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RESIDUAL CIRCULATION SYSTEM AND ITS DRIVING MECHANISM IN THE BOHAI SEA

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Abstract: The typical seasonal (summer and winter) residual circulation in the Bohai Sea is studied with the ODEM 3-D flow model. The averaged tidal current distributions present the strong and weak current regions in the Bohai Sea. There are many vortexes rather than one big vortex in the Bohai Sea which constitute the tidal residual circulation system. The topography and the shape of coastal line induce the tidal residual circulation pattern. The effects of seasonal wind on tidal residual current and local thermally-driven current on tide-induced current are analyzed. The corresponding mechanisms and the interaction of tide, wind and heat exchange are discussed.

Key words: Residual Circulation; Bohai; Tide; Wind: Heat-exchange

1. INTRODUCTION

The Bohai Sea is a semi-enclosed basin. It is rather shallow except for the submerged valley near the north of Bohai Strait with approximately 100 km wide and the maximum depth of 70 m which connects the Bohai Sea with the Yellow Sea. The Bohai Sea contains three main Bays, namely Liaodong Bay in the northeast, Bohai Bay in the west and Laizhou Bay in the south. In Liaodong Bay, the averaged water depth is 30m. The topography of water bottom in Bohai Bay is rather flat. The water depth in most part is less than 20m except for the north part where the water depth is more than 30m. Laizhou Bay is the shallowest bay in the Bohai Sea. In most part of the bay, the water depth is less than 10m, the deepest depth is 18m. The water depth of central basin approximately in triangle shape changes from 20m to 40m.

Quite a big number of interests and studies from different researchers have been given to the Bohai Sea since 1980's. Firstly, it is so shallow with a mean depth of 18 m that the circulation system induced by external forcings such as periodical tidal current, wind driven current and density driven current becomes so complicated. Secondly, the Bohai Sea is typically enclosed coastal water that a very weak water exchange occurs through Bohai Strait with the north the Yellow Sea. Some researches are mainly concentrated on the tidal residual current since it is the fundamental constitute of residual circulation system and contributes to the long-term materail transport. (see Dou and Luo et al,1981; Sun and Xi, 1989; Huang,1992; Zhao and Shi,1993; Su,1998; Feng,1998; Fang,2000). But the other dynamic factors — wind, solar surface heating and so on also play important roles for such shallow ocean waters. Zhao and Zhuang et al(1995) shows us a interesting picture of the Bohai circulation based on field data. Huang and Chen et al(1996) made a meaningful discussion on the tidal residual current , wind-induced current and their interaction. Table 1 shows the main results of the researches mentioned above.

Table 1 Researches on residual circulation in the Bohai Sea

Authors	Season	Central basin	Liaodong Bay	Bohai Bay	Laizhou Bay
Dou (1981)	Summer	CW	CCW	N: CCW S: CW	CW
	Winter	CCW	W: CCW E: CW	CCW	CCW
Sun (1989)		CW	CCW	CCW	CCW
Wang (1992)	Summer	CW	CCW	CW	CW
	Winter	CCW	CW	CCW	CCW
Huang (1992)		CW	CW	NW: CW NE: CCW	CCW
Zhao (1995)		CW	CW	N: CCW S: CW	CW
Huang (1996)	Winter	CW	CW	CCW	CCW
	Summer	CW	CCW	CW	CW
Fang (2000)	Winter	CCW	CW	CCW	CCW

Note: (CCW: Counter Clockwise; CW: Clockwise; W: West; E: East; S: South; N: North; C: Central part; NW: NorthWest; NE: NorthEast)

In Table.1, the main features for different parts of the Bohai Sea is nearly the same, but the residual current chart is quite different among the researches above. The driving mechanism of residual current system is diverse depending on researchers. In this paper, more emphases are concentrated on the contributions of tide, wind and solar surface heating and their relative importance on the practical circulation system. At same time, the mechanism of residual circulation system under different external forcings and the interaction of tide, wind and heat exchange are discussed in detail.

2. NUMERICAL MODEL AND ARRANGEMENT

2.1 MATHEMATICAL MODEL

ODEM (Osaka Daigaku Estuary Model) is a three-dimensional baroclinic flow model developed by Osaka University, which has been employed to simulate tide flow, density current in enclosed waters such as Osaka Bay, Tokyo Bay and Ise Bay (See Nakatsuji and Fujiwara(1997)). The basic hydrodynamic equations are based on the conservation of mass, momentum and scalar transport (temperature and salinity) under Boussinesq assumption. Total Variation Diminishing (TVD) numerical scheme based on finite volume conception and space-staggered grid system is adopted. Successive Over Relaxation(SOR) method is used for the calculation of water elevation ζ in order to prevent unexpected numerical instability. More details about the model described by Nakatsuji and Fujiwara et al (1994).

The Sub Grid Scale(SGS) model proposed by Smagorinsky (1963) is employed to estimate horizontal eddy viscosity coefficient. The eddy viscosity and eddy diffusivity are used for representing the turbulent transport constituents. In summer, there is strong thermal stratification in the central part of the Bohai Sea, so it is necessary to estimate the vertical eddy viscosity and diffusivity carefully. Webb's formula(1970) and Munk and Anderson(1948) formula are applied to calculate the vertical eddy viscosity and diffusivity coefficient respectively, equations (1)−(3) are as following:

$$\frac{A_V}{A_{V_0}} = \frac{1}{1+5.2R_i} \quad (1)$$

$$\frac{K_V}{A_{V_0}} = \frac{\left(1+\frac{10}{3}R_i\right)^{-3/2}}{\left(1+10R_i\right)^{-1/2}} \quad (2)$$

$$R_i = -\frac{g\left(\frac{\partial \rho}{\partial z}\right)}{\rho_a\left(\frac{\partial U}{\partial z}\right)^2} \tag{3}$$

Here, the value A_{V_0} for neutral condition is set to A_{V_0} =0.005 m^2/s.

2.2 NUMERICAL ARRANGEMENT FOR THE BOHAI SEA

2.2.1 Grid system

This model uses 4 km × 4 km mesh in horizontal plane and 17 layers in vertical direction with the thickness of 3m for 4 layers, 2m for 4 layers, 3m for 3 layers, 4m for 3 layers, 5m for 2 layers and 6m for 2 layers from surface to bottom.

2.2.2 Computation arrangement

To examine the contribution of tide, wind and heat forcings on the residual circulation receptively, these factors are added to drive the model step by step. Table 2 lists the outline of numerical computation in present paper.

Table 2 Outline of computation

No.	Name of Condition	tide	wind	Heat exchange
1	Tide (T)	Yes	No	No
2	Tide + Summer Wind (TSW)	Yes	Yes	No
3	Tide + Winter Wind (TWW)	Yes	Yes	No
4	Tide + Summer wind+ Heat (TSH)	Yes	Yes	Yes
5	Tide + Winter wind+ Heat (TWH)	Yes	Yes	Yes
6	Tide + Summer Heat (TSH)	Yes	No	Yes
7	Tide + Winter Heat (TWH)	Yes	No	Yes

2.2.3 External forcings

External forces induce the flow in the Bohai Sea are: tide, wind, heat exchange .

(1) Tides: At the horizontal open boundary, sea surface elevation is prescribed according to the two tide stations: Dachangshan(39°16′N,122°35′E) in the North and Ji Mingdao (37°7′N,122°29′E). Five tidal constitutes M_2, S_2, N_2, K_1,O_1 are considered. Table 3 is the common tidal amplitude (m) and tidal phase(°) of the major tidal constitutes.

Table 3 Amplitude (m) and phase(°) of major tidal constitutes at open boundary

Position / Constitutes		Dachangshan	Jimingdao
M_2	H	1.32	0.46
	θ	30.0	349
S_2	H	0.34	0.1
	θ	37.0	8.0
K_1	H	0.26	0.22
	θ	185	230
O_1	H	0.17	0.14
	θ	154	201
N_2	H	0.19	0.10
	θ	118	92

(2) Wind: On the water surface, seasonal-averaged wind velocity field are interpolated onto the model grid points based on the Zhang(1983)'s statistic for both summer and winter, see Figs.1 and 2.

(3) Heat or Exchange: The heat exchange at the air-sea interface are calculated according to the formula in Defant(1961) and Murakami (1989). The heat exchange(Q_{flux}) in the sea surface is composed of four constitutes: short wave radiation(Q_S), long wave radiation(Q_R), sensible heat flux(Q_C) and latent heat flux (Q_E) (see Fig.3) The meteorological parameters (cloud cover, air temperature, wind speed, air pressure, relative humidity) are based on monthly multi-year-averaged value of the Bohai Sea area.

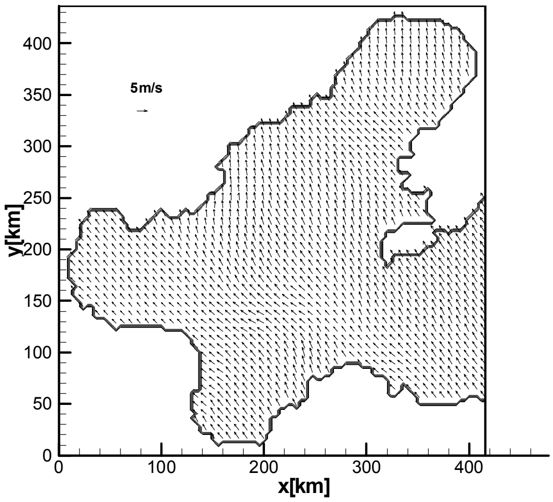


Fig. 1 Wind velocity distribution in summer

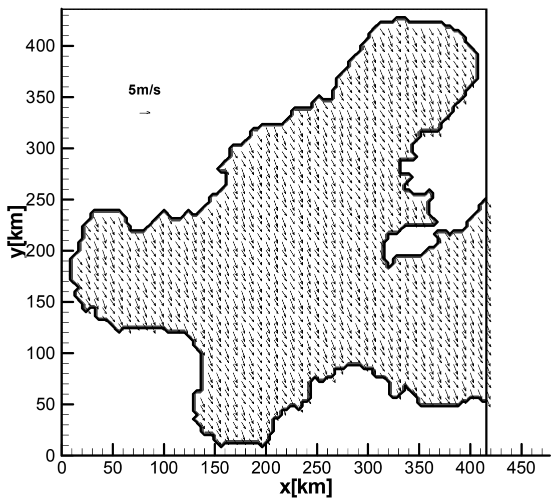


Fig. 2 Wind velocity distribution in winter

2.2.4 Boundary and initial conditions

In the barotropic flow model, the salinity and temperature field is given as the constant value while the corresponding initial field is prescribed with the month-averaged salinity and temperature distributions in the baroclinic flow model. the boundary condition is descried as following:

At water surface:

$$K_V \frac{\partial \Delta T}{\partial z} = \frac{Q_{flux}}{\rho_s C_P}, \quad K_V \frac{\partial \Delta S}{\partial z} = 0, \quad W = 0 \tag{4}$$

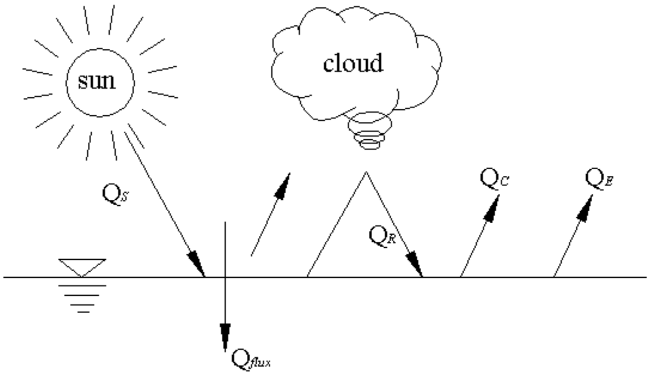


Fig. 3 Heat exchange between sea surface and air

At water bottom:

$$K_V \frac{\partial \Delta T}{\partial z} = 0, \quad K_V \frac{\partial \Delta S}{\partial z} = 0, \quad W = 0 \tag{5}$$

Along wall:

$$K_H \frac{\partial \Delta T}{\partial x_n} = 0, \quad K_H \frac{\partial \Delta T}{\partial y_n} = 0, \quad K_H \frac{\partial \Delta S}{\partial x_n} = 0, \quad K_H \frac{\partial \Delta S}{\partial y_n} = 0 \tag{6}$$

$$\frac{\partial u_i}{\partial n} = 0 \ (i = 1, 2, 3) \tag{7}$$

At Bohai strait:

$$\Delta S_0(t) = \Delta S_{\max} \quad \text{(inflow case)} \tag{8}$$

$$\Delta S_0(t) = \Delta S_{\text{inner}}(t) \quad \text{(outflow case)} \tag{9}$$

Here , $\Delta S_{\max}$: S value for inflow boundary , so is the temperature.
At river mouth:

$$\Delta T_r = T_r - T_a, \quad \Delta S_r = S_r - S_a \tag{10}$$

Here, T_a is the norm temperature of sea water, S_a is the norm salinity of sea water

3. RESULTS AND DISCUSSION

3.1 TIDES

3.1.1 Tidal elevation

Since the tides are dominant hydrodynamic process in the Bohai Sea, firstly, the ODEM is applied to simulate the tides. Many studies of tides by field surveys and numerical simulation have been performed on tides, as a result, common recognized conclusion has been achieved. Nakatsuji et al.(2001) has already confirmed that ODEM can predict the tidal characteristics of Bohai Sea.

3.1.2 Tidal current

The semi-diurnal tidal current dominates in the Bohai Sea, whereas the tidal flow distribution changes from the tide in different M_2 period. The time series of velocity for 85% grid points take on the characteristics of semi-month period macroscopically. Fig.4 shows the monthly averaged absolute velocity of surface tidal current in which the current changes from 0.1 m/s to 0.8 m/s. There are three strong current regions in the Bohai Sea. One is the at mouth and in the east of Liaodong Bay, the second is the in north of Bohai Strait, the third one is in the northeast of Bohai Bay and at the mouth of Yellow River. The currents in the heads of the three Bays are very weak, the weakest current is located in the head of Laizhou Bay. There are weak current regions in the center basin of the Bohai Sea.

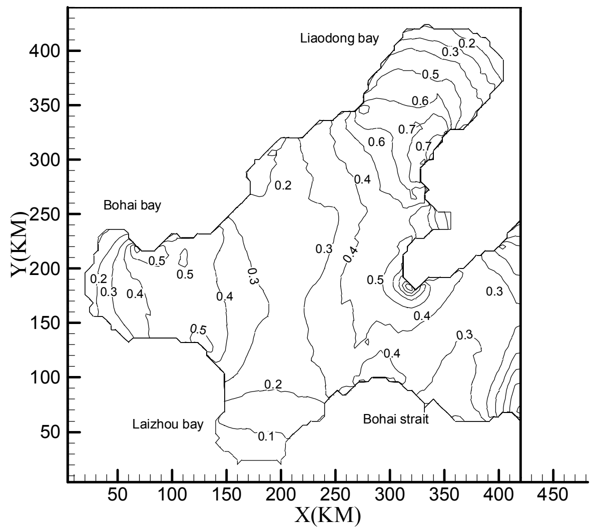


Fig. 4 Horizontal distribution of the absolute velocity of surface tidal current

3.1.3 Tide Induced Residual Current

Since the residual circulation system is well-known to contribute to the long-term transport process and water exchange, many researchers have paid their attention to it. The residual current is calculated by the simple method in which the velocity vector is time-averaged within one month. The direction and magnitude of surface tide induced residual current is showed in Fig.5. Generally speaking, the residual current is very weak and the area-averaged value is 1.49cm/s. In the head of Liaodong Bay, there is a count clock-wise vortex, a pair of vortices are located in the middle east and middle west of Liaodong Bay. Therefore a good ability of water exchange can be expected in the bay. A strong out-flowing residual current induces another pair of vortices outside the Laodong Bay mouth. There are two clock-wise vortices in the north part of Bohai Bay and the along-shore current reaches maximum value near the Yellow river moth. A clock-wise vortex occupies the west part of Laizhou Bay while the residual current is much less than 1cm/s in the head of Laizhou Bay. A distinct characteristic of tidal residual current for the whole Bohai Sea is the strong residual current in the north of Bohai Strait and along the Laotieshan water passageway, the maximum value is about 30cm/s. The inflow current is strong and narrow while the outflow current is weak and wide in the Bohai Strait.

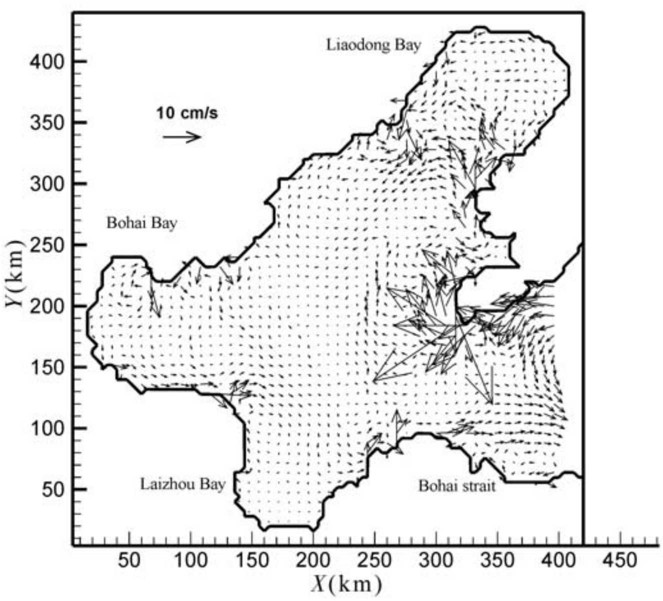


Fig. 5 Surface tidal residual current

Compared with the surface tidal residual current, the averaged bottom residual current is only 60% of that. In the mouth of Liaodong Bay and Bohai Strait, the residual current is much less than that of surface layer. The maximum value is 14 cm/s. The structure of residual circulation at the mouth of Liaodong bay and the south of Bohai Bay is different from the pattern in the surface layer. In the east part of the Bohai Sea, the direction of residual current changes dramatically and the out-flowing current direction of residual current changes dramatically and the out-flowing current direction of residual current changes dramatically and the out-flowing current dominates. There is no obvious in-flowing current and the out-flowing is strong and uniform in the Bohai Strait. Therefore, the water exchange in the bottom is stronger than that of surface layer. However, the residual current in the Laizhou Bay is almost the same as that of surface layer since the water depth in Laizhou Bay is very shallow.

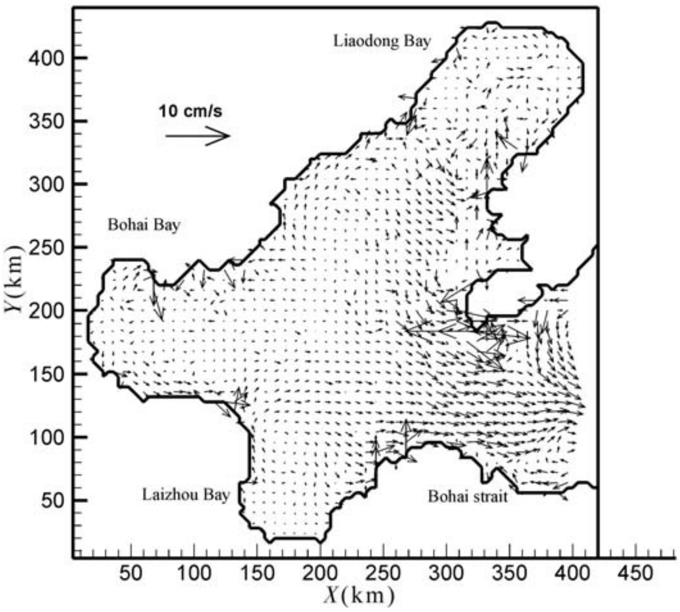


Fig. 6 Bottom tidal residual current

3.2 TIDES AND WIND

3.2.1 Wind-induced residual Current

In this chapter, the effects of wind blowing on the residual current system are discussed. The condition of forcing in summer is simplified as TSW while the condition of forcing in winter is called as TWW. Comparison of Fig.7 with Fig.5 demonstrates that the surface residual currents under the condition of TSW change a lot. The area-averaged residual current of surface layer is about 1.86 cm/s, increasing about 25%. In Laizhou Bay, the residual currents flow upward to the center of the Bohai Sea instead of flowing along the coastline to the Bohai Strait. The tendency is same in the mouth of Bohai Bay, which means the suspended solid coming from Yellow River can be transported to the center of the Bohai Sea. The strong out-flowing current in the mouth of Liaodong Bay also changes the direction to west. Therefore, it is more difficult for water exchange in the three bays although the magnitude of residual current in center of the Bohai Sea increases in this condition. The bottom residual currents have no much change both in magnitude and direction. The averaged value increases only about 7%. In summary, wind forcing in summer has great effect on the residual circulation structure of the most parts of the Bohai Sea but little effect on Liaodong Bay.

Fig. 8 shows the surface residual current under the condition of TWW. For this case, the residual currents increase greatly in all layers. In the surface layer, the averaged value increase 76% to 2.63 cm/s and that of bottom layer also increases 30% to 1.14 cm/s. Under the strong winter wind, the strong out-flowing currents dominate the center of The Bohai Sea, Bohai Bay and Laizgou Bay. The out-flowing current in the south of Bohai Strait becomes stronger and wider. All the longshore currents show the tendency of flowing out in the west part of the Bohai Sea. Another remarkable change is the appearance of a strong longshore current in the head of Laizhou Bay. The strong winter wind can help improve the ability of water exchange for the Bohai Sea except for Liaodong Bay. In Laiodong Bay, the three vortices change into one big clock-wise vortex which can not change its poor water exchange. However, the change of inflow near the north of Bohai Strait should be noticed. When the strong inflow residual current reachs the north of the headland, it returns back and flows out of the Bohai Sea from the south of Bohai Strait. So this incomplete circulation should affects the water exchange in some way.

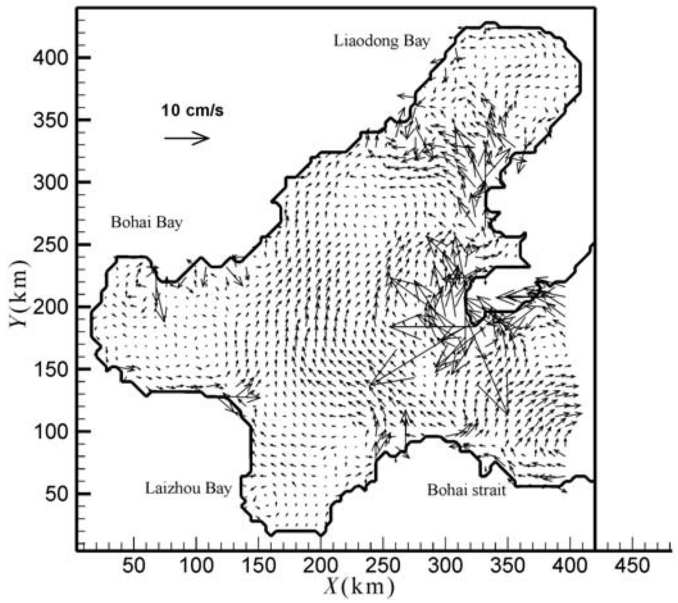


Fig. 7 Surface residual current under tide and wind in summer

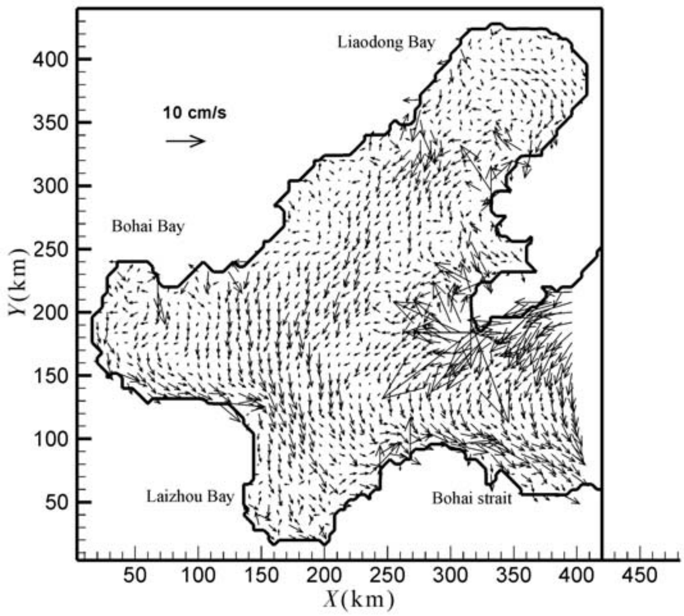


Fig. 8 Surface residual current under tide and wind in winter

3.3 TIDES , WIND AND HEAT EXCHANGE

The phenomenon of thermal stratification is remarkable in summer in the Bohai Sea and local thermally-driven circulation is important in determining the circulation system (Davis and Bogdan 1989). In this chapter, the effect of surface heat flux is examined.

In Fig.9, the area-averaged surface residual velocity including the thermally-driven current is about 3.48cm/s which is 1.87 times as large as that of TSW and the maximum value of residual velocity increases sharply to 40 cm/s. Referred to the results of tide residual current, it is clear that the effect of tide, wind and heat exchange on the residual circulation is in the same order. Compared with Fig.7 and Fig.9, a few interesting phenomena should be noticed. One is appearance of a pair of large vortexes near the headland of Liaodong peninsula. The anti-clockwise one is narrow along the north of Bohai Strait and Laotieshan water passageway, the clockwise one is large and squeezed to the left by the strong westward residual current. The other is the appearance of a out-flowing current from the north of Yellow River to the Bohai Strait. This strong out-flowing current becomes stronger near the Bohai Strait and the direction change to east instead of northeast, which should improve the water exchange between the center of the Bohai Sea and the Yellow Sea. Under the effect of thermal stratification, the bottom residual current of the center of the Bohai leaves us another picture. The original eastward current change to westward and a clock wise vortex is formed in the center. Undoubtedly, the water exchange between the Bohai and the Yellow Sea becomes weaker in the bottom layers compared with the condition of TSW.

Although there is no thermal stratification in winter, surface solar heating also plays an important role on the residual current. The averaged residual velocity reaches 3.96 cm/s. In the Fig.11, there is strong out-flowing current which origins from the mouth of Liaodong Bay, converges part of the flow of Bohai Bay and flows out of the Bohai Sea from the south of Bohai Strait. The outflow is wider and stronger compared with the narrow outflow in Fig.9. The difference between bottom layers for the two cases also lies in the center part. But it is not as strong as that of surface layers. The averaged velocity is almost the same as that of TWW, the noticeable change is the residual current around Yellow River mouth, the original northeastward flow changes to southwestward which is unfavorable for the transport of Yellow River water.

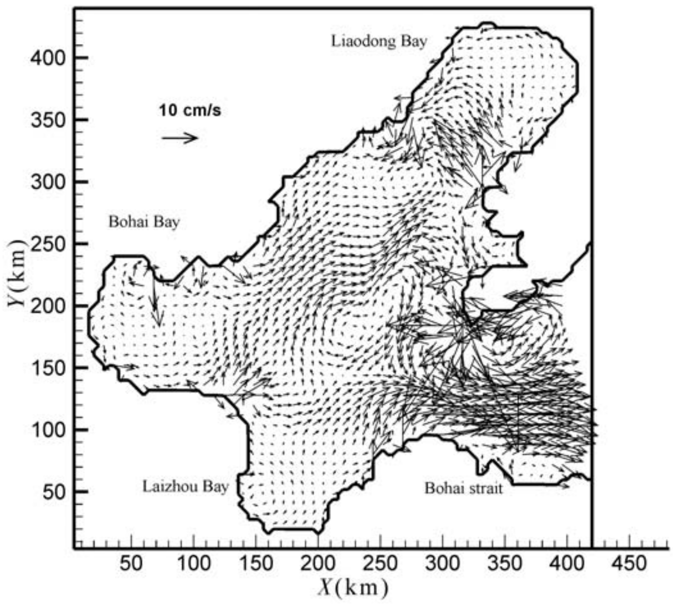


Fig. 9 Surface residual circulation under tide, wind and heat exchange in summer

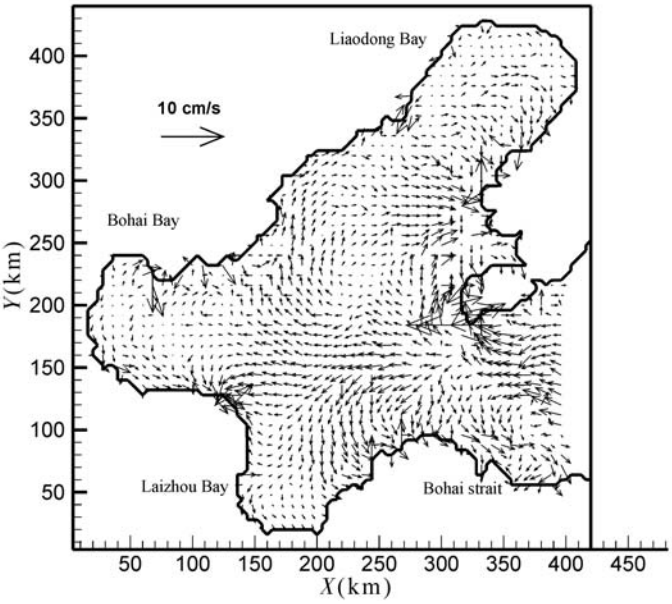


Fig. 10 Bottom residual circulation under tide , wind and heat exchange in summer

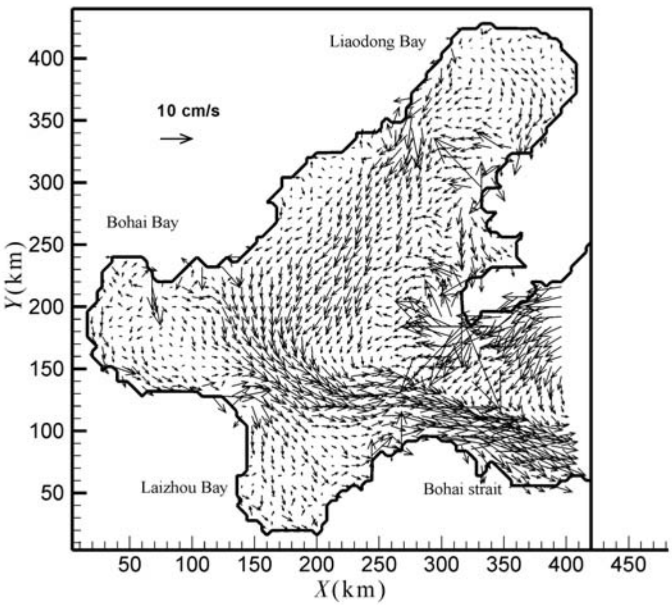


Fig. 11 Surface residual circulation under tide , wind and heat exchange in winter

3.4 MECHANISM OF CIRCULATION SYSTEM

3.4.1 Wind-driven current on tide-induced current

Compared Fig. 7 with Fig. 5, there is no much difference for the lonshore current under the effect of summer wind. So it is topography that determines the longshore current. In the center part of the Bohai Sea, under the persistent wind, the Ekman transport changes the original general tendency of residual current system. According to the theory of Ekman transport, net motion direction is to the right of wind in the north hemisphere. Fig 13 (b) − (d) and Fig. 14 (b) − (d) show the typical vertical distribution of residual velocity for different computation cases in the center of Bohai Sea. In summer, in upper layers, the tendency of tide-induced residual current and wind-driven current is adverse. The magnitude of wind-driven current is larger than that of tide-induced residual current. As a result, the flow tendency of residual current system changes, see Fig13(b) − (c) and Fig14(b) − (c). In lower layers, the tendency of tide-induced residual current and wind-driven current is identical, so it has little affect on the residual circulation structure although the magnitude of velocity increases.

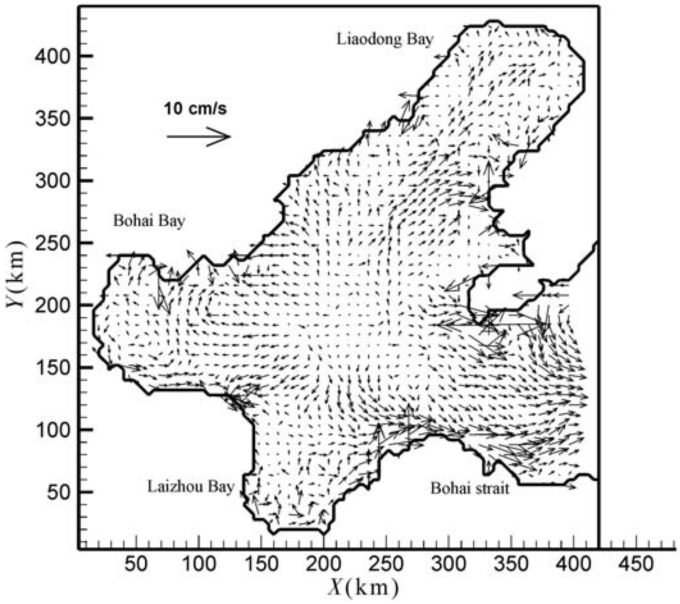
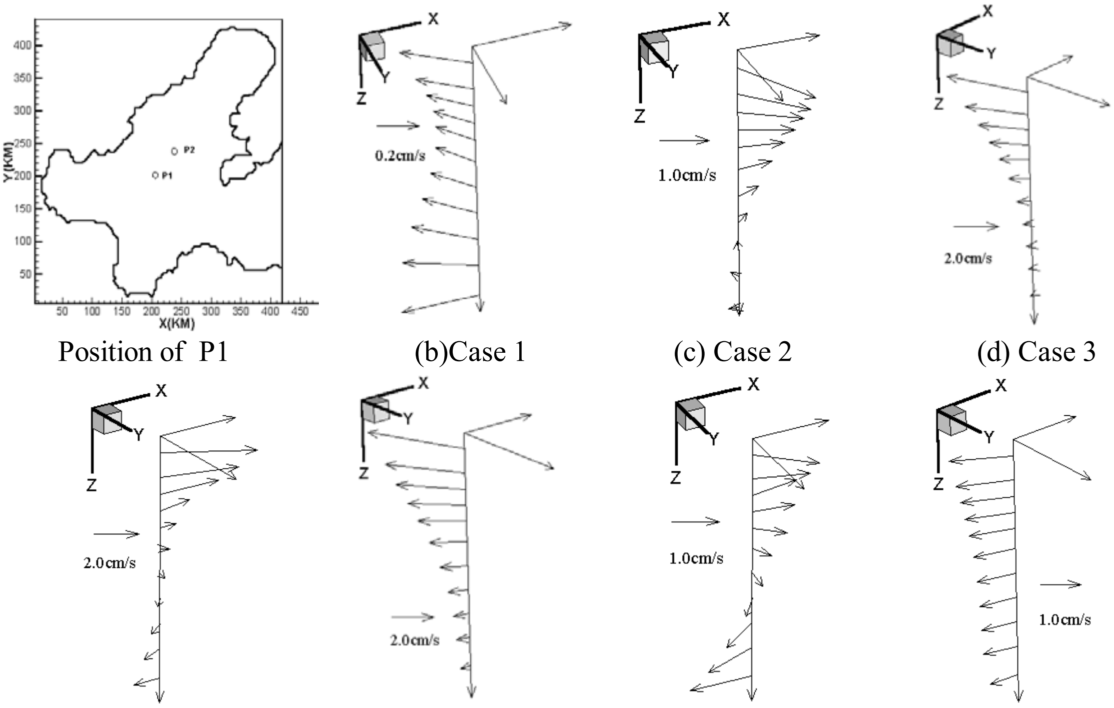


Fig. 12 Bottom residual circulation under tide ,wind and heat exchange in winter

The effect of wind-driven flow on tidal residual current in winter is apparently different for Fig.9. The flow direction of the longshore current changes little although their magnitude increases in the Laizhou Bay and south coastline. It results from the water pilling-up under the constant northwest winter wind and the shallow water depth in Laizhou Bay. Under this condition, both wind and tide determines the longshore current. In the center of the Bohai Sea, in upper layers, Ekman transport leads to the wind-driven current flowing to northeast, which is in the same direction as tidal residual current. Comparison between (b)s and (d)s presents this feature vividly. So the magnitude of co-circulation current increases sharply while the direction almost keep the same in the upper layers. However, The tendency of tide-induced residual current and wind-driven current is adverse in the lower layers. However, the effect is not strong as that of surface .

3.4.2 Thermally-driven flow on tide-induced current

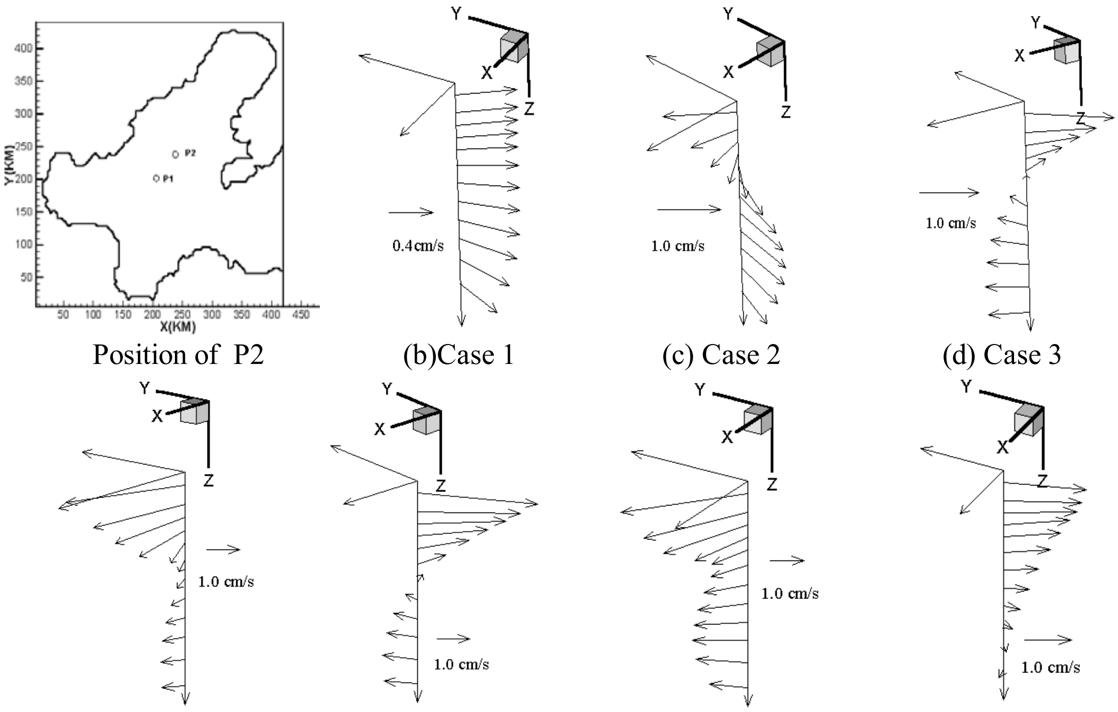
In summer, a cold water mass penetrates into the Bohai Sea from Bohai Strait, see Fig.15. In the center part of the Bohai and around the headland of Liaodong peninsula, the thermally-driven stratification is remarkable. If Coriolis force doesn't change with the latitude, the thermally-driven current should flow along the isodensity line. Furthermore, the salinity difference is so little that the thermally-driven current flows along the isotherms. Based on the rules of gradient current, the density of right-side should be smaller than that of the left-side along the current direction, so the thermally-driven current should be clockwise as shown in Fig.9 and Fig. 10. In the center of Bohai Sea, in upper layers, the direction of thermally–driven current is adverse to that of tide-induced



Position of P1 (b)Case 1 (c) Case 2 (d) Case 3

(e) Case 4 (f) Case 5 (g) Case 6 (h) Case 7

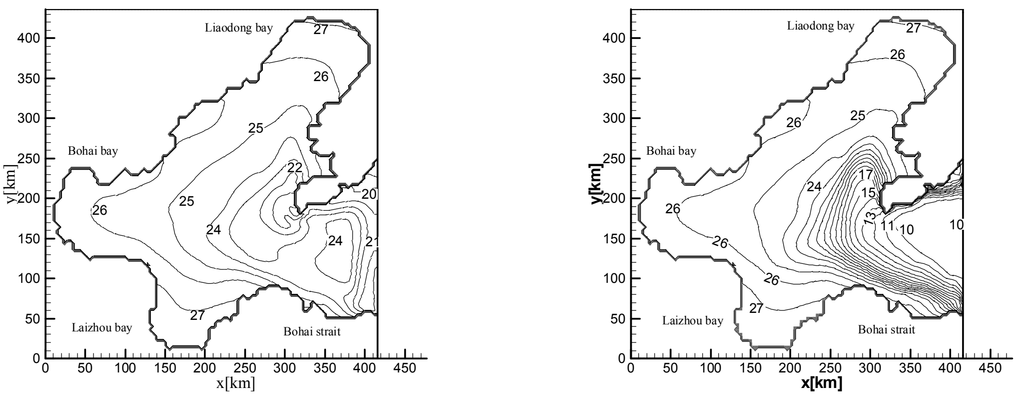
Fig. 13 Vertical distribution of residual velocity of P1



Position of P2 (b)Case 1 (c) Case 2 (d) Case 3

(e) Case 4 (f) Case 5 (g) Case 6 (h) Case 7

Fig. 14 Vertical distribution of residual velocity of P2

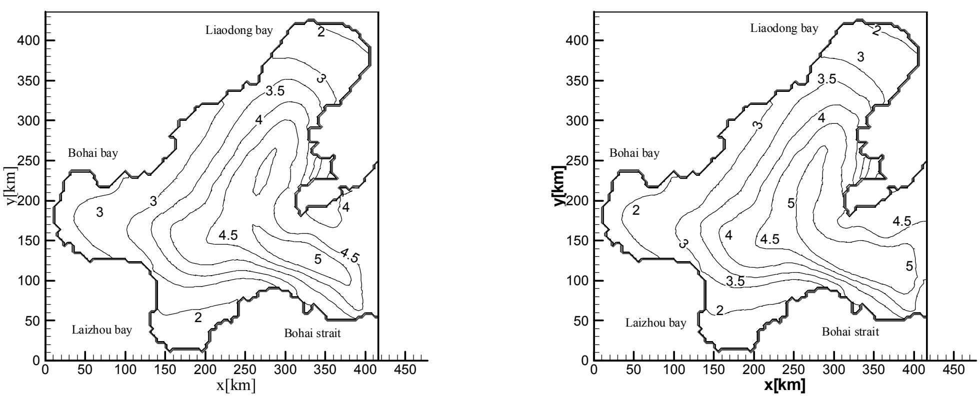


(a) Surface temperature for case 6 (b) Bottom temperature for case 6

Fig. 15 Horizontal distribution of temperature in summer

current according to the comparison between Fig.13 (b)s and (g)s in summer. But the magnitude of thermally-driven current is much larger that that of tide-induced current , so the tendency of residual circulation changes.

In winter, there is no stratification in the Bohai Sea and temperature distribution in upper layers is almost same with the that of lower layers. The water temperature in the three bays is lower than that of other parts. The isotherms are parallel to coastal line. The isotherms lines from mouth of Yellow river to Bohai strait are densely distributed, which means that the thermally-driven current caused by the difference of horizontal density is strong. At the same time, it is in the same direction with wind-driven flow. So the out-flow current in this part in the Fig.11 is very strong. In lower layers, the effect of thermally–driven current on tide–induced current is changing based on different positions.



(a) Surface temperature for case 6 (b) Bottom temperature for case 6

Fig. 16 Horizontal distribution of temperature in winter

3.4.3 Interaction of tide, wind and heat exchange

When all the above external forcing are considered, they acted each other besides contributing to the whole residual circulation system. Wind stress augments the heat exchange both in horizontal and vertical directions. In summer, the effects of wind and heat exchange are identical no mater in summer or in winter, but both adverse to tide-induced current. In lower layers, in summer, the effects of wind and heat exchange is adverse, thermally-driven current is in the same direction as tide-induced current. The thermally-driven current is dominant, wind-induced current follows and tide-induced current is weakest in most parts based on the analysis of (c)s , (e)s and (g)s in Fig. 13 and Fig.14. In winter, the wind is leading factor according to comparison of (d)s, f(s) and (h)s, therefore, the circulation structure is simple for winter cases.

4. SUMMARY AND CONCLUSION

The tidal residual current in the majority of the Bohai Sea is weak and the magnitude of the averaged current for center region is less than 1 cm/s. The nearshore currents are much stronger and the directions are irregular. The maximum value occurs in the Laotieshan water passagway and it is about 30cm/s. There are many vortexes rather than one large vortex in the Bohai Sea which constitute the tidal residual circulation system. The topography and the shape of coastal line induce the tidal residual circulation.

The effect of seasonal wind on the tidal residual current is great for the center of Bohai Sea although it has little effect on longshore current. In upper layers, under summer wind, the tendency of wind-driven current caused by Ekman transport is adverse to that of tide-induced residual current, however, the wind-driven flow in winter is in the same direction with tide-induced residual current direction. The effects are adverse to surface layers in lower layers. Therefore, the residual circulation pattern in the center of the Bohai Sea under different seasonal winds is apparently different. The summer wind makes the water exchange between the Bohai Sea and the Yellow Sea more difficult. But it is rather weak and can hardly affect bottom layers. On the contrary, the strong winter wind effects the residual current to all the layers.

The surface solar heatings increase the residual velocity remarkably whether they can induce stratification or not. The effect is in the same order as tide and wind action. In summer, the thermally-driven current forms a large clockwise circulation in the center of Bohai Sea. The outflow is strong in the middle of Bohai Strait in surface layer. In winter, the noticeable strong out-flow current dominates the center and the south of the Bohai Sea except Laizhou Bay which not only increases the magnitude of averaged residual velocity but also improve the water exchange of the Bohai Sea. However the direction of the residual current in the bottom layer is unfavorable for water exchange.

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