



## Research papers

# Circulations associated with cold pools in the Bohai Sea on the Chinese continental shelf



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## ARTICLE INFO

## Keywords:

Bohai Sea  
Circulation  
Cold pool  
Cyclonic gyre  
Lagrangian particle

## ABSTRACT

Circulations associated with cold pools in the Bohai Sea were investigated in the summers of 1959 and 2006 using observations and numerical simulations. The climatological forcing was incorporated to drive a model based on the Regional Ocean Modeling Systems (ROMS) to reconstruct the monthly evolution of flow structure. Cold pools were found to be separated into two parts by an undersea ridge in the central Bohai Sea. A set of numerical experiments were conducted to evaluate the relative contributions from the exchange across the strait, heat flux, wind, and tides. Baroclinic circulation was the dominant component of the circulation. A basin-scale cyclonic gyre was the main feature during the stratified seasons from May through August. Cyclonic and anticyclonic sub-basin scale gyres emerged in late spring and peaked during July and early August, accompanied by intensifying frontal jets along the west and south coasts of the Bohai Sea. The cyclonic frontal jet in the model was responsible for rapid reduction of particles released from the surface layer of the Bohai Sea in summer; and 2) Experiments using Lagrangian particle tracking also showed that particles released in Liaodong and Bohai bays were retained longer than those released in the other regions as the surface convergence in the western Bohai Sea resulted in an intense concentration of particles.

## 1. Introduction

Cold pools are isolated low-temperature areas and often form dense water masses below the seasonal thermocline. They are usually associated with topographic depressions. For example, cold pools have been observed worldwide including the Yellow Sea (He et al., 1959; Su and Huang, 1995; Pang et al., 2004; Wang et al., 2014), the western Irish Sea (Hill et al., 1994, 2008), the North Sea (Brown et al., 1999), Bay of Fundy (Aretxabaleta et al., 2008), and the Bering Sea shelf (Reed and Stabeno, 1996; Zhuang et al., 2014). Strong horizontal temperature gradients separate the cold pools from the well-mixed regions of water bodies (Simpson et al., 1978). Using an analytical model, Hill (1996) suggested that cyclonic circulation always occurs near the surface around dome-like cold pool. A circular frontal jet has also been observed from field surveys (Hill et al., 1997; Brown et al., 1999; Horsburgh et al., 2000; Lin et al., 2002; Pang et al., 2004).

The presence of cold pools in the Bohai Sea has been well recognized. Three shallow bays, Liaodong, Bohai and Laizhou, form the Bohai Sea, which is a semi-enclosed shelf sea connected to the Yellow Sea through the Bohai Strait (Fig. 1). A subsurface Central Bank dissects the three bays in the central Bohai Sea. The bowl-shaped northeastern depression is enclosed by the 30-m isobath, while the band-shaped southwestern depression lies in the southern Bohai Sea and is slightly deeper than 25 m. During stratified periods of the year, typically from late April to mid-September (Bao et al., 2004; Wu et al., 2004), cold pools were frequently observed in the Bohai Sea (Liu et al., 2003; Wan et al., 2004; Lin et al., 2006; Jia et al., 2008). Bottom temperature in the northern region appears to be 1–3 °C lower than that in the south because of persistent cold water advection from the Yellow Sea along the east coast of the Bohai Sea (Zhou et al., 2009). The Laotieshan Channel forms the main entrance through which cold water enters from the northern Yellow Sea (Feng, 1987).

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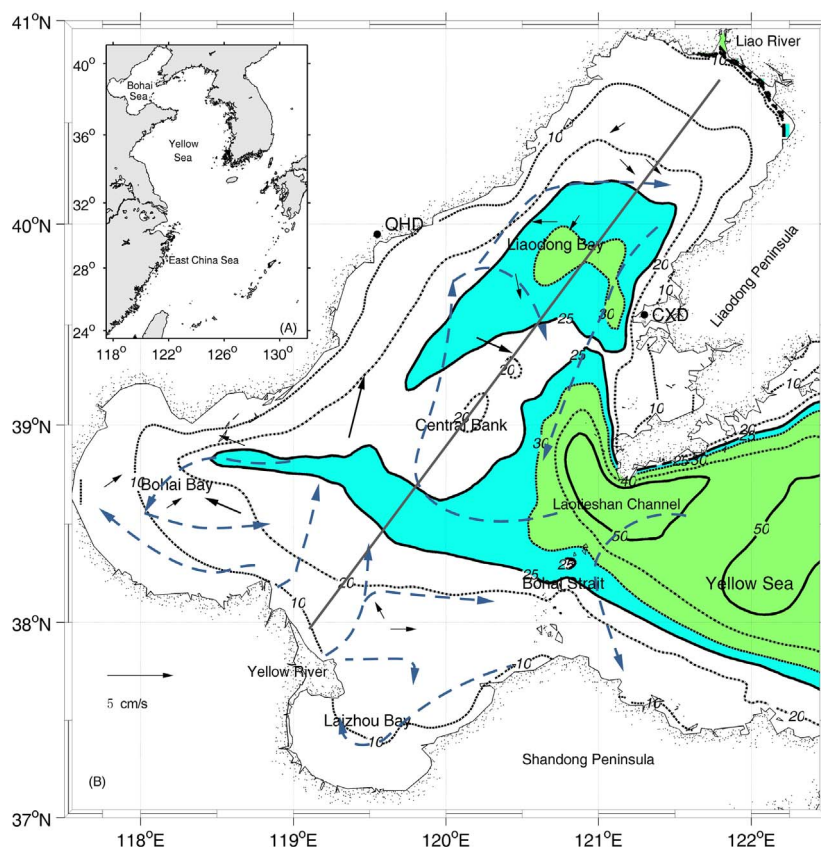
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<http://dx.doi.org/10.1016/j.csr.2017.02.005>

Received 12 June 2015; Received in revised form 10 November 2016; Accepted 10 February 2017

Available online 12 February 2017

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**Fig. 1.** (a) Model domain and (b) topographic features of the Bohai Sea. Isobaths of 10, 20, 25, 30, and 50 m are indicated by contours, while topographic depressions are emphasized by shadings. Solid arrows are depth-averaged flow measurements from oil platforms, and dashed arrows are schematic circulations (after Zhao et al., 1995). Traditional Liaodong Bay represents the region in the north of Qinhuangdao (QHD) and Changxindao (CXD). In the paper, Liaodong Bay refers to the region north of the Central Bank. The transect (solid line) was highlighted as an indicator of the cold/dense pools in previous studies, e.g., Liu et al. (2003) and Lin et al. (2006).

Although the spatio-temporal characteristics of the cold pools and overlying stratification in the Bohai Sea have been intensively investigated (Huang et al., 1999; Zhao et al., 2001; Bao et al., 2004; Liu, 2007), knowledge of the corresponding circulations and their contributions to the basin-scale gyre remains unclear. Based on hydrographic observations, Guan (1994) suggested there were a basin-scale counter-clockwise circulation and two cyclonic cells above the two depressions. In contrast, Zhao et al. (1995) documented a clockwise-dominant flow pattern in the northern Bohai Sea based on current observations taken from oil platforms (see dashed arrows in Fig. 1b). Most historical hydrographic and current data available were the results of episodic monitoring programs or occasional research cruises; therefore, they were limited in temporal or spatial extent and, consequently, in the amount of information they could provide.

The bay experiences weak tidal currents except in the Bohai Strait (Ogura, 1936) and along the coast of Liaodong Bay (Qiao et al., 2006). The average amplitude of  $M_2$  barotropic tide in the three bays is listed in Table 1. Residual tidal currents over most the basin are essentially less than 2 cm/s according to model simulations (Fang and Yang, 1985; Huang et al., 1999). Monsoon wind plays an overwhelming role on the circulation in winter (Miao and Liu, 1988), while the rather weak winds in summer plays a less important role in driving the circulation except at the surface (Zhao and Shi, 1993). Recent modeling studies suggested

the importance of a horizontal density gradient to the basin-scale gyre (Liang et al., 2006; Wang et al., 2010). Using a diagnostic model, Wan et al. (2004) recognized the significance of density-driven circulation using a set of experiments based on a hydrographic survey conducted in August 2000. However, the intra-seasonal variability of circulations associated with the cold pools remains unknown.

As a semi-enclosed sea neighboring large human population and rapidly urbanized cities, the Bohai Sea is vulnerable to increasing inputs of nutrients and pollutants (Wei et al., 2002). Zhai et al. (2012) observed a band-like low oxygen zone west of Central Bank, where oxygen depletion rate was larger than the rest of the surveyed region. Only a few studies have addressed biological influences of the cold pools in the Bohai Sea (e.g. Lin et al., 2006), even though similar issues have been extensively addressed in other regions. Pingree et al. (1975) reported high phytoplankton biomass along the shelf sea front in the English Channel. It was suggested that the cyclonic sub-surface gyre in the western Irish Sea was a retaining system for the larvae of Norway lobster (*Nephrops norvegicus*) in spring (Hill et al., 1994, 1997). High concentration of fish larvae around the cold pool in the southern Yellow Sea was also documented (Wei et al., 2003).

This study aims at understanding the contributions of different forcing factors to regional circulations, namely, how will the baroclinicity associated with these cold pools affect the circulations in the

**Table 1**  
Amplitude of  $M_2$  barotropic current in different parts of the Bohai Sea (units: m/s).

Region	Liaodong Bay	Bohai Bay	Laizhou Bay	Central Bank	Bohai Strait	Bohai Sea
Mean	0.29	0.31	0.17	0.28	0.26	0.08
RMS	0.31	0.33	0.20	0.29	0.27	0.09

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