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The summertime circulation of the Bohai Sea simulated from a high-resolution wave-tide-circulation coupled model

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Abstract

The Bohai Sea is a shallow semi-enclosed inner sea with an average depth of 18 m and is located at the west of the northern Yellow Sea. The climatological circulation pattern in summer of the Bohai Sea is studied by using a wave-tide-circulation coupled model. The simulated temperature and the circulation agree with the observation well. The result shows that the circulation pattern of the Bohai Sea is jointly influenced by the tidal residual current, wind and baroclinic current. There exists an obvious density current along the temperature front from the west part of the Liaodong Bay to the offshore area of the Huanghe Estuary. In the Liaodong Bay there exists a clockwise gyre in the area north to the 40°N. While in the area south to the 40°N the circulation shows a two-gyre structure, the flow from the offshore area of the Huanghe Estuary to the Liaodong Bay splits into two branches in the area between 39°N and 40°N. The west branch turns into north-west and forms an anti-clockwise gyre with the south-westward density current off the west of the Liaodong Bay. The east branch turns to the east and forms a clockwise gyre with the flow along the east coast of the Liaodong Bay. The forming mechanism of the circulation is also discussed in this paper.

Key words: Bohai Sea, summer circulation, baroclinic current, wave-tide-circulation coupled model

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1 Introduction

The Bohai Sea is China's semi-enclosed inner sea. It is connected to the Yellow Sea through the Bohai Strait. It is a shallow sea with the averaged depth of 18 m. The tidal current in the Bohai Sea is strong while the residual current is rather weak, in most area of the Bohai Sea the amplitude of the M_2 tidal current is larger than 40 cm/s (Fang and Yang, 1985) while the residual current is only several centimeters per second. The water flow into the Bohai Sea in the northern part of the Bohai Strait and out in the southern part. The water with high temperature and high salinity from the offshore area splits into two branches when it reaches the west coast. The north branch turns northward along the west coast of the Liaodong Bay, while the low salinity water in the Liaodong Bay flows to the south along the east coast, so a clockwise gyre is formed in the Liaodong Bay and central Bohai Sea. The south branch turns southward along the Bohai Sea west coast and passes the old Huanghe Estuary and the Laizhou Bay, it flow out of the Bohai Sea through the southern part of the Bohai Strait. Some modifications were put forward to the main concept circulation pattern in recent years. Based on the flow observation on the oil-platform and coastal observation, Zhao et al. (1995) pointed out that the averaged flow in the central Bohai Sea and the Liaodong Bay is clock-wised except in summer in certain years and in the offshore area of the Huanghe River Delta there is a north-northeastward current, which reaches the offshore area off Qinhuangdao all the year around. Xu et al. (2006) concluded in the Liaodong Bay there exists a clock-wise gyre in the area north to 40°N. These studieds mainly reflect the circulation in winter or the cold half year.

In summer the circulation in the Bohai Sea is rather complicated. The survey in August 1959 showed that the low salinity water from the Liaohe River turns to the south along the west coast of the Liaodong Bay. The observed depth averaged flow direction of Station 5 pointed to the west coast of the Liaodong Bay (Zhao et al., 1995). At Station SZ36-1, the observed summer flow direction at the depth of 15 m is southwest and the bottom flow direc-

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tion is southward (Xu et al., 2006). This suggests besides the clock-wised gyres in the central and east part of the Liaodong Bay there may exists a southwestward flow off the west coast of Liaodong Bay and there may exist an anticlockwise gyre in the west part of the Liaodong Bay. At Station BZ28-1 which located in the offshore area of the Yellow Sea, the observed flow direction summer is southeastward at the depth of 5 m which is opposite to the wind direction (Xu et al., 2006). This suggests there may exists a frontal current in this region.

Direct filed surveys on the current in the Bohai Sea are expensive, numerical simulation can make up shortage of observation. Many scholars have studied the summer circulation in the Bohai Sea using numerical models. Huang et al. (1999) simulated the thermal stratification and baroclinic circulation in the Bohai Sea using HAMburg Shelf Ocean Model (HAMSOM). The model starts in early spring and ends in later autumn. The results show a cyclonic (anticlockwise) baroclinic circulation is well defined in the upper layers when the stratification is strong and the wind is weak in summer. Liu et al. (2003) studied the density residual currents in summer using a diagnostic ECOM-si model based on observed climotogical temperature and salinity data. The model results indicated that the density residual currents are robust in summer. Wei et al. (2003) studied summertime circulation in the Bohai Sea and the water transport in the Bohai Strait using a diagnostic POM model. Wu et al. (2004) studied the summer diagnostic circulation of the Bohai Sea in 1958 and 2000 based on observed temperature and salinity data. Wan et al. (2004) also studied the summertime tide-induced, wind driven and diagnostic thermohaline currents using ECOMSED. The model results indicate that in the Bohai Sea during summertime, the tide-induced residual currents are weak while the thermohaline currents are strong and dominant. Diagnostic model was used in most previous studies and the temperature and salinity fields are given as a prior, so the seasonal variation of the circulation and the interaction between the temperature field and the current field can not be obtained. Lin et al. (2006) studied the forming mechanism of the well-mixed warm water column in the central Bohai Sea in summer. The result showed that surface wave mixing plays an important role in summer in Bohai Sea. The horizontal resolution of these previous studies are not fine enough to simulate the detailed structure of the circulation in the Bohai Sea. In this study, we will use the high-resolution (~4 km) MASNUM (Laboratory of Marine Sciences and Numerical Modeling) wave-tide-circulation coupled model to study the circulation structure of the Bohai Sea in summer. The model is a 3-D primitive equation prognostic model with real topography.

The rest of the paper is organized as follows. The MASNUM wave-tide-circulation coupled model and model design are described in Section 2. In Section 3 the simulated temperature and salinity fields are compared with the observations. The simulated circulation results are analyzed in Section 4. Finally, conclusions are given in Section 5.

2 Numerical model

The MASNUM wave-tide-circulation coupled model is set up and used in this study. The circulation part of the model is based on the Princeton Ocean Model (POM). POM employs the level-2.5 Mellor and Yamada (M-Y) turbulence closure scheme to calculate the vertical turbulence mixing (Mellor and Yamada, 1982). However, a common problem of such scheme is the underestimate of surface mixing and mixed-layer depth, and thus the sea surface temperatures is overestimated, the upper mixed layer is too shallow, especially in summer (Kantha and Clayson, 1994; Ezer, 2000). To solve the problem, researchers' focus has been put on the contribution of surface waves to oceanic mixing and on wave-current interaction theories recently (Mellor, 2003; Mellor and Blumberg, 2004; Kantha and Clayson, 2004). Qiao et al. (2004a) suggested that the mixing Bv induced by surface wave plays a key role in the formation of the upper mixed layer in spring and summer. The wave-induced vertical viscosity/diffusivity is expressed as a function of wave number spectrum:

$$Bv = \alpha \iint_{\vec{k}} E\left(\vec{k}\right) \exp\{2kz\}\,\mathrm{d}\vec{k} \times \frac{\partial}{\partial z}\left(\iint_{\vec{k}} \omega^2 E\left(\vec{k}\right)\exp\{2kz\}\,\mathrm{d}\vec{k}\right)^{1/2}, \tag{1}$$

where α is the mixing coefficient, generally setted to 1.0, $E\left(\vec{k}\right)$ represents the wave number spectrum, ω is the wave angular frequency, $\vec{k}$ is the wave number, and z is the vertical coordinate axis down ward positive with z=0 at the surface. Bv, a factor determining the wave-induced mixing strength, is added to the coefficient calculated from Mellor-Yamada scheme:

$$Km = Km_c + Bv,\ Kh = Kh_c + Bv. \tag{2}$$

The coupled model employs the MASNUM wave number spectral model (Yuan, 1991; Yang et al., 2005) was used to calculate Bv. The wave model has been validated by the observations (Yu et al., 1997) and widely accepted in ocean engineering (Qiao et al., 1999). An additional wave-induced mixing Bv is computed by the MASNUM wave model and added to the vertical viscosity Km and diffusivity Kh calculated by M-Y scheme in POM (Qiao et al., 2004a, b). The NCEP (National Centers for Environmental Prediction) reanalyzed wind fields with the horizontal resolution of 1.25° by 1.0° and time interval of 6 h interpolated into the model grid are used in the wave model. The Bv varies with time and location.

The numerical model domain covers the Bohai Sea, the Yellow Sea and the East China Sea. The study area of this paper is shown in Fig. 1. The open lateral boundary of the model is far from the Bohai Sea to reduce the influence of the boundary condition. The horizontal resolution is (1/24)° latitude by (1/24)° longitude, about 4 km. Thirty vertical sigma layers with a fine resolution in the upper layers are used. The value of the sigma layer is (0.000 0, –0.002 5, –0.005 0, –0.007 5, –0.012 5, –0.018 7, –0.025 0, –0.031 2, –0.037 5, –0.050 0, –0.062 5, –0.075 0, –0.100 0, –0.125 0, –0.150 0, –0.175 0, –0.200 0, –0.225 0, –0.250 0, –0.275 0, –0.300 0, –0.325 0, –0.350 0, –0.375 0, –0.437 5, –0.500 0, –0.625 0, –0.750 0, –0.875 0, –1.000 0). The topography of the model is interpolated based on the global 5′×5′ Etopo 5. The sea chart topography data are also incorporated into the model.

The circulation model is driven by wind stress and heat flux at the sea surface. Monthly climatological wind stress and net heat flux data of the Comprehensive Ocean-Atmosphere Data Set (COADS) settled by da Silva et al. (1994) with a resolution of 1° by 1° are used. The heat flux is of Haney type:

$$Q = Q_c + \left(\frac{\mathrm{d}Q}{\mathrm{d}T}\right)_c \left(T_c^0 - T^0\right), \tag{3}$$

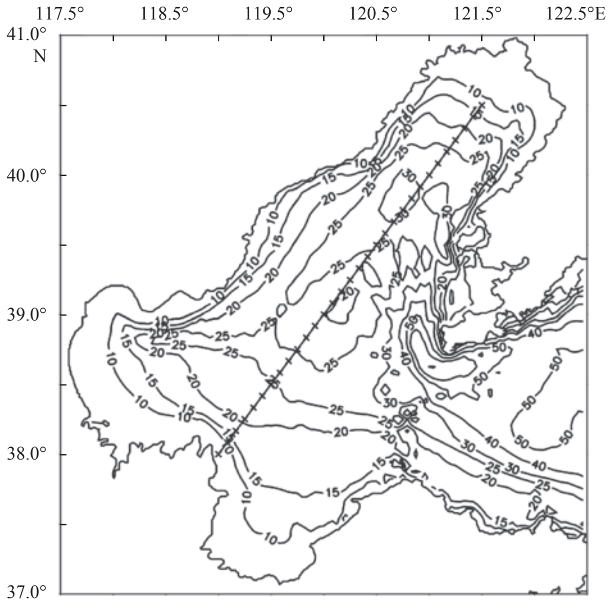

Fig. 1. Study area of the Bohai Sea and the model topography (m, the contour interval is 5 m from 0 to 70 m). The study area is a portion of the whole model domain (15°–41°N, 105°–135°E). The straight line stands for the section from the Huanghe Estuary to the head of the Liaodong Bay.

where the subscript c means data from COADS, Q_c is the net heat flux, dQ/dT is the variation of the net heat flux with the SST, T_c^0 is the monthly mean climatological SST from COADS, T^0 is the sea surface temperature computed from circulation model.

The initial temperature salinity fields are prescribed using the annual mean Levitus climatology (Levitus, 1982). A mean vertical density profile, calculated from the initial density filed, is subtracted from density field before the horizontal pressure gradient term difference is carried out to reduce the error (Mellor et al., 1994, 1998; Ezer, 2000). The initial sea level and velocity is interpolated from the North Pacific (1/6)° by (1/6)° model result (Xia et al., 2006). The lateral boundary conditions (temperature, salinity, sea level and velocity) are obtained by interpolation of the North Pacific model result. To include tidal current, a radiation condition is used for open boundary velocity, i.e.,

$$U = U_g - (\pm)\sqrt{\frac{g}{H}}\,(\zeta_g + \zeta_T - \zeta_M)\,, \tag{4}$$

where U_g and ζ_g are from the global simulation results; H is the water depth; g is the gravitational acceleration; and ζ_M is the boundary elevation computed by the model; $(\pm)$ is determined according to the direction of the outward normal at the open boundary; ζ_T represents the tidal elevation, i.e.,

$$\zeta_T = A\cos(\omega t - \phi), \tag{5}$$

where t is time.

Only the tidal component M_2 is added because it is prevailing in the Bohai Sea and it is easy to derive Eulerian residual current, here ω represents the angular frequency, A is amplitude, and ϕ is the phase lag. The tidal amplitude and lag are taken from the global 0.25°by 0.25° TPXO.6 tide model of the Oregon State University.

The Changjiang River Diluted water is included as a boundary condition (Qiao et al., 2004a) by using the climatological monthly mean discharge from a 35-year record at the Datong observation station. The model is integrated for 6 years and the obtained temperature, salinity and Eulerian residual current fields of last year are used to study the circulation patterns.

3 Verification of temperature field

The simulated horizontal distributions of the temperature are compared with the climatological observations collected in the surveys during 1958–1999 (Guo, 2004). All the data are under strict quality control and interpolated to the grid of 20′ by 20′ for the analysis.

The simulated and observed surface temperatures are shown in Figs 2 and 3, respectively. The temperature in the central Bohai Sea and the Bohai Strait is generally between 24°C and 25°C. The temperature in the Bohai Bay, the Liaodong Bay and the Laizhou Bay is higher than that in central Bohai Sea. Both the simulated and observed temperature distributions show the same pattern.

Figures 4 and 5 give the simulated and observed bottom tem-

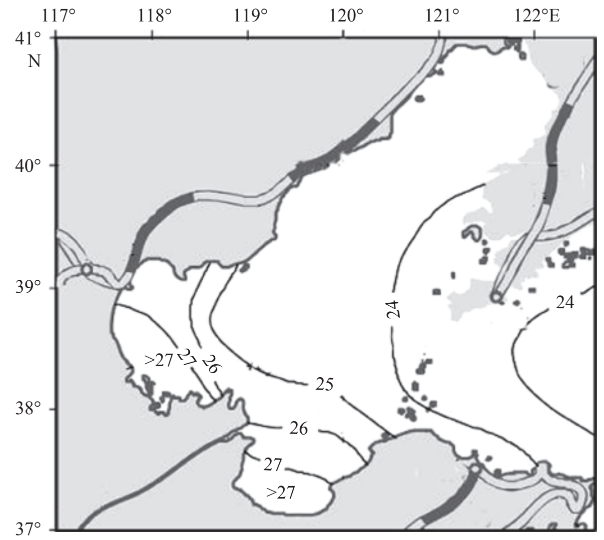

Fig. 2. The observed surface temperatures (°C) in summer. (after Guo, 2004).

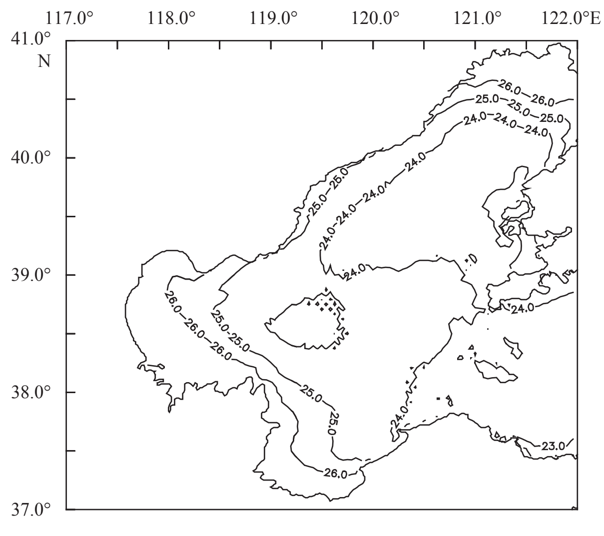

Fig. 3. The simulated surface temperatures (°C) in summer.

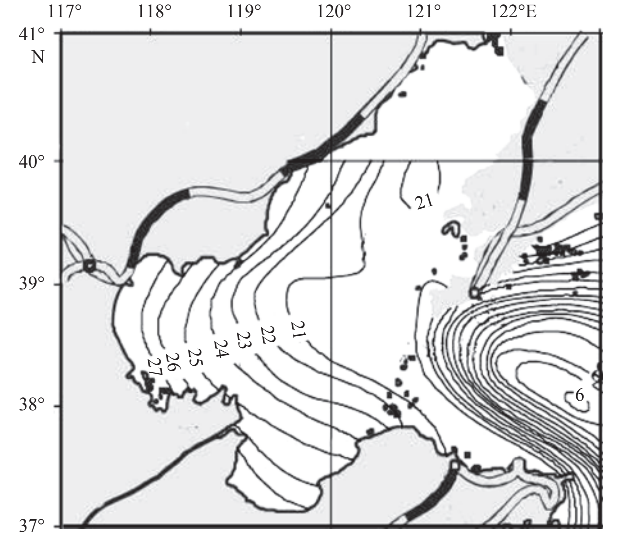

Fig. 4. The observed bottom temperatures (°C) in summer. (after Guo, 2004).

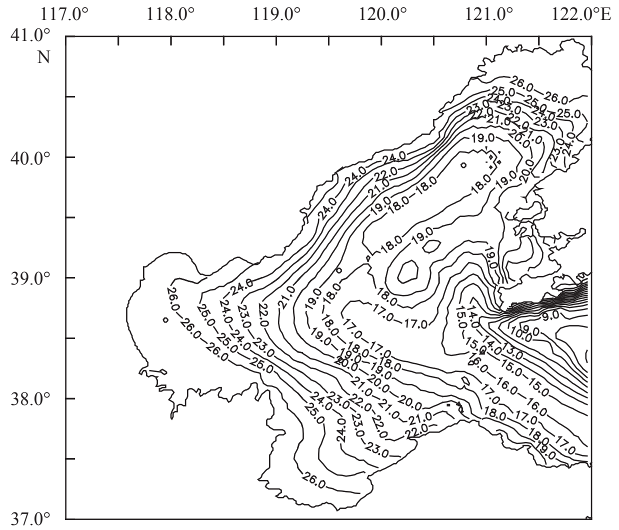

Fig. 5. The simulated bottom temperatures (°C) in summer.

perature. The two figures show that there exists obvious temperature front in the area off the west coast of the Liaodong Bay, in the Bohai Bay and in the offshore area of the Huanghe Estuary. There is a warm water core in the central Bohai Sea, the center of the core is (39°N, 120.3°E). There are also two cold water area, one is northeast to the warm core, the other is to the south of the warm core. The simulated bottom temperature in the central Bohai Sea is somewhat lower than the observation. The possible reason is that only M_2 tide is added in the model, the tidal mixing is not strong enough to bring the warm water down to the bottom.

The simulated temperature along the section from the Huanghe River mouth to the head of the Liaodong Bay is also compared with the observation. Figures 6 and 7 give the result. There are two cold cores along this section, both the simulated result and the observation show this pattern. This result is similar to Lin et al. (2006).

4 Circulation pattern analysis

In this section the simulated current field at the depth of 5 m

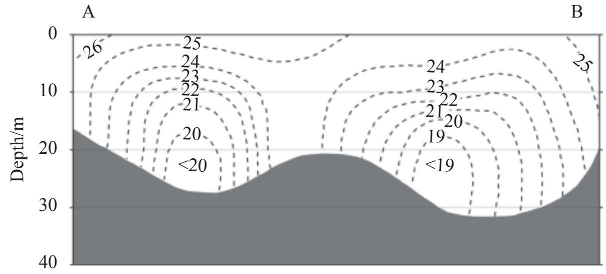

Fig. 6. The observed temperature (°C) along the section from the Huanghe Esturary (A) to the head of the Liaodong Bay (B). After Editorial Board of Ocean Atlas (1992).

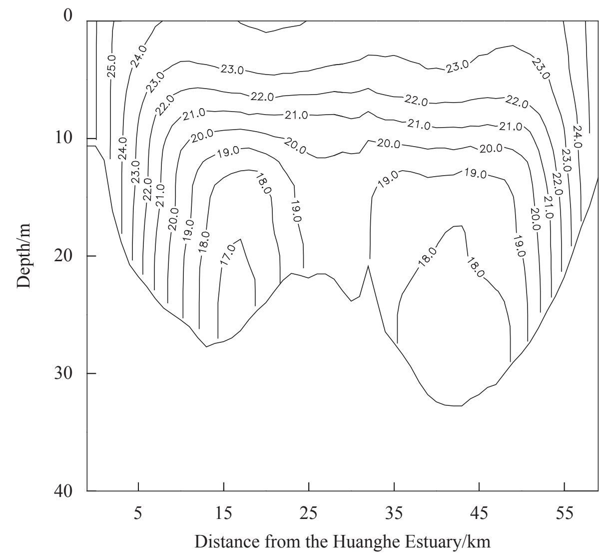

Fig. 7. The simulated temperature (°C) along the section from the Huanghe Estuary to the head of the Liaodong Bay.

and 15 m are compared with the observation result of Xu et al. (2006). The summer circulation patterns are given based on the model result and the observation and the forming mechanism are discussed.

Figure 8 gives the model current field at the depth of 5 m. There exists an obvious density residual current along the temperature front from the west part of the Liaodong Bay to the offshore area of the Huanghe Estuary. It flows out the Bohai Sea through the Bohai Strait. At Station BZ28–1 the current direction is southeastward, which agrees with the observation result of Xu et al. (2006). This result also agree with the circulation result of Huang et al. (1999). In his study, the circulation at the depth of 0–3 m with strong stratification and weak wind in the Bohai Sea is generally a basin scale cyclonic gyre, the result in this study also has this pattern with fine structure in the Liaodong Bay and Bohai Bay. It should be pointed out that the summer prevailing wind is southeast wind. So the current direction is opposite to the wind, this suggests the forming mechanism of this current is not mainly driven by wind. The simulated bottom temperature (Fig. 5) shows that there exists obvious temperature front in the area off the west coast of the Liaodong Bay, in the Bohai Bay, the offshore area of the Huanghe Estuary. So this current is mainly driven by the baroclinic force of the temperature front. This current is also obvious at the depth of 15 m (Fig. 9).

In the Liaodong Bay there exists a clockwise gyre in the area

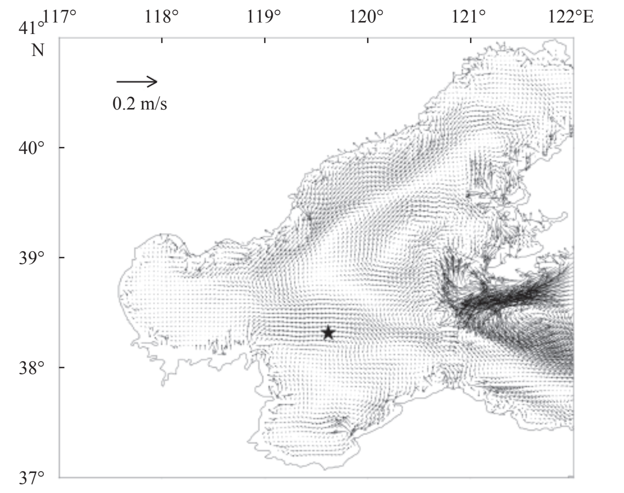

Fig. 8. The simulated circulation at the depth of 5 m. ★ stands for Station BZ28-1.

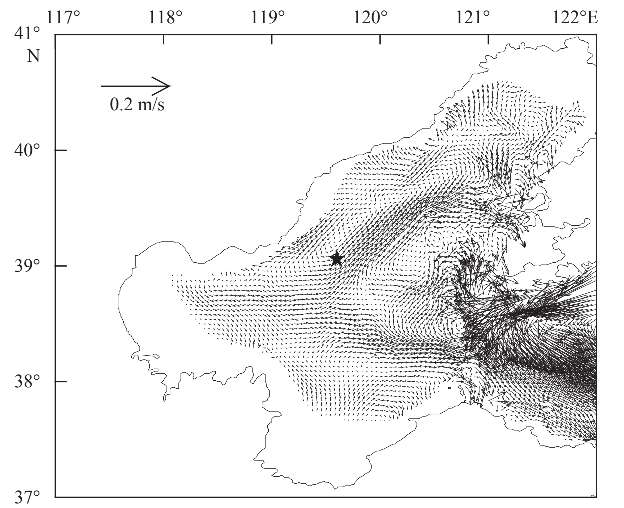

Fig. 9. The simulated circulation at the depth of 15 m. ★ stands for Station 8.

north to the 40°N. This agrees with Xu et al. (2006). While in the area south to the 40°N, the circulation shows a two-gyre structure, the flow from the offshore area of the Huanghe Estuary to the Liaodong Bay splits into two branches in the area between 39°N and 40°N. The west branch turns into north-west and forms an anti-clockwise gyre with the south-westward density residual current off the west of the Liaodong Bay. The east branch turns to the east and forms a clockwise gyre with the flow along the east coast of the Liaodong Bay. The flow from the offshore area of the Huanghe Estuary to the Liaodong Bay is mainly tidal residual current which exists all year around. At Station 8, the simulated flow direction is northeast in summer which agree with Zhao et al. (1995). The west branch is mainly driven by the baroclinic force of the temperature front (see the bottom temperature in Figs 3a and b).

In the Bohai Strait, the water flow into the Bohai Sea through the northern part of the strait and flow out through the south part of the strait. There exists a strong temperature front in the northern part of the strait and the Yellow Sea near the strait. So the flow in the Bohai Strait is the extension of the cyclonic gyres in the North Yellow Sea.

5 Conclusions

The climatological circulation pattern in summer of the Bohai Sea is studied using a wave-tide-circulation coupled model. Based on the model result and the observation the summer circulation in the Bohai Sea have the following patterns.

There exists an obvious density residual current along the temperature front from the west part of the Liaodong Bay to the offshore area of the Huanghe Estuary. This current is mainly driven by the baroclinic gradient force of the temperature front.

In the Liaodong Bay, there exists a clockwise gyre in the area north to the 40°N. While in the area south to the 40°N the circulation shows a two-gyre structure.

In the Bohai Strait, the water flow into the Bohai Sea through the northern part of the strait and flow out through the south part of the strait.

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