uda (1934). The YSCWM is considered a remnant of the vertically well-mixed, cold water in winter (Ho et al., 1959); when the upper mixed layer is heated from spring to autumn by the solar radiation, the water in the middle and the bottom layers remains cold owing to the stable stratification. The YSCWM is believed to be the most important hydrographic feature in the YS, exerting profound influences on the three-dimensional circulation in summer (e.g., Hu et al., 1991; Yuan and Li, 1993; Su and Huang, 1995; Takahashi and Yanagi, 1995). The semidiurnal tide of M_2 constituent in the YS are well known for the huge tidal range and strong tidal currents (e.g., Choi, 1990; Fang et al., 2004), which lead to a conspicuous tidal mixing front (TMF) featuring the

* Corresponding author at: The First Institute of Oceanography, State Oceanic Administration (SOA), 6 Xianxialing Road, Hi-Tech Industrial Park, Qingdao 266061, PR China. Tel./fax: +86 532 88967400.
E-mail addresses: Lxg@fio.org.cn, gary.lxg@gmail.com (X. Lü), qiaofl@fio.org.cn (F. Qiao), xiacs@fio.org.cn (C. Xia), wanggs@fio.org.cn (G. Wang).

0278-4343/$ - see front matter
doi:10.1016/j.csr.2009.09.002

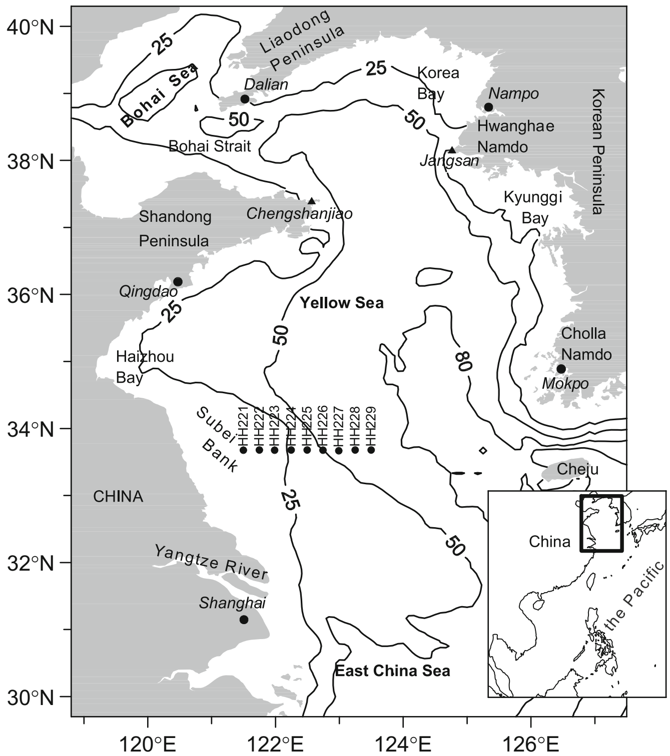

Fig. 1. Bathymetry and geography of the study area. Contour unit is meter. The whole model domain is indicated by the inset, in which the study area is marked by thick lines. The dots with station numbers along 33.67°N show the CTD casts in the cruise survey in July 2006.

thermal structure in marginal waters around the YSCWM (Zhao, 1987; Lie, 1989; Lee and Beardsley, 1999).

As far as the upwelling in China seas is concerned, most studies focused on the coastal waters off Zhejiang (e.g., Hu et al., 1980; Liu and Su, 1991; Lü et al., 2006, 2007) and Fujian (e.g., Cai and Lennon, 1988; Hu et al., 2001) in ECS, and Guangdong (e.g., Li, 1990; Qiao and Lü, 2008) and Hainan (e.g., Han et al., 1990; Lü et al., 2008) in the South China Sea (SCS). The Yellow Sea, though attracting many investigations on the circulation system, has never been a hot spot for systematic upwelling study. On the geographical distribution map of upwelling in China Seas given by Yan (1991), the high incidence of upwelling concentrates off the coasts in ECS and SCS; in contrast, the whole YS is almost a blank area except the small patch off the tip of Shandong Peninsula (Xia and Guo, 1983).

The upwelling in the YS was generally studied as a part of the YSCWM-related circulation. In fact, the vertical circulation pattern of YSCWM is still a controversial issue. Early studies suggested that the circulation consisted of a large gyre with upwelling penetrating the thermocline at the center and downwelling on the edges of the YSCWM (Guan, 1963), and such a structure was partially supported by a model that produced a similar gyre at the mature stage and an opposite gyre during the growing stage of YSCWM (Miao et al., 1990). Hu et al. (1991) set up a model, which showed a double-cell circulation pattern in which the vertical velocity did not penetrate the thermocline. The simplified theoretical solution of Yuan and Li (1993) revealed a thin circulation cell, which clung closely to the thermocline with central upwelling and fringe downwelling. In contrast, a different double-gyre structure was proposed by Su and Huang (1995): on a vertical transect across northern YS, the upper layer gyre consists of an upwelling branch in the center of the YSCWM and downwelling within the frontal zone; below the thermocline, a reverse and much larger gyre occurs with upwelling over the edge of the bottom front. Analyzing the field data obtained during a cruise survey, Zhao (1987) suggested that upwelling was present near the frontal area in the west SYS, and inferred that upwelling was possibly ubiquitous along the boundaries of the YSCWM. Liu et al. (2003) modeled the tidal fronts in the YS, and presented the vertical motions near the fronts along two latitudinal sections. These studies provided informative and enlightening backgrounds, but they were either geographically limited to their survey region or specific vertical sections, or confined to simplified theoretical aspects. We believe that a three-dimensional, baroclinic numerical model including complete set of physical processes is necessary to reveal the detailed distribution and physical mechanisms of the upwelling in the whole YS.

Surface cold patches (SCPs) are often observed scattering around the YSCWM, especially off the tips of peninsula (Xia and Guo, 1983; Lie, 1986; Seung et al., 1990; Zou et al., 2001). Such isolated cold patches are very distinct against the background of high sea surface temperature (SST) in boreal summer. Some of the cold waters, such as those around the southwest coast of Korea, were previously regarded as a consequence of pure tidal mixing (Lie, 1986; Kim et al., 1991). However, it may also be that the SCP is a result of upwelling, which carries the deep water up to the sea surface, just as the SCP off Chengshanjiao (Xia and Guo, 1983) and that off the southwestern tip of Nova Scotia (Garrett and Loucks, 1976).

Despite the sparse reports on the upwelling mentioned above, it is still unclear whether systematic upwelling exists in the YS. Besides, there is still dearth of numerical simulations of the SCP. This study seeks to explore the vertical circulation related to the SCP, and attempts to clarify the distribution and mechanisms of upwelling in the whole Yellow Sea in summer by using a fully prognostic, wave–tide–circulation coupled numerical model. Special attention will be paid to the effects that the strong tidal mixing has on vertical circulation.

2. Methods

2.1. Numerical model

Following the wave–circulation coupling idea suggested by Qiao et al. (2004), a wave–tide–circulation coupled numerical model based on Princeton Ocean Model (POM) is developed to simulate the general circulation in the YS.

As one of the most classic numerical ocean models, during the past two decades POM has been widely applied in the ocean modeling cases ranging from global through basin to coastal scales (e.g., Ezer and Mellor, 1997; Lü and Qiao, 2008), although it was originally intended for regional simulations. POM is a sigma-coordinate, primitive-equation, free-surface model, whose detailed descriptions were given by Blumberg and Mellor (1987). The most important feature of POM is the imbedding of the Mellor–Yamada turbulence closure sub-model (Mellor and Yamada, 1982) to provide vertical mixing coefficients. Following Qiao et al. (2004) and Xia et al. (2006), a wave-induced vertical mixing, which is computed from the MASNUM wave model (Yuan et al., 1991; Yang et al., 2005), has been added to the vertical viscosity (K_M) and diffusivity (K_H) produced by the Mellor–Yamada scheme in order to improve the simulation of the upper mixed layer in warm seasons.

The model domain (1.5°N–41°N, 99°E–137°E, see the inset in Fig. 1) covers the whole SCS, ECS, YS, and the Bohai Sea with a horizontal resolution of 1°/12 by 1°/12 and 16 sigma levels in the vertical. The values of sigma coordinate are 0.000, -0.003, -0.006, -0.013, -0.025, -0.050, -0.100, -0.200, -0.300, -0.400, -0.500, -0.600, -0.700, -0.800, -0.900, and -1.000