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Comparison of summer thermohaline field and circulation structure of the Bohai Sea between 1958 and 2000

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Abstract **The analysis of observed salinity data over 35 years (1961—1996) at four stations around the Bohai Sea, i.e. Huludao, Qinhuangdao, Tanggu and Beihuangcheng, reveals that the salinity of the 4 observation stations has increased 1.1, 1.6, 1.9 and 0.4, respectively. The data also show that over the past 35 years, there have been at least 5 large salinity variation processes. The salinity data from two cruises of the Bohai Sea in August 1958 and 2000, show that the salinity pattern of the Bohai Sea has changed markedly. Low salinity in the sea surface layer around the old Yellow River mouth in August 1958 had been replaced by high salinity in August 2000 and the maximum variation of salinity is over 10.0. In addition, the values and distribution of salinity were almost the same from surface to bottom there in August 2000, but there existed significantly different salinity levels between the surface layer and the deep layer in August 1958. When a comparison is made between the salinity levels of the above-mentioned two years, it is found that the salinity in August 2000 is on average 2.0 higher than that of August 1958 in the main part of the Bohai Sea. The change of temperature and salinity field in the Bohai Sea leads to the change of the circulation. The numerical simulation shows that in comparison with the circulation structure of the Bohai Sea in August 1958, the circulation in August 2000 changes markedly. The significant changes of circulation appeared in Bohai Bay, Laizhou Bay and in the middle of the Bohai Sea. The clockwise current loop outside of the Bohai Bay and counterclockwise current loop outside of the Laizhou Bay in August 1958 disappeared in August 2000, and the counterclockwise current loop of the Bohai Bay migrated obviously outward. The flow direction in the Laizhou Bay turned 180° around. Corresponding to the variation of the Bohai Sea circulation, the amount of water exchange between the Bohai Sea and the Yellow Sea has also changed. The water exchange rate through the Bohai Strait decreases, on average, 0.7×10^4 m^3/s in August 2000 in contrast to that of August 1958.**

Keywords: Bohai Sea, temperature and salinity field, summer circulation.

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The Bohai Sea (37°07′—41°N, 117°35′—121°10′E) is a shallow semi-enclosed sea. Since the Bohai Sea is the only inner sea of China and also an important strategic sea, it is one of the most investigated seas in China. A large number of studies on the tide and the tidal current as well as numerical simulation of circulation have been carried out, enhancing our understanding of the Bohai Sea.

Long-term variations of the sea surface salinity (SSS) and sea surface temperature (SST) of the Bohai Sea were analyzed. Lin et al.[1] found that the positive trends of the annual mean SSS and SST were 0.074/a and 0.011℃/a, respectively, during 1960—1997. Based on the historically observed data analyses of SSS, SST, air temperature and precipitation from 1965 to 1997 in seven stations along the Bohai Sea, Fang et al.[2] found that SST had raised 0.48℃ with a rate 0.015℃/a; SSS 1.34 with a rate 0.042/a; the air temperature 1.09℃ with a rate 0.034℃/a and the precipitation had decreased 87 mm with a rate –2.72 mm/a during the past 32 years (1965—1997). Responding to the change of the Bohai Sea temperature and salinity field, its circulation structure should also change. In this paper, based on the observed salinity data over 35 years (1961—1996) at four stations around the Bohai sea, and data with highly horizontal resolution of two cruises of the Bohai sea in August 1958 and 2000, the circulation in the Bohai Sea is diagnostically simulated with the three-dimensional ECOMSED model, and the variation characteristics of the circulation in summer of the two years are revealed.

1 Data and model

The data used in this article are the salinity data over the past 35 years (1961—1996) from four stations, i.e. Huludao(120°59′E,40°43′N), Qinhuangdao (119°38′E, 39°54′N), Tanggu (117°42′E, 39°N) and Beihuangcheng (120°54′E, 38°21′N), the precipitation data of Qinhuangdao and Tanggu, and the data of temperature and salinity in standard layer of the two cruises in August 1958 and 2000. The wind field data are the averaged NCEP wind field at 10 m over the sea surface in summer of 1958 and 2000, and the objectively analyzed mean wind field data in August offered by Ocean University of China (OUC). The three-dimensional baroclinic ECOMSED model[3] forced by the M_2 tide and the mean wind field of Ocean University of China is used to diagnostically simulate the Bohai Sea circulation in August 1958 and 2000.

2 Results and discussion

(ⅰ) Variations of temperature and salinity in the Bohai Sea. Figure 1 shows the time variation of the salinity of the four stations (Huludao, Qinhuangdao, Tanggu and Beihuangcheng) and of the precipitation of the two stations (Qinhuangdao and Tanggu). The beelines in Fig. 1 stand for the changing trends of salinity and annual precipitation determined by linear regression. The increasing rates of annual mean salinity at the four stations were 0.0311/a, 0.0458/a, 0.0546/a and 0.0126/a, respectively. In the past 35 years (1961—1996), the average salinity in each station referred above had raised 1.1, 1.6, 1.9 and 0.4, respectively. Fig. 1 also shows that there had been at least five large salinity variation processes in the Bohai Sea during 1961—1996.

Figures 2 and 3 show the distributions of temperature and salinity in August 1958 and 2000 in the Bohai Sea (surface, 10 m and bottom), respectively. When the two figures are compared, it can be seen that there exist no significant differences of the temperature distribution between 1958 and 2000, except the region of a diagonally striped area from Bohai Bay to the south of the Strait and the northwestern part of the Bohai Sea. For instance, there is a significant low temperature strip in the surface layer from the mouth of the Bohai Bay to the south of the Strait, and there is a low temperature center in 10 m layer located at the mouth of the Bay in 2000. In the middle of the Bohai sea there is a high temperature center in the whole depth in 2000. All these features are not conspicuous in August 1958. Comparing the salinity of two figures, we can see that there are significant differences of the salinity distribution structures between August 1958 and 2000. The low salinity in the sea surface layer outside of the old Yellow River mouth in August 1958 had been replaced by a high salinity in August 2000. The high salinity exists in the whole depth and extended northeastward to the middle of the Bohai Sea. Except the top region of the Liaodong Bay, the salinity of the surface and 10 m layer in the whole Bohai Sea is higher than that near the Strait. The impact of the Yellow Sea on the salinity is only limited in the region adjacent to the Bohai Strait in 2000. The maximum salinity of the Bohai Sea was 30.5 and the minimum salinity less than 22.0 in August 1958. In most parts of the Bohai Sea, the salinity was higher than 31.7 with the maximum salinity higher than 32.2 in 2000. On average, the salinity of the whole Bohai Sea in August 2000 is 2.0 higher than that of August 1958.

The variation of the salinity in the whole Bohai Sea is controlled by several factors, namely, river discharge, precipitation, evaporation, groundwater discharge, as well as water exchange through the Bohai Strait. Lack of data prevents us from estimating the contribution of the groundwater discharge and water exchange through the strait. Without regard to the contribution from the Yellow Sea water and the groundwater discharge, based on the viewpoint of freshwater budget and by means of the proportion of the decadal averaged precipitation, evaporation and the Yellow River discharge from the 1970s to the 1990s to those decadal averaged values in the 1960s, Wu et al. analyzed each factor's contribution to the raising salinity level in the Bohai Sea. They pointed out that the sharp decrease of the Yellow River discharge played a dominant role in the salinity rise in the whole Bohai Sea and speculated that the five large salinity variation processes during the past 35 years may, to some extent, re-

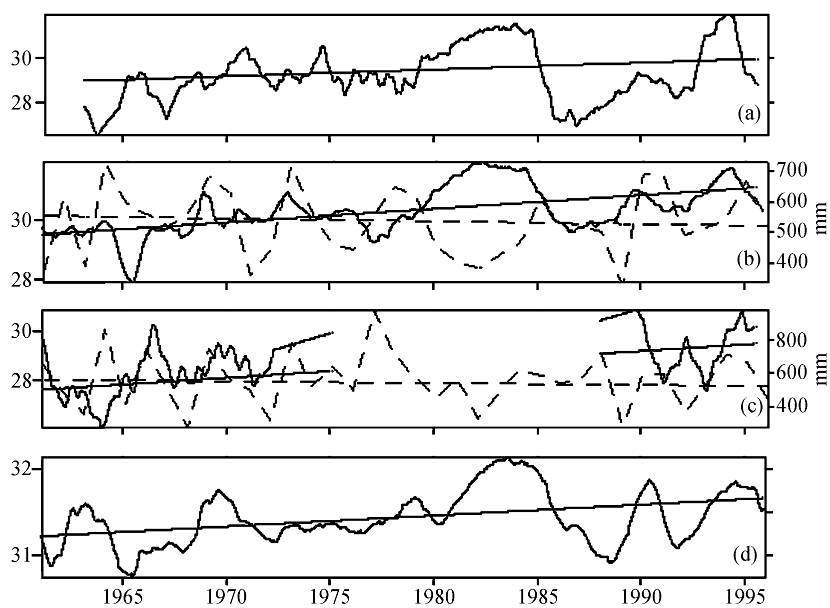

Fig. 1. Variation of the salinity (solid lines) of the four stations and the annual precipitation (dashed lines) of the two stations in the Bohai Sea. (a) Huludao; (b) Qinhuangdao; (c) Tanggu; (d) Beihuangcheng.

1) Wu, D., Mu, L., Li, Q. et al., Long-term variation characteristic of the salinity of the Bohai Sea and the possible dominant factor, Progress in Natural Science (accepted, in Chinese).

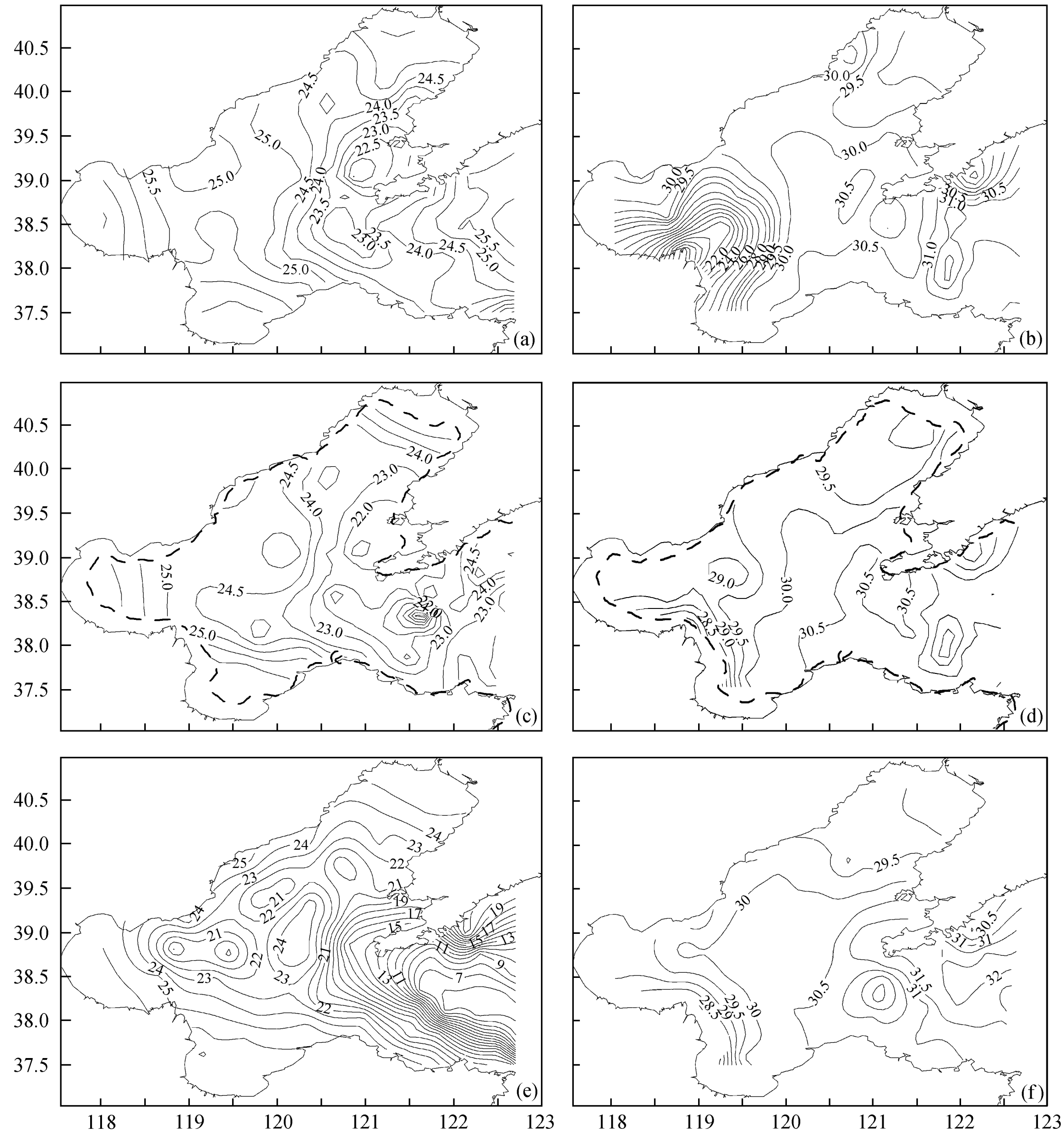

Fig. 2. Temperature and salinity distribution of the Bohai Sea in August, 1958. (a), (c), (e) Surface, 10 m and bottom temperature; (b), (d), (f) surface, 10 m and bottom salinity.

spond to the variation of the high salinity water intrusion from the north Yellow Sea. By comparing the variation of the annual precipitation and the salinity of Qinhuangdao (Fig. 1(b)), we can find that the more (less) the precipitation is, the higher (lower) the salinity will be during 1961—1975 and 1985—1996, implying that the strong intrusion of high salinity water from the north Yellow Sea may also make contribution to the salinity increase of the Bohai Sea. However, the more (less) the precipitation was, the lower (higher) the salinity was during 1975—1985, meaning that the variation of precipitation can also make contribution to the salinity variation of the Bohai Sea. The reason why there was a high salinity area adjacent to the old Yellow River mouth and it extended tongue-like to the middle of the Bohai Sea in August 2000 also needs to be investigated. On the basis of the preliminary analysis, we speculate that the location change of the estuary of the Yellow River and the sharp decrease of the Yellow River discharge weakens the input of fresh water to that area. On the other hand, a strong higher salinity water intrusion from the north Yellow Sea to the Bohai Sea during 1998—1999 and the decrease of precipitation in Bohai Bay in 2000, contributed to the increase of the salinity of that area. All the above-mentioned might cause the high salinity in the region adjacent to the old Yellow River mouth.

(ii) The summer circulation in the Bohai Sea and its

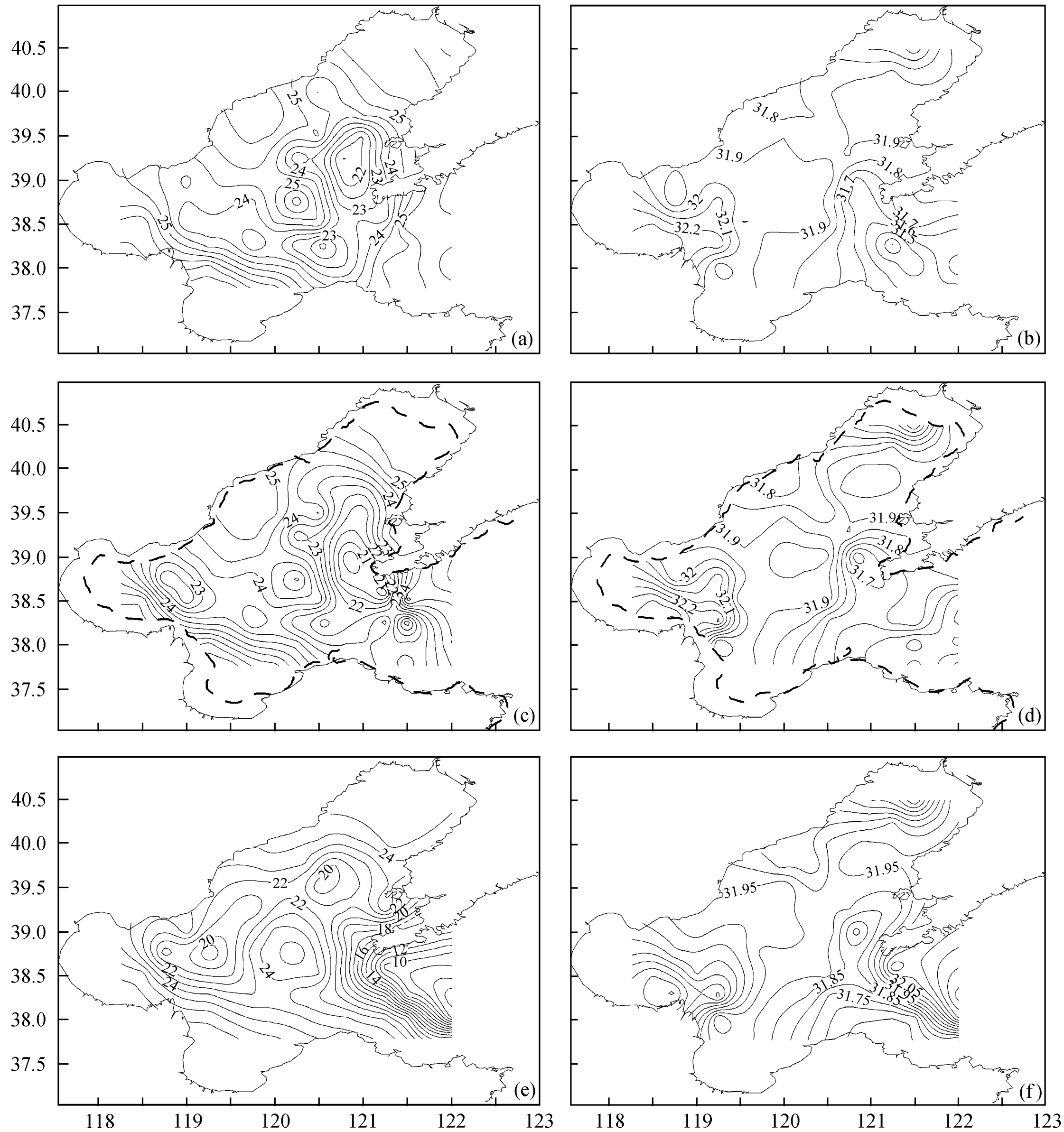

Fig. 3. Temperature and salinity distribution of the Bohai Sea in August, 2000. (a), (c), (e) Surface, 10 m and bottom temperature; (b), (d), (f) surface, 10 m and bottom salinity.

variation. The circulation of the Bohai Sea is composed of tide-induced circulation, wind-driven circulation and thermohaline circulation. The tide-induced circulation of the Bohai Sea is stationary. However, the Bohai Sea is a shallow sea with an average water-depth of 18 m and the wind-driven circulation structure of the Bohai Sea is sensitive to the change of wind-stress. In order to analyze the circulation change of the Bohai Sea caused by the change of the thermohaline field, it is necessary to see whether there are obvious differences between the summer wind-field in 1958 and in 2000. Fig. 4 shows the average summer wind-field based on NCEP wind data at 10 m above the sea surface. From the figure we can see that the average summer wind velocity of the Bohai Sea and the Yellow Sea in 1958 and 2000 is about 3 m/s, and there are no obvious differences of wind-field structures between the summers of 1958 and 2000. Since the resolution of NCEP wind-field is comparatively coarse, we adopt the mean wind-field in August designed by Ocean University of China (OUC) as the external force. The three-dimensional baroclinic ECOMSED model forced by the M_2 tide and by the mean wind field of OUC is used to simulate diagnostically the variation of the Bohai Sea circulation associated with the change of temperature and salinity structure.

Figure 5 shows the circulation distributions of the

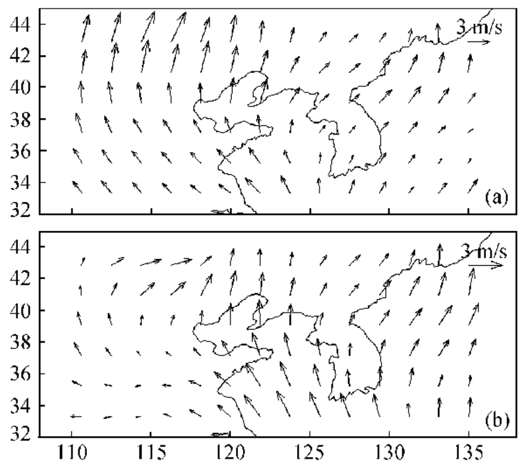

Fig. 4. Mean wind field of the Bohai Sea and the Yellow Sea in the summer of 1958 (a) and 2000 (b).

surface (2 m), 10 m and the bottom layer of the Bohai Sea in August 1958. It can be seen from Fig. 5 that the surface current field of the Bohai Sea is similar with the 10 m layer current field. The structure of the circulation in the middle of the Bohai Sea is composed of three current loops including a clockwise loop with its center in 120.3° E, 38.9° N, a counterclockwise loop with its center in 120° E, 38.3° N and a clockwise loop with its center in 119.25° E, 38.5° N corresponding to the low-salinity area adjacent to the Yellow River mouth. There exists a "one-half loop" structure in the surface layer of the Bohai Bay with a counterclockwise loop in the northern part and a half clockwise loop in the southern part of the Bohai Bay. There is a two-loops structure in 10 m layer there. The surface current structure mentioned above is basically consistent with the surface current of the Bohai Bay derived from the ERTS images[4] and the frame structure from the observations data analysis[5]. A part of the flow out of the Laizhou Bay comprises the south part of the middle Bohai Sea counterclockwise loop and the part of outflowing the Bohai Strait. The loop structure in the Liaodong Bay looked also basically like that of Guan and Chen1). The clockwise loop adjacent to the old Yellow River mouth and the counterclockwise loop outside of the Laizhou Bay weakens remarkably in the 10 m layer. The current field in the bottom layer appears to be a compensation flow. The water inflow of the Bohai Sea from the northern part of the Bohai Strait is separated into two parts, one flowing into the Liaodong Bay and the other rushing into the Bohai Bay. The current of flowing out the Strait is located mainly in the southern part of the Bohai Strait. There is also a counterclockwise loop outside of the Bohai Strait. The distribution of sediment in the Bohai Sea described by Qin[6] has effectively demonstrated the existence of the circulation structure mentioned above in the Bohai Sea.

Figure 6 shows the circulation distribution of the surface (2 m), 10 m and bottom layer of the Bohai Sea in August 2000. It is clear that the surface circulation structure is consistent with 10 m layer circulation. The current velocity in the bottom layer of the Bohai Sea is comparatively small and the loop structure is unobvious. The flow in the bottom layer appears to be a compensation flow. The inflow of the northern Yellow Sea water is still separated into two branches, one flowing to the Liaodong Bay and the other flowing to the Bohai Bay. There are 5 obvious current loops in the surface layer of the Bohai Sea, including a clockwise loop with its center in 120.3° E,

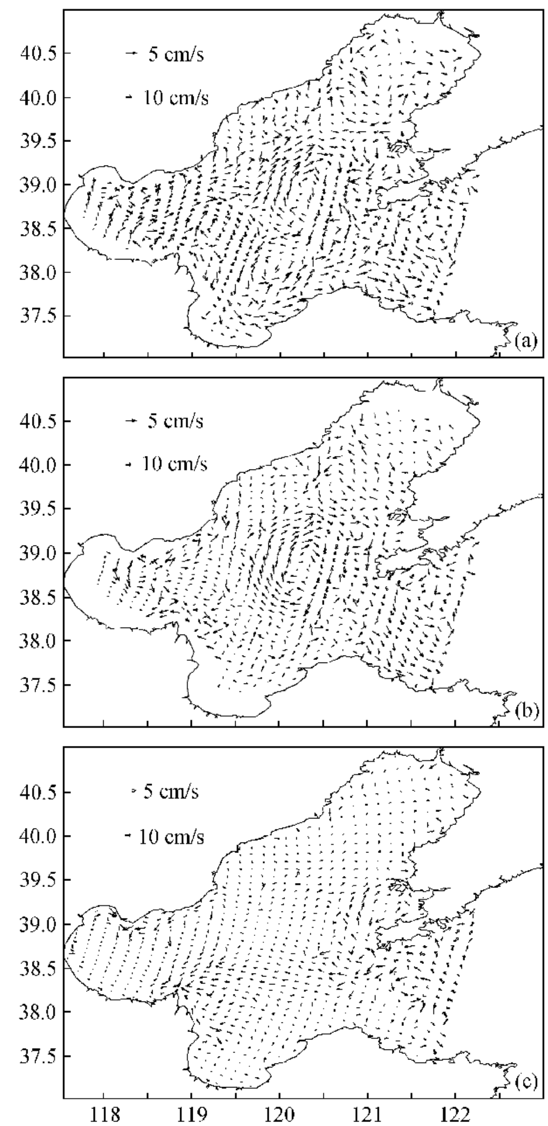

Fig. 5. Summer circulation of the Bohai Sea in 1958. (a) 2 m layer; (b) 10 m layer; (c) bottom.

1) Guan, B., Chen, S., Reports of the National Marine Comprehensive Survey (in Chinese), Vol. 5, 1964, 51—54.

38.6° N, a counterclockwise loop and a clockwise loop near the Liaodong Bay mouth, a counterclock wise loop and a clockwise loop in the Bohai Bay and its adjacent region. A stronger outflow in the surface and 10 m layer flows towards the northern Yellow Sea through the middle region of the Bohai Strait, and there is still a counterclockwise loop in the northeastern outside region of the Bohai Strait.

From Figs. 5 and 6, we found that compared with the circulation structure of the Bohae Sea in August 1958, the circulation structure of the Bohai Sea in August 2000 has to a significant extent changed. The existing clockwise loop outside of the Bohai Bay in 1958 disappeared in 2000. Instead of "one-half loop" structure of the surface circulation in August 1958, the surface circulation is a "two-loops" structure with southwest-northeast direction indicated in the Bohai Bay in August 2000. The counterclockwise current loop in the northeastern Bohai Bay is strong, and the clockwise current loop in the southern side of the Bay is relatively weak. The counterclockwise loop adjacent to the Laizhou Bay mouth did not exist any more, and the current direction of the Laizhou Bay in 2000 has turned almost 180°, in comparison with that in 1958. In August 1958, the water flowed into the Bohai Sea through the northern side and out through the southern side of the Bohai Strait. In August 2000, the outflow of the Bohai Sea water mainly occurred in the upper and middle layers in the middle of the Bohai Strait. In addition, the center of the clockwise current loop in the middle of the Bohai Sea migrated, an obvious displacement southward, in August 2000.

(iii) The impact of the Bohai Sea circulation variation on the water exchange rate through the Bohai strait in summer. The circulation variations described above are forced by the same mean wind-driven field, so the circulation variations result mainly from the change of temperature and salinity structure. For example, in August 2000 the counterclockwise current loop in the Liaodong Bay is corresponding with the cold center of the temperature, and the clockwise current loop adjacent to the Bohai Bay mouth is corresponding with the low-salinity structure in August 1958. The "two-loops" current structure with the southwest-northeast direction of the Bohai Bay is corresponding with the high salinity field in August 2000.

From the discussion above, we can see that there exist the obvious differences of the circulation between August 1958 and 2000 in the Bohai Sea. The variation of the Bohai Sea circulation should lead to the variation of the water exchange through the Strait. The average inflow or outflow along a section of the Bohai Strait was calculated. The results show that the average inflow or outflow is 7.0×10^4 m^3/s and 6.3×10^4 m^3/s in August 1958 and 2000 respectively. It is obvious that the average inflow or outflow through the Bohai Strait in August 1958 was larger than that in August 2000. It implied that the Bohai Sea circulation in August 2000 is in company with a weaker water exchange between the Bohai Sea and the Yellow Sea than the water exchange in August 1958.

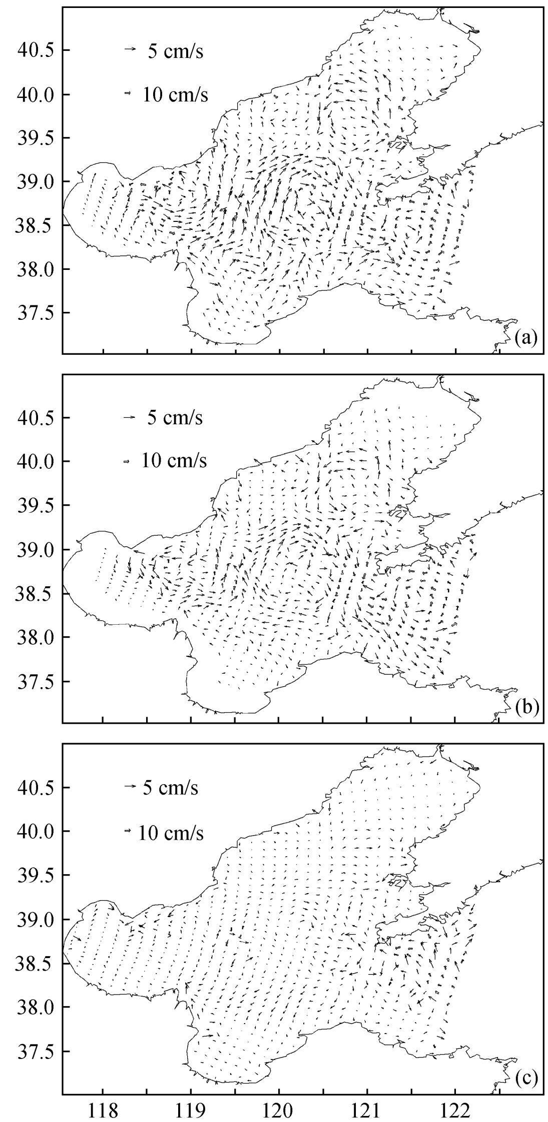

Fig. 6. Summer circulation of the Bohai Sea in 2000. (a) 2 m layer; (b) 10 m layer; (c) bottom.

3 Conclusions

By analyzing the salinity data over the past 35 years (1961—1996) from the 4 observation stations along the Bohai Sea and the Bohai Strait, and by comparing the structure of temperature and salinity of the Bohai Sea in August 1958 and 2000, we can conclude that there are no large variations of the temperature field, but a radical variation of the salinity field of the Bohai Sea. The significant variation of the Bohai Sea salinity field occurs in the Bohai Bay and the region adjacent to the old Yellow

River mouth. The low salinity of the surface layer in the region near the Yellow River mouth in August 1958 has been replaced by high salinity in August 2000, with a maximum variation lager than 10. Except the top region of the Liaodong Bay, the average salinity of the whole Bohai Sea has increased 2. The time-salinity curve of the Beihuangcheng station shows that during 1961—1996, there have occurred at least 5 intensive water exchange processes between the northern Yellow Sea and the Bohai Sea. One or two years before and after the years of 1963, 1970, 1983, 1990, and 1994, there was abnormal high-salinity water intrusion from the north Yellow Sea. In 1983, the intrusion was the most intense one and its impact present in all the salinity data of the coastal stations along the Bohai Sea. The abnormal high-salinity water intrusion may significantly contribute to the increase of the Bohai Sea salinity. Corresponding to the variation of the Bohai salinity field, the Bohai circulation also changed. The significant changes of the circulation appeared in the Bohai Bay, the Laizhou Bay and the middle of the Bohai Sea. The existing clockwise loop outside of the Bohai Bay and the counterclockwise loop outside of the Laizhou Bay in August 1958 disappeared in August 2000, and the counterclockwise loop in the Bohai Bay migrated obviously outward. The center of clockwise loop in the middle of the Bohai Sea migrated southward, and the flow direction in Laizhou Bay turned around 180°. The variation of the Bohai Sea circulation also affects the water inflow or outflow through the Bohai Strait. The result shows that the water exchange rate through the Bohai Sea strait reduced, monthly mean, 0.7×10^4 m^3/s in August 2000 compared with the water exchange rate in August 1958.

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