Continental Shelf Research 167 (2018) 14–31

Contents lists available at ScienceDirect

Continental Shelf Research

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

Effect of coastal-trapped waves on the synoptic variations of the Yellow Sea Warm Current during winter

Yang Ding[a], Xianwen Bao[a,b], Zhigang Yao[a,*], Dehai Song[a], Jun Song[c], Jia Gao[d], Junyi Li[e]

[a] Key Laboratory of Physical Oceanography (Ocean University of China), Ministry of Education and Qingdao National Laboratory for Marine Science and Technology, Qingdao, China
[b] College of Oceanic and Atmospheric Sciences, Ocean University of China, Qingdao, China
[c] School of Marine Science and Environment Engineering, Dalian Ocean University, Dalian, China
[d] National Marine Data and Information Service, Tianjin, China
[e] Guangdong Ocean University, Zhanjiang, China

A R T I C L E I N F O

Keywords:
Yellow Sea Warm Current
Synoptic variation
Coastal-trapped waves
Cheju warm current
Frontal circulation
Ocean model

A B S T R A C T

Significant short-term fluctuations of the Yellow Sea Warm Current (YSWC) at several days' time scale were observed in the Yellow Sea (YS) during winter of 2006–2007. Observations indicated that the synoptic fluctuations of the YSWC appear to be associated with low-frequency sea level variations. By analyzing direct current measurements, sea level elevations and results from a regional ocean model, this study characterizes the variation of the YSWC at synoptic time scale and examines its connection with propagation of coastal-trapped waves during winter. The model captures the observed short-term fluctuations of the YSWC at several days' periods and suggests a close relation between coastal-trapped waves and the YSWC variability. The YSWC is intensified (weakened) when the westward sea level-related barotropic pressure gradient is enhanced (diminished) due to the propagation of coastal-trapped waves. Model experiments with idealized periodic surface forcing further identify the important role of the coastal-trapped waves on adjusting the strength of the YSWC. The model results also suggest that the propagation of coastal-trapped waves contribute to the intermittent northwestward intrusion of Cheju Warm Current (CWC) in the frontal region northwest of Cheju. Generation and propagation of the coastal-trapped waves give rise to the westward barotropic pressure gradient in the YS entrance, which periodically pumps the CWC water into the YS interior west of Cheju.

1. Introduction

The Yellow Sea (YS) and the Bohai Sea (BS) form a shallow semi-enclosed continental shelf sea bounded by the mainland China in the west and the Korean Peninsula in the east (Fig. 1). The YS connects to the Northwestern Pacific Ocean through the East China Sea (ECS). A north-south elongated deep trough with maximum depth more than 90 m is located in the central YS. Two shallow shelves lie to the west and east of the central trough with the shelf along the Chinese coast wider than that along the Korean coast.

In winter a distinct warm tongue west of Cheju extending northwestward into the YS trough can be clearly observed in the satellite-derived sea surface temperature distribution (Zheng and Klemas, 1982; Xie et al., 2002; Ma et al., 2006; Song et al., 2009; Lin et al., 2011). This feature suggests the existence of a northward current flowing against the winter wind. As the water within this winter current is distinctly warmer and saltier than the surrounding waters, this current is commonly named as the Yellow Sea Warm Current (YSWC). Considered to be the only open ocean water flowing into the YS, the YSWC transports warm and saline water into the YS and BS from Kuroshio origin under prevailing northwesterly monsoon during winter season (Guan, 1962; Su, 2001; Lin et al., 2011). Due to the obvious high temperature and salinity character, the variations of the YSWC have a crucial effect on the regional circulation, sea ice coverage and biogeochemistry in the YS and BS (Lie et al., 2001; Bao et al., 2004; Su et al., 2005; Isobe, 2008; Wei et al., 2010; Liu et al., 2015).

The YSWC was initially proposed by Uda (1934, 1936) based on the distribution of the warm and saline water that originates from the branch of the Tsushima Warm Current southeast of Cheju (Uda, 1934; Beardsley et al., 1992). A large number of oceanographers have been paying great attention to the YSWC since it was proposed, as the YSWC is one of the most important hydrographic phenomena in the YS. The formation mechanism, characteristics, and the westward shift of the flow axis of the YSWC have been intensively studied based on

* Correspondence to: Ocean University of China, Qingdao 266100, China.
E-mail address: yaozhigang@ouc.edu.cn (Z. Yao).

https://doi.org/10.1016/j.csr.2018.08.003
Received 7 September 2017; Received in revised form 29 April 2018; Accepted 4 August 2018
Available online 08 August 2018
0278-4343/

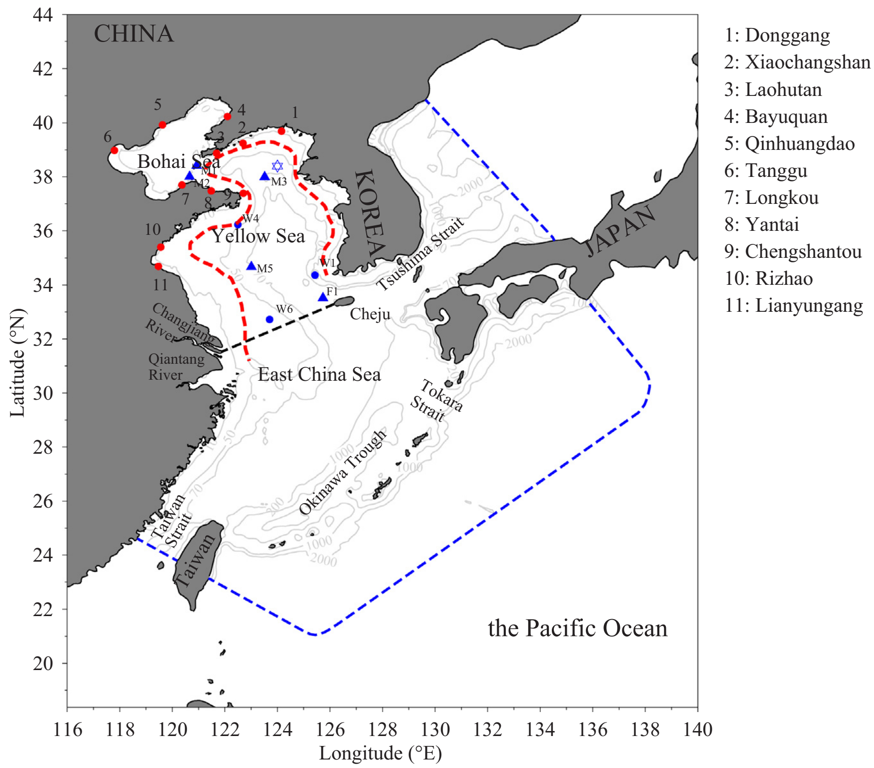

Fig. 1. Regional map and topography of the Bohai Sea, Yellow Sea, and East China Sea and locations of coastal sea level stations (Red dots), and current mooring stations (Blue triangles M1, M2, M3 and M5). The red dashed line along the 30 m isobath denotes the locations where sea level elevations were sampled in Section 3. Station W1 and W6 (blue dots) were selected to examine the sea level anomalies that were discussed in Section 4.1. Stations F1 is located northwest of Cheju where the currents and salinity were sampled, as discussed in Section 4.2. The blue star denotes a CTD station where the profiles of temperature and salinity were sampled. The black thick dashed line from the Changjiang River mouth to Cheju denotes the boundary between the East China Sea and Yellow Sea. The open boundaries for the ocean model are shown in blue dashed lines. Gray contours are model depth in meters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

temperature and salinity measurements (Chen et al., 1994; Lie et al., 2009, 2015), satellite observations (Wang and Liu, 2009; Wang et al., 2012; Guo et al., 2016; Hu et al., 2017), direct current measurements (Teague and Jacobs, 2000; Yu et al., 2010; Lin et al., 2011) and also numerical models (Takahashi et al., 1995; Mask et al., 1998; Riedlinger and Jacobs, 2000; Qiao et al., 2001; Huang et al., 2005; Ma et al., 2006; Lin and Yang, 2011; Tak et al., 2016).

Variations of the YSWC and the related mechanism are also concerned in the YS. Researchers have studied the seasonal and long-time variations of the YSWC (Cui et al., 2004; He et al., 2014; Ta et al., 2017) and linked the long-term variation of the YSWC to the East Asian winter monsoon variability. It should be noted that the circulation in the YS features strong variations at synoptic time scale due to the frequent weather systems (Yuan et al., 2008), especially during winter. The YS is influenced by the East Asian monsoon. The winter storms attack this region frequently due to the strong Siberia high in winter season, and the YS is dominated by northerly or northwesterly wind during winter. Synoptic events characterized by storm burst and attenuation with period of 2–7 days occur one after another, which dominates the weather system in the YS during winter. There are a few studies focused on the synoptic variations of the YSWC, particularly on the episodic events during winter storm burst. Hsueh (1988) and Teague and Jacobs (2000) attributed the episodic occurrences of northward currents to a sporadic event induced by the north-south pressure gradient due to strong northerly winter storm bursts based on current, pressure, and temperature measurement in the YS trough and also sea level data along the Korean coast. The response of the YSWC to the episodic northerly wind bursts was considered to be barotropic based on barotropic numerical model (Hsueh et al., 1986; Hsueh and Yuan, 1997). Based on trajectories of drifting floats, *in situ* hydrographic measurements, satellite images and moored current observations, Lie et al. (2001), Lie et al. (2009) and Lie et al. (2013) proposed that the intermittent intrusion of the warm and saline northward current corresponding to the source origin of the YSWC may be closely related to the northerly wind bursts. Wan et al. (2015) analyzed the current measurement in the northern YS and BS strait together with sea level observations along the BS coast and found that the current fluctuations of strong southward current followed by a strong northward current was coupled with residual sea level fluctuations. Qu et al. (2017) and Tak et al. (2016) studied the evolution process of the YSWC during a winter northerly storm burst based on a regional ocean model. Both of their studies indicated that the westward shift of the YSWC during a specific winter storm event and Qu et al. (2017) attributed this westward shift of the YSWC to the generation and propagation of continental shelf wave accompanied by the geostrophic adjustment during the northerly wind burst. Based on the surface currents derived from Geostationary Ocean Color Imager (GOCI) and a homogenous ocean model, Hu et al. (2017) attributed the episodic northward surface current intrusion events to the relaxation of the strong northerly winds during winter. Their study also revealed that the strong northward current in the ECS was related to a coastal-trapped wave (Fig. 2).

The 2006/2007 winter cruise conducted by Chinese oceanographers between December 2006 and February 2007 included several moorings with Acoustic Doppler Currents Profile (ADCPs). Two moorings were located in the BS strait, one was in the northern YS (M1, M2, and M3 in Fig. 1, Bao et al., 2010), which were deployed by the Ocean University of China (OUC). Three moorings were in the southern YS (Yu et al., 2010) and were deployed by the First Institution of Oceanography, State Oceanic Administration (FIO). The mooring station M3 underwent two strong northerly wind burst events on January 8, 2007 and January 28, 2007. The observed sub-tidal current at mooring station M3 indicates that the mooring captured the current fluctuations during the two events (Fig. 3). Noted that the current fluctuations occurred at all depth levels throughout the winter at mooring M3 with the southward current followed by northward current. In particularly between January 9–26, 2007 when there was no northerly wind burst events, the observed sub-tidal current fluctuated at period of approximately 2–7 days, which was accompanied by the sub-tidal sea level oscillations. Generally, the northward current occurred or strengthened when the subtidal sea level decreased, and disappeared or reversed to southward current when sea level increased. The current fluctuations can also be noted in the current observations at mooring stations deployed by FIO