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Seasonal changes and driving forces of inflow and outflow through the Bohai Strait

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ABSTRACT

This work focuses on analyzing seasonal variation of inflow and outflow through the Bohai Strait that greatly affect the marine environment in the Bohai Sea, using observational data including sea bed mounted acoustic Doppler current profiler currents, CTD salinity data on deck, sea level anomalies of coastal tide gauge stations, and climatological monthly sea level anomalies from Archiving, Validation and Interpretation of Satellite Oceanographic data. Our results show three patterns of outflow and inflow through the Bohai Strait. The first is such that outflow and inflow occur respectively in the southern and northern parts of the strait, as in the traditional understanding. Our results suggest that this pattern occurs only in autumn and winter. Beginning in late September, Ekman currents driven by the northwesterly monsoon carry Bohai Sea water that piles up in the southern part of that sea and then exits eastward to the Yellow Sea. In this process, the pressure and current fields are continuously adjusted, until a quasi balance state between wind stress, Coriolis force and pressure gradient force is reached in winter. Inflow with a compensating property through the northern channel is close to the outflow through the southern channel in winter. The second pattern is a single inflow in spring, and the current and pressure fields are in adjustment. In early spring, the northwesterly monsoon ceases, Yellow Sea water enters the Bohai Sea under the pressure gradient force. With southeasterly monsoon establishment and strengthening, northern Yellow Sea water continually flows into the Bohai Sea and causes sea level rise northward. In the third pattern, outflow is much greater than inflow in summer. The currents run eastward in the central Bohai Sea and then enter the northern Yellow Sea through the northern channel and upper layer of the southern channel, while a westward current with a compensating property enters via the lower layer of the southern channel. Larger net transport is through the Bohai Strait to the northern Yellow Sea, which is related to strong precipitation and runoff into the Bohai Sea.

1. Introduction

The Bohai Strait provides the only waterway for the Bohai and Yellow seas (Fig. 1). The Bohai Sea is a semi-enclosed shallow inland sea with average depth ~18 m, surrounded by land on three sides. The strait is about 90 km wide and has relatively complex bathymetry. All except the northern strait is characterized by a relatively flat bottom, and there are a chain of islands in the southern part, bordered by two principal channels. The northern one is the Laotieshan Channel (called the northern channel), with maximum depth 86 m, and the southern one is the Dengzhou Channel (or southern channel), with depths 20–30 m. As with other straits in the world, the Bohai is important for the exchange of water and materials between the Bohai and Yellow seas (Bi et al., 2011; Martin et al., 1993). This exchange strongly affects the marine environment of the Bohai Sea. Moreover, the southern Bohai Strait is considered the primary pathway for the movement of materials from the Bohai Sea into the northern Yellow Sea (Cheng et al., 2004; Lu et al., 2011; Martin et al., 1993; Qin and Li, 1983; Wang et al., 2014b).

Over the past few decades, water circulation in the Bohai strait and sea has been studied mainly on the basis of numerical models. Traditionally, outflow and inflow through the strait are considered such that Bohai Sea water flows out through the southern channel, while Yellow Sea water enters the Bohai Strait via the northern channel; this is referred to as “outflow in the southern and inflow in the northern” (Fang et al., 2000; Guan, 1994; Xu et al., 2009; Yuan, 1997; Li et al., 2005; Lu et al., 2011; Jiang et al., 2002; Wei et al., 2003; Huang et al., 1998, 1999). However, long-term current observations supporting this view are still strongly lacking. Some works have even indicated that this

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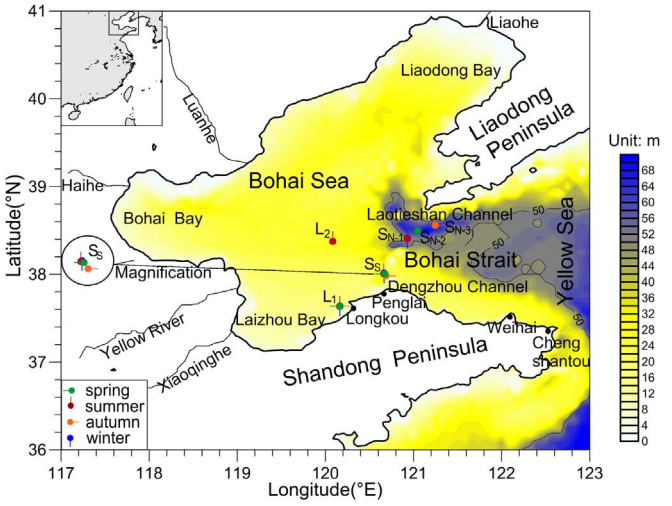

Fig. 1. Bathymetry of Bohai Sea and the ADCP observation stations (–●) located near the Bohai Strait.

configuration does not appear in summer (Wei et al., 2001; Huang et al., 1996; Lin et al., 2002; Bi, 2013; Zhang et al., 2010; Wang et al., 2016).

Li et al. (2015) indicated that the key processes controlling water circulation in shallow straits is the difference in mean sea level and tides on either side of the strait, wind, the meandering of the oceanic currents in adjoining seas, and bathymetry. However, the case of the Bohai Strait is slightly different. Wind is considered an essential force driving the current (Zhao and Cao, 1998; Zhao and Shi, 1993; Lin et al., 2002; Huang et al., 1999; Wang et al., 2014a). There are various different understandings about other forces, such as topography, tides, and baroclinic forces (Lin et al., 2002; Huang et al., 1999, 1998; Wei et al., 2003; Liu et al., 2003; and Wan et al., 2004).

For the first time, this paper investigates seasonal variability of inflow and outflow through the Bohai Strait based on long-term current observation. Illustrations of the observational data used are given in Section 2. In Section 3, we analyze seasonal variations of the currents at observational stations. In Section 4, we present an estimate of net transport through the strait using observational data by means of the water quantity conservation principle, and analyze major driving forces of the inflow and outflow through the Bohai Strait in all seasons. Main conclusions are in Section 5.

2. Data

Since 2006, the Chinese Offshore Marine Environment Investigation Project has supported multidisciplinary oceanographic observations in the Bohai and Yellow seas during different seasons. We used in-situ hydrographic datasets to show the current distribution in the Bohai Strait from four observation periods: over ~32 days from July 30 to September 1, 2006 (Summer); 29 days from December 25, 2006 to January 23, 2007 (Winter); 30 days from April 15 to May 15, 2007 (Spring); and 38 days from September 30 to November 7, 2007 (Autumn). Datasets from the four periods describe the current distributions in the Bohai and Yellow seas in different seasons, and are thus expected to reveal seasonal variability of inflow and outflow through the Bohai Strait.

Around the Bohai Strait, upward-looking acoustic Doppler current profiler (ADCP) instruments were deployed on the seabed. The current measurement stations in four seasons covered the main passage of the Bohai Strait (Fig. 1), including station S_S in the Dengzhou Channel, station S_N (including S_{N-1}, S_{N-2}) in the Laotieshan Channel, station L_1 off the east coast of Laizhou Bay, and station L_2 in the middle of the Bohai Sea. Vertical sampling intervals of the currents were 2 m or more. In addition, current measurements during November 2012 at station S_{N-3} (Fig. 1) were collected to compensate for a lack of observations in the Laotieshan Channel during autumn 2007. Station S_{N-3} was in the deep part of the Laotieshan Channel in the northern Bohai Strait, slightly northeast of station S_{N-1} (Fig. 1). All these continuous current data were quality controlled through the instrument software and manual experience. We applied the cosine-Lanczos squared low-pass filter to the current data to obtain the residual current. These residual currents were averaged over the measurement period, and the average residual currents were determined from the surface to bottom layers. The average residual currents (hereafter referred to as currents) at each station except S_S in autumn were averaged monthly. The current at S_S in autumn was only four daily means from September 29 to October 2, 2007.

Onboard Sea Bird CTDs were released during ADCP observational periods, and CTD observation stations covered the Bohai Sea and northern Yellow Sea (Fig. 2b). We used salinity data in the surface layer to supplement analyses of the current field.

The Communique on Sea Level of China during 2007 and 2015 (www.mlr.gov.cn/zwgk/tjxx/) furnish monthly mean coastal sea level variation data of the Bohai and Yellow seas, which were obtained from coastal tide gauge stations. According to these data, the seasonal variation of sea level of the Bohai Sea in 2007 and 2008 was analyzed, and sea level differences between the Bohai and Yellow seas in 2007–2015 were computed. For studying the relationship between net current transport through the Bohai strait and the seasonal sea level variation, we collected the climatological monthly sea level anomaly (MCSLA) referenced to the 1993–2015 period, with a resolution of 0.25° × 0.25° in both seas. These data were provided by the Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO). Furthermore, four coastal tide gauge station data, at T02, T07, T13 and T18 around the Bohai Strait, were collected during 1990 and 2006.

In addition, precipitation data were obtained from averaged monthly Tropical Rainfall Measuring Mission (TRMM) Version 7 3B43 precipitation data set of 2007–2008 (Huffman et al., 2014; Huffman and Bolvin, 2017) with a resolution of 0.25° × 0.25°, which are provided by the National Aeronautics and Space Administration / Goddard Space Flight Center's Mesoscale Atmospheric Processes Laboratory and the Precipitation Processing System. Evaporation data used were monthly average Objectively Analyzed air-sea Fluxes (OAFlux) data (Yu and Weller, 2007) of 2007–2008 with a resolution of 1.0° × 1.0°. These were provided by the Woods Hole Oceanographic Institution (http://oaflux.whoi.edu) and funded by the National Oceanic and Atmospheric Administration Climate Observations and Monitoring program.

3. Analysis and results

3.1. Current through southern channel of the Bohai strait

The flow of lower salinity water via the southern channel running eastward along the northern coast of Shandong Peninsula is traditionally called the Lubei coastal current (hereafter, LBCC). Seasonal variation of this current is based on the ADCP current and salinity data during 2006–2007.

In winter, there is a northeastward current with average speed ~2 cm/s at station L_1 near Longkou, east of Laizhou Bay (Fig. 2a) but an eastward flow in the surface layer at station S_S in Dengzhou Channel. This suggests that the LBCC flows out of the Bohai Sea. The salinity distribution (Fig. 2a) shows that the coastal current in the southern Bohai Sea forms a low-salinity water mass with $S < 31.0$ psu at its core and eastern edge, reaching the Longkou. The lower-salinity water core east of Longkou is marked by a salinity front of 31.0–31.75 psu. The salinity east of the front along the northern coast of the Shandong Peninsula is < 31.75 psu. This low-salinity water may spread eastward and turn to the south near Chengshantou.

The current at station L_1 in spring near Longkou runs southwestward along the coast at 2 cm/s (Fig. 2b), which is opposite to its