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The study on three-dimensional numerical model and fronts of the Jiulong Estuary and the Xiamen Bay

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Abstract
Applying the methods of on-site observation and dynamic model, the research on the fronts at the Jiulong Estuary has been carried out, during which spatial and temporal distribution, dynamic characteristics and formation mechanism of salinity fronts are analyzed and discussed. The research shows that the estuarine fronts mainly lie in the area from the Jiyu Islet to the Haimen Island, outside of Yuweizai to Hulishan cross-section, the near coast of Yuweizai and the south of the Songyu-Gulangyu Channel. The fronts in the former two regions are formed directly by plume, while the one near the coast of Yuweizai is a tidal intrusion front caused by flood current and the one at the south of the Songyu-Gulangyu Channel is the result of current shear transformation. Under normal circumstances, fresh water of the Jiulong River mainly influences the inside of the Xiamen Bay, and when it is in typhoon seasons, plume front can affect the Taiwan Strait and has an effect on the biogeochemical processes in the strait.

Key words: Jiulong Estuary, Xiamen Bay, three-dimensional numerical model, fronts

1 Introduction

Estuarine front is the transition belt where the river water and the seawater mix intensively. In the belt, both of marine physical and chemical properties are different from the sides, and its existence has a great influence on the circulation of the estuarine area, the process of material migration and deposition, the process of ionic adsorption and description, and the ecological process. Early in the 1950s Pritchard (1954, 1956), through analyzing the on-site observation data of 72 tide-gauge stations, 205 test stations of current velocity and 199 test stations of salinity, discussed the salinity distribution and circulation structure of the Chesapeake Bay, and studied the salinity balancing mechanism and dynamic structure of the estuary. In the late 1970s, researchers such as Simpson and Hunter (1974) and Garvine and Monk (1974), made systematic researches on small scale estuarine fronts near the shore. In 1990s, the research on estuarine fronts reached its peak, the study on American Chesapeake Bay being outstanding. Charise (1993), applying CTD and ADCP, made composite observation and found a shear front 6 m underwater. Marmorino and Trump (1996) and Brubaker and Simpson (1999), at the James Estuary of the Chesapeake Bay and by using towed ADCP, carried out an underway observation, and described precisely the current field's 3-D structure and its varying process. Shen and Boon (1999) further applied three-dimensional baroclinic models to simulate the generating process of the front, studied the circulation and the material transportation in neap-spring cycle, and carried out a dynamic analysis of front's influence on larva. Xu et al. (2008) used a three-dimensional numerical model (EFDC) to examine the wind impact on pollutant age distributions and residence time in the Pamlico River Estuary (PRE). It suggests that across-river winds may lead to longer residence time through enhanced turbulence mixing. And Xu et al. (2009) applied the HEM-3D model to investigating the pollutant age distribution under different river discharge conditions in the PRE. The results show that the salinity intrusion plays an important role in the spatial variation of the pollutant transport age. Luo et al. (2008) used a coupled 3-D hydrodynamic-ecological numerical model to investigate the distribution and causes of the hypoxia phenomena in the Zhujiang River Estuary. It shows

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that the front and the salinity stratification impact on the range and intensity of the low oxygen water. Ou et al. (2009) used the on-site observation data of salinity, wind and river discharge and numerical simulations of hydrodynamics from 1978 to 1984 to investigate the dynamics of the buoyant plume off the Zhujiang Estuary during summer. It shows that there are four major horizontal buoyant plum types in summer, and both the river discharge and the wind conditions affect the plume evolution. On the whole, the main theme of estuarine fronts' research is the dynamic mechanism of the formation and maintenance of fronts. The actual stability of estuarine frontal areas is poor, always varying considerably and displaying complex geometric characteristics, but fronts have many similar physical characteristics. Therefore, O'Donnell (1993), according to the maintenance mechanism of different fronts and in terms of dynamics, classified estuarine fronts into three class: plume or tidal intrusion fronts, tidal mixing fronts and shear fronts.

In developing countries and recent years, as the consequence of human's activity to the estuarine regions becomes more and more severe, problem, such as runoff reduction, aggravation of environment pollution and ecology unbalance, appear in those regions. As a result, researches on estuarine front catch people's attention again. The region researched in this study is the Jiulong Estuary, located on the Xiamen Bay which is in the west of the Taiwan Strait (Fig. 1). The Xiamen Bay is made up of the inner bay and the outer bay. The outer bay locates on the east of Yuzaiwei Hulishan cross-section; on the other side of this section is the inner bay. The estuary, whose average water depth is 7 m, with the length from east to west of 21km and the width from north to south of 6.5 km. Fresh water of the Jiulong River passes through the fork in the western and enters into the estuary, salinity fronts created by the joint of river water and seawater appearing at the south of the estuary. The northeast of the estuary is the West Harbor, whose sea water passes through the Xiamen-Gulangyu Channel and Songyu-Gulangyu Channel out and in the estuarine area. The annual runoff of the Jiulong River is 117.46×10^8 m^3, and the tide of the Xiamen Bay belongs to regular semidiurnal tide and the average tidal range is 3.99 m. So the Jiulong estuarine fronts under such tide have some particular characteristics.

Early in the 1990s, researchers launched work on the Jiulong estuarine fronts. Wen et al. (1999) by adopting the established numerical model in the Xiamen Bay, and combining field data and float tracking test with it, analyzed the dynamic mechanism of the "ebb current cutoff" in this estuary. Wang et al. (2000) analyzed the on-site observation salinity data of the winter neap tide, finding that its front, with a narrow width and big gradient salinity, has a northwest-to-southeast isohaline on the surface. Its front has the salinity range of 15.00–27.00, the width between 2.60 km and 4.30 km and the salinity gradient from 2.10 km^{-1} to 2.60 km^{-1}. The aim of this paper is to further understand the foresaid two estuarine fronts, and to know about whether other kinds of estuarine fronts exist in the study area.

2 Sampling and analysis

Fresh water of the Jiulong River and seawater from the Taiwan Strait is the main factor that controls the salinity changes in this estuary. The distributions of salinity are not the same in different seasons and tidal hours. So this field work is carried out in the winter and spring of 2008 during the process of spring-neap tide (Fig. 1). The CTD has been used to make underway observation on the surface and cross-section, and a submerged buoy observation has been made by using integrated ADCP and OBS-3A, prolonged sequencing data of tide level, current and thermohaline being collected.

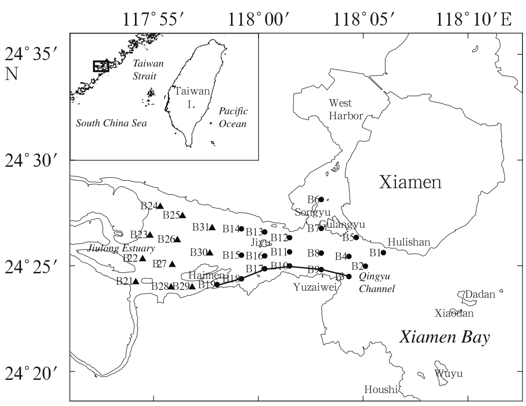

Fig.1. Map of sampling station in the Jiulong Estuary. Sampling stations for B1 to B19 are taken in winter (8 January 2008), and B1 to B30 are taken in spring (28 April 2008).

2.1 *Horizontal salinity distribution*

According to the observed result, it is known that the salinity fronts occur mainly during ebb tide, so the observation data acquired during ebb tide in winter and spring have been chosen to analyze the horizontal distribution characteristics of salinity. In Figs 2a and b, waters mix homogeneously in winter, distribution rules of bottom and surface salinity being basically the same. Surface salinity increases from 15.12 of western to 29.11 of eastern and isohaline is mainly from northwest to southeast. The isohaline from the Haimen Island to the Jiyu Islet distributes intensively, the salinity gradient surpassing 2.00 km^{-1}. This shows that it is an intensive mixing region of river water and sea water and also the position of salinity front during winter ebb tide.

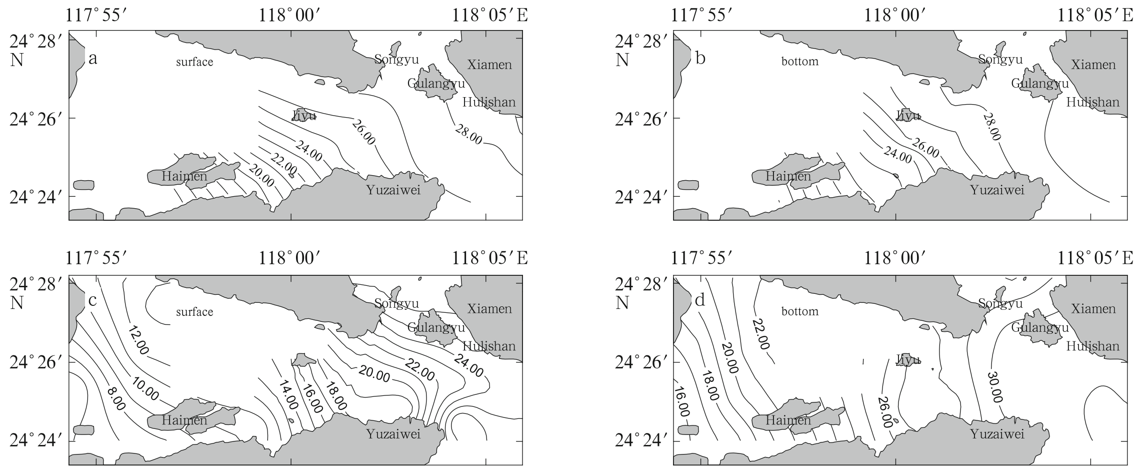

Fig.2. The horizontal distribution of salinity in winter (8 January 2008) (a and b), and the horizontal distribution of salinity in spring (28 April 2008) (c and d).

From Figs 2c and d, it is obvious that distributions of surface and bottom salinity are different, showing that stratification appears in spring. Surface salinity increases from 5.72 of western to 27.84 of eastern. Isohaline distributions from the Haimen Island to the Jiyu Islet, south of the Gulangyu Island and north of Yuzaiwei are dense. The west of the Haimen Island has the salinity lower than 12.00, which shows that this region is mainly influenced by river water. From the Haimen Island to the Jiyu Islet is the joint place of fresh water and inner bay water; south of the Gulangyu Island is the joint area of fresh water and the West Harbor water; and north of Yuzaiwei is the joint region of inner bay water and outer bay sea water. Fronts exist in all of these regions. Isohaline distributions are thinner at the bottom, and only from the Haimen Island to the Jiyu Islet, the isohaline is distributed densely and moving toward the estuary.

2.2 *Vertical salinity distribution*

The distribution of salinity varies with local and tidal changes. Under the topographic influence of Haimen Island fresh water mainly transports toward the outer bay along the south coast; hence, a cross-section along the south coast (Fig. 1) is chosen to analyze the vertical salinity distribution during ebb tide.

From cross-section salinity distribution (Fig. 3) in LW–2.5 h time chart (LW is time of low water), the stratification of the west side and east side of the section is notable, while in the middle mixing well, which shows that the area from Stations B18 to B17 is where the ebb front lies. The salinity distribution rules at this section in LW chart are similar, but the location of the mixing region has moved toward the outer bay and its salinity value reaches the lowest with the gradient reaches the strongest. In LW+2.5 h chart salinity increases and isohaline moves toward the estuary. The formation of the salinity front at this section is caused by the joint of fresh water and inner bay water. Its position and salinity gradient differs as the tide changes; in ebb tide, it moves towards out of the mouth and increases its salinity gradient, while in flood tide, it moves toward the mouth.

From the analysis of the horizontal and vertical distributions, the fronts have the characteristics of narrow width and big-gradient salinity. Salinity fronts moves toward the mouth as the water depth increases, and its width becomes narrow and salinity gradient is

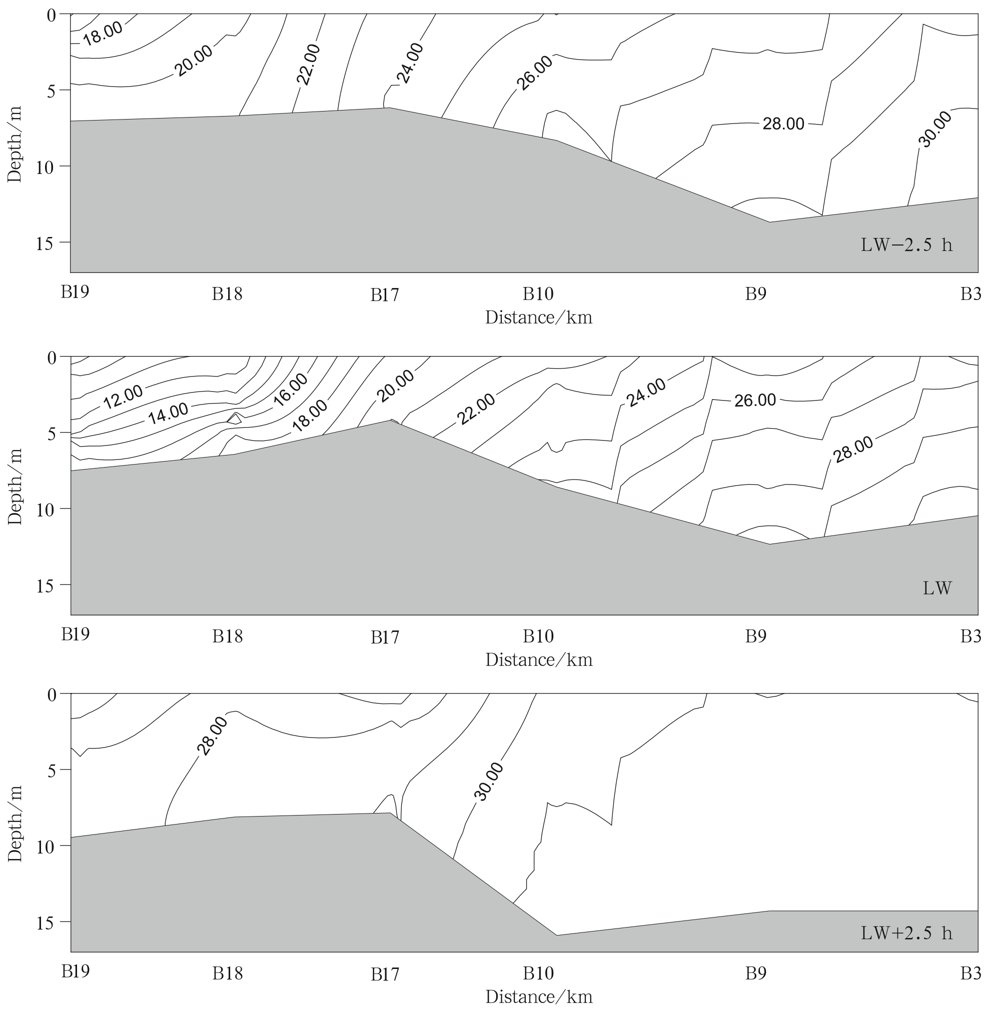

Fig.3. The vertical distribution of salinity in spring (28 April 2008).

bigger. The fronts mainly locate from the Jiyu Islet to the Haimen Island, from Yuzaiwei to out side of Hulishan, north side of Yuzaiwei, south of Songyu-Gulangyu Channel, their width being about 1.0–6.9 km, salinity gradient from 2.00 km^{-1} to 3.20 km^{-1}, and whose temporal and spatial variation is obviously regulated by tide.

3 Numerical model

From the observation data, the distribution of the position and salinity of the Jiulong estuarine front is shown generally, but field works always limit to observing conditions, and the synchronous and real-time data cannot be required, detailed discussion of the formation mechanism of fronts being difficulty to make. This shortage can be made up by using a dynamical numerical model (the MEC ocean model), so a 3-D dynamic model for shallow water (Luo Zhibin et al., 2008) is adopted to describe the characteristics of different kinds of fronts.

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0, \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=fv-\frac{1}{\rho_0}\frac{\partial p}{\partial x}+ A_{\mathrm{m}}\Big(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\Big)+\frac{\partial}{\partial z}\Big(K_{\mathrm{m}}\frac{\partial u}{\partial z}\Big), \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-fu-\frac{1}{\rho_0}\frac{\partial p}{\partial y}+ A_{\mathrm{m}}\Big(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\Big)+\frac{\partial}{\partial z}\Big(K_{\mathrm{m}}\frac{\partial v}{\partial z}\Big), \tag{3}$$

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}= A_{\mathrm{h}}\Big(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\Big)+\frac{\partial}{\partial z}\Big(K_{\mathrm{h}}\frac{\partial T}{\partial z}\Big), \tag{4}$$

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z}= A_{\mathrm{h}}\Big(\frac{\partial^2 S}{\partial x^2}+\frac{\partial^2 S}{\partial y^2}\Big)+\frac{\partial}{\partial z}\Big(K_{\mathrm{h}}\frac{\partial S}{\partial z}\Big), \tag{5}$$

where u and v are the eastward and northward velocities respectively, S the salinity, T the temperature, η the sea surface elevation from the mean sea surface, f the Coriolis parameter, $A_{\rm m}$ and $A_{\rm h}$ the horizontal eddy viscosities, $K_{\rm m}$ and $K_{\rm h}$ the vertical eddy viscosities.

3.1 *Result of numerical model*

Figure 4 displays the surface trend and distribution of salinity of Jiulong Estuary before and after the ebb tide. During the ebb tide, the Jiulong River fresh water moves outward along the north and south sides of the Haimen Island, transports further outward along south coast when it is pushed by the ebb tide water of the West Harbor in south of the Gulangyu Island, and forms a tongue-shaped plume. Salinity of the upper plume, from the Haimen Island to the Jiyu Islet, changes notably with the salinity gradient above 2.00 km^{-1}, so a salinity front exists here. This front appears in the south of the Haimen Island during the ebb tide with the frontal salinity between 18.00 and 24.00, and moves outward during the ebb tide with the salinity gradient increasing. Moreover, in the south of the plume, at the joint of fresh water and the West Harbor water also exist salinity front, whose salinity is around 25.00–26.00 and isohaline goes from east to west. And on edge of the plume, front appears at the joint of fresh water and the outer bay water. These front moves out of the bay during the ebb tide and can reaches to the Wuyu Islet. Meanwhile, in Yuzaiwei south of the plum a bigger-gradient front appears after the ebb tide. This result agrees with the on-site observation as foresaid.

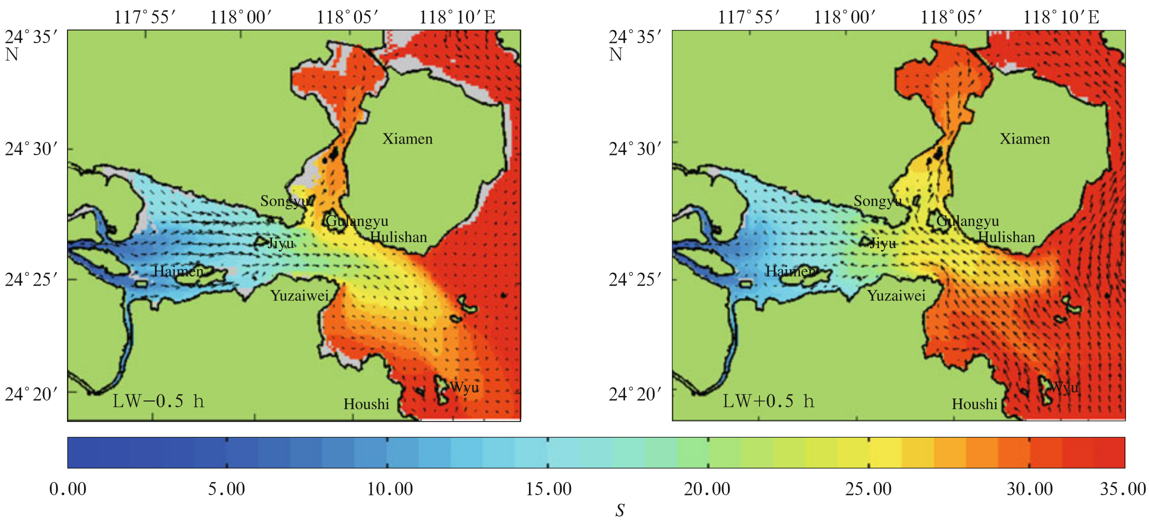

Fig.4. The current and salinity of calculation during spring tide.

3.2 *Stratification parameter*

From the analysis of horizontal distribution of salinity, the front appearing place has been found, and "stratification parameter" defined by Simpson and Hunter (1974) is used to fix the existence and location of front, the calculation formula is as follow:

$$k = \log\left(\frac{h}{\overline{u}^3}\right), \tag{6}$$

where k is stratification; h is water depth; and $\overline{u}^3$ is the average current velocity vertically.

This formula is used to discuss the front distribution characteristics of the research region. The value of $\overline{u}$ is the calculation result of M_2 tidal component and Fig. 5 shows the calculation result of the stratification parameter. According to the special topographic and water depth conditions, we believe that, the area in

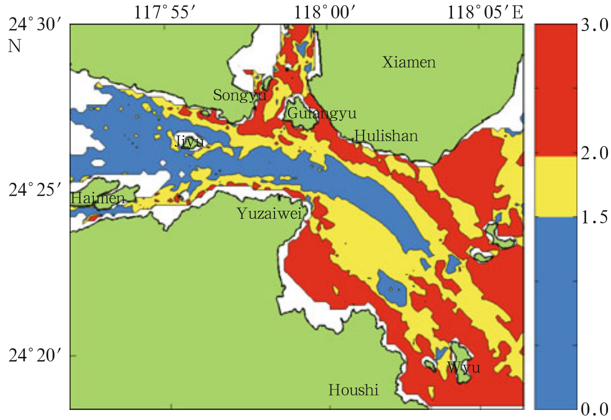

Fig.5. Stratification parameter k.

the outer bay with the value of k no less than 2.0 is stratification obviously; while the water in the estuary with the value of k is no more than 1.5 is mixing homogenously due to the strong current and turbulent mixing. The joint areas of notable stratification and homogenous mixing are mostly the position where front appears, and they lies respectively from the Haimen Island to the Jiyu Island, on the both sides of the Qingyu Channel, in the north of Yuzaiwei and in the south of the Songyu-Gulangyu Channel, which is very similar with the results of on-stage observation and the numerical model. Below, these fronts will be analyzed and discussed concretely and meticulously.

4 Salinity fronts in the Jiulong Estuary

The above passages have fixed the salinity frontal positions as the elliptic region in Fig. 6, so choose three cross-sections to discuss these fronts. Figure 7 is the salinity and current velocity distribution of Sections A, B and C respectively.

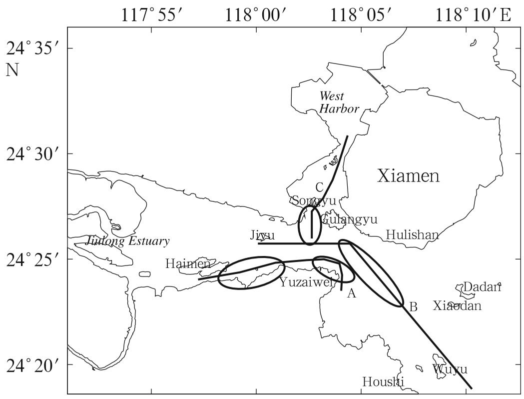

Fig.6. Position of the section.

4.1 *Salinity front in Jiulong River*

The previous researches show that the turbidity maximum always appears in the upper estuary, and the joint of river water and seawater there forms salinity front. The deep groove of the estuarine region is close to the south coast, so this kind of front has physical characteristics of that along the main channel. In Figs 7 a, b and c, in the zone from the Haimen Island to the Jiyu Islet, fresh water running out from the south of the Haimen Island approaches the inner bay water during the ebb tide, when the horizontal density gradient by horizontal convection is big enough, the isohaline presses downward to form salinity front. When the flood water of the inner bay is blocked by the fresh water, the isohaline goes upward to form front. Because the horizontal convection contributes to its formation, the front is controlled by the horizontal barocline density gradient force, the current velocity and the turbulence to keep its existence; it is a plume front by dynamics. Whereas it appears near the upper estuary, in this paper it is called Jiulong salinity front to distinguish it from other fronts in the study areas. Moreover, the position of this front is regulated by tide notably, moving towards the mouth in the neap tide and outwards the mouth in the spring tide.

4.2 *Outer bay plume front*

The salinity distribution of Section B in the middle of the plum in the spring tide is shown in Figs 7 d, e and f. From the figure, it is seen that fresh water with low density transports mainly from the surface to the outer bay during the ebb tide, while the outer bay water with high density moves mainly from the bottom to the inner bay during the flood tide, and before and after the time of low water, the front is formed in the joining area of them. In the LW time chart, two sides of the front there has opposite current direction: at the right side, the current direction of outer bay water is left, while at the right side, the water mass has a two-layer velocity, of which the top layer is to the right while the bottom layer is to the left. Meanwhile, the current direction of top layer is downward and the bottom layer is upward in the vertical direction. This front is generated by the density gradient caused by the horizontal convection, maintained by the horizontal barocline density gradient force and has the same vertical circulation structure of plum fronts, so it is a typical plum front. In consideration of that plume front appears in outer bay, it is named outer bay plume front. Because the runoff of Jiulong River is little, the tide of the Taiwan Strait is strong, so the strength of plum is regulated obviously by tide. The position and strength of plum front vary also with the tide: in the neap tide it mostly locates from the cross-section of the Yuzaiwei-Gulangyu Island to the Dadan and Xiaodan Island, while in the spring tide it move outward of the bay to the Wuyu Islet.

4.3 *Yuzaiwei tidal intrusion front*

Both from the on-stage observation and Section A salinity calculation result, a salinity front has been found in the north of Yuzaiwei. From Fig. 7a, it also forms at the cross plane of fresh water and outer bay water, and owing to the intrusion of the bottom high salt water with the isohaline going upward to generate it. In Fig. 4, the tide current under the topographic condition of Yuzaiwei forms a clockwise circulation in the south-east of Yuzaiwei, a high salt water mass forming under the movement of this circulation; while in the initial stage during the flood tide the mass

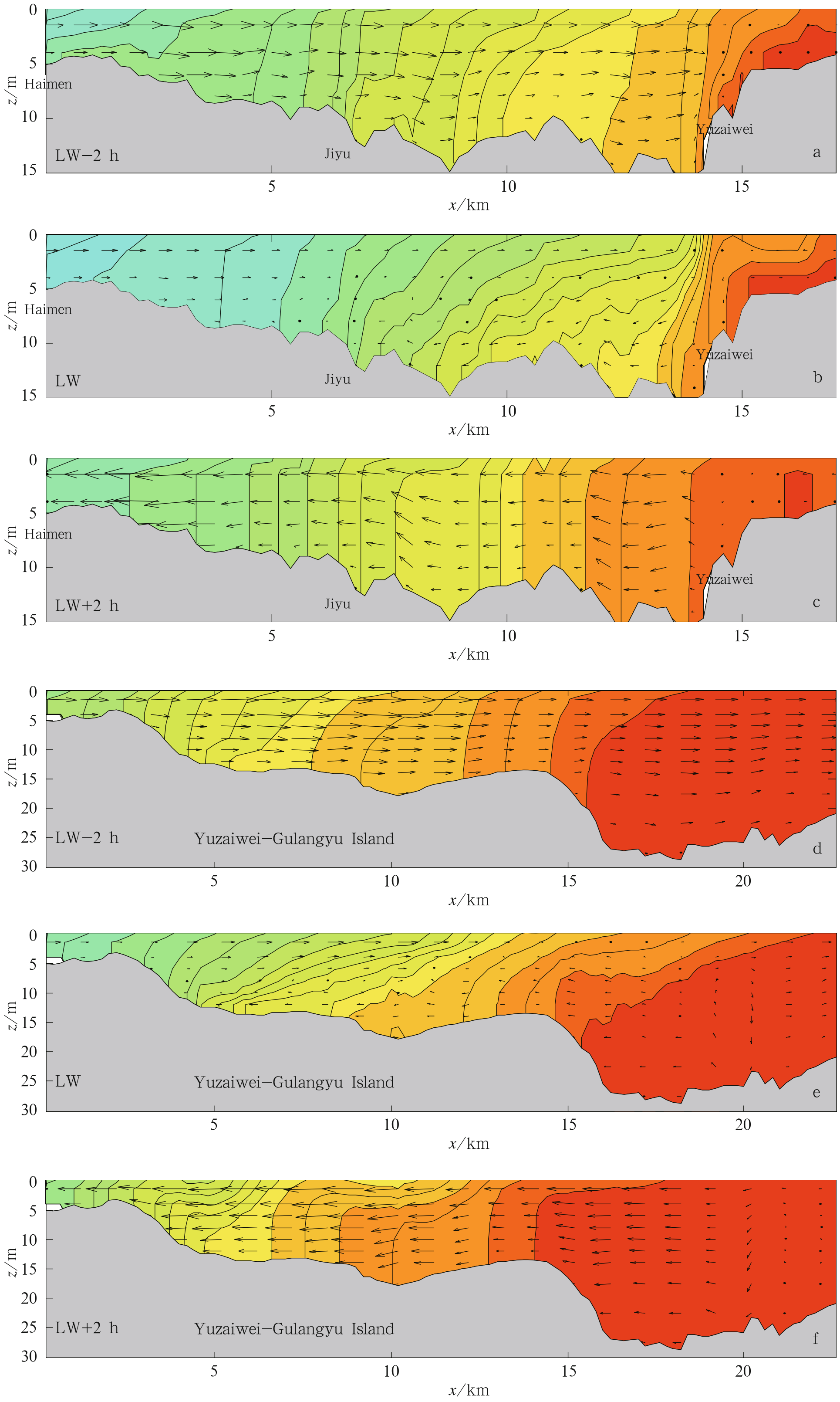

Fig.7.

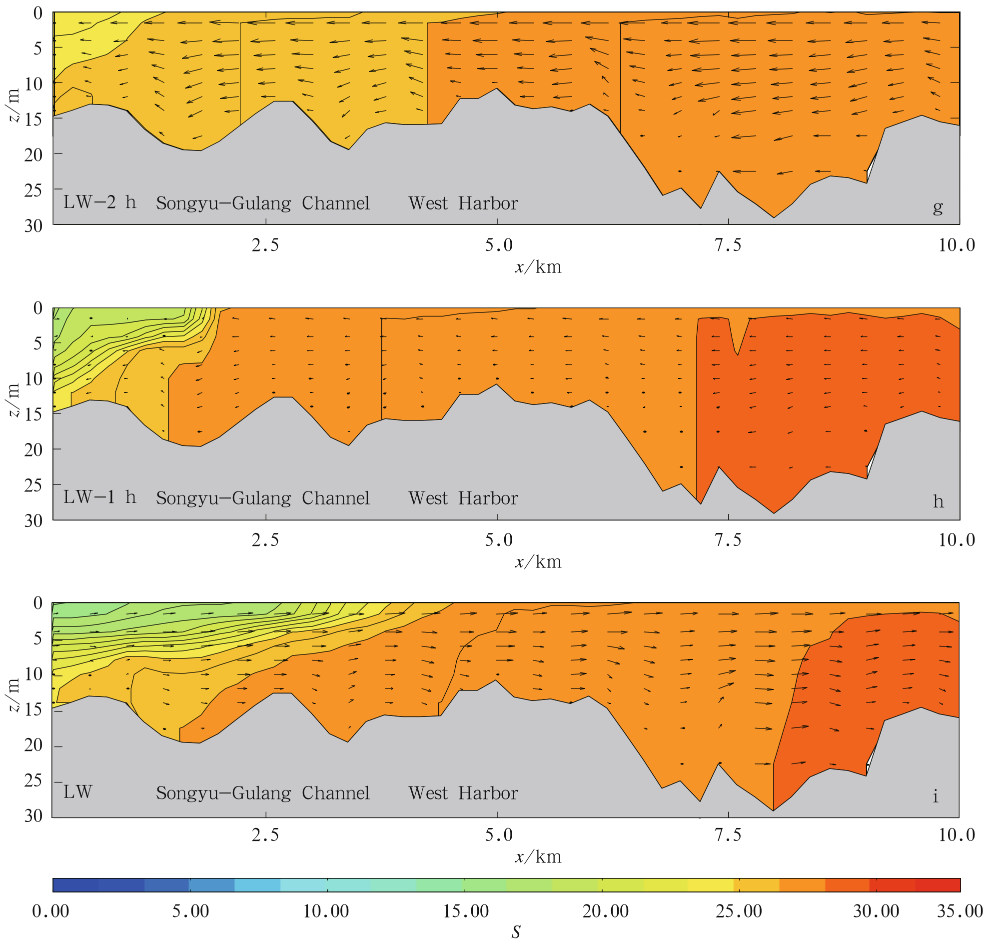

Fig.7. The distribution of salinity in Section A during spring tides (a, b and c), the distribution of salinity in Section B during spring tides (d, e and f), the distribution of salinity in section C during spring tides (g, h and i).

intrudes toward the inner bay. Though it has a similar formation mechanism with plum fronts, yet it has reversed direction and is a tidal intrusion front. This front is regulated by the tide: in the spring tide it has a high salinity gradient while in the neap tide it is a relatively lower one. As compared with the plume front, it has the characteristics of narrow width and high salinity gradient, which is due to the topographic condition of Yuzaiwei, therefore it is called the Yuzaiwei tidal intrusion front.

4.4 *Ebb current cutoff front*

In the south of the Gulangyu Island, there is an turbid zone during the ebb tide, formed by two different water bodies, one of which is the water from Jiulong Estuary and the other from the West Harbor, will be seen, with foam lines and dirty gathering scattered, which is called "ebb current cutoff". Cross-section C is chosen to analyze the vertical profile structure. From Figs 7g, h and i, a front exists in Section of Songyu Islet-Gulangyu Island in the ebb tide. Accompanied by the eastern motion of current in Ssection C during the ebb tide (Fig. 8), the current direction is opposition on both sides of the ebb current cutoff and the current shows shear obviously. So it is a shear front, which is named the ebb current cutoff front.

4.5 *Relations between Jiulong estuarine fronts and the Taiwan Strait*

Because of the construction of hydraulic engineering in the upper estuary, the runoff of the Jiulong River reduces in recent years. As compared with the tidal volume from the Taiwai Strait, fresh water takes up a smaller amount, so generally, it can only affect the inside of the Xiamen Bay and even in the wet seasons from March to May, and its farthest stretch only reaches the area of Houshi. However, owing to its location being in subtropical zone where annually the tropical cyclone and typhoon seasons last from April to September, the study region is influenced 5–6 times

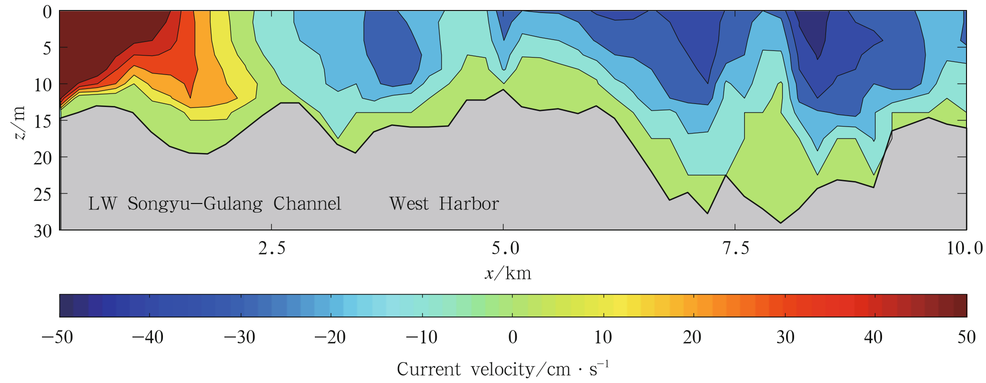

Fig.8. The distribution of current velocity of east part in Section C during the spring tide. The east of current direction is mean as positive, and west as negative.

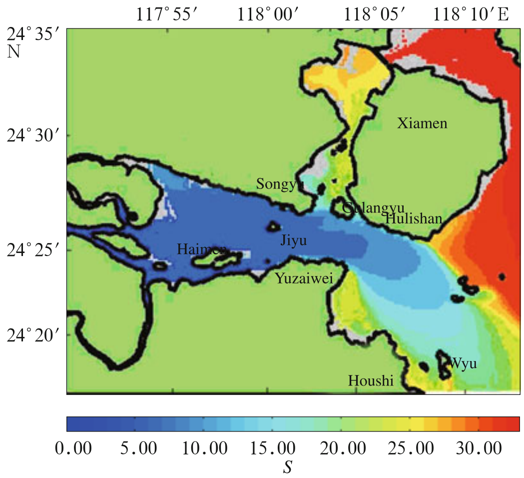

Fig.9. The distribution of salinity 3 d after.

each year by tropical cyclone and typhoon, especially in July and August. Large amounts of precipitation continuously enter by the flood into the estuarine area, which makes the region with the characteristics of low salinity, high nutrient and turbid concentrations. Figure 9 is the calculation results of 3 d after the flood influence under the peak discharge condition of 6230 m^3/s. From the figure, it is clear that plum is transported alone the south coast of the Xiamen Bay to the Taiwan Strait and forms a plume front with large span. The existence of this plume front reflects the influence of the Jiulong River on the Taiwan Strait, especially the mass with the characteristics of high nutrient and suspended sediment concentrations play an important role in the process of biogeochemical variety in the Taiwan Strait.

5 Conclusions

There are three kinds of salinity front in the Jiulong Estuary: plum front, tidal intrusion front and shear front. The Jiulong salinity front is in the region from the Jiyu Islet to the Haimen Island with salinity from 10.00 to 20.00 and big gradient, its location varies with tidal hour and relates to tides closely. The outer bay plume front lies outside from Yuzaiwei to Hulishan cross-section. Owing to the surface salinity ranging from 25.00 to 28.00 and having an obvious vertical stratification, it protrudes outward like a tongue and can reach almost to the area of Houshi. The Yuzaiwei tidal intrusion front in the north of Yuzaiwei with the characteristics of narrow width and high salinity gradient is caused by topographic condition of Yuzaiwe. The ebb current cutoff front locates in the south of Songyu Gulangyu Channel, with the front salinity of around 25.50, and is formed by the shear transformation of current velocity owing to the extrusion and lockup from the joint of fresh water and the West Harbor water. Its effect of convergence and obstruction creates the peculiar phenomenon of the ebb current cutoff.

Estuarine fronts are mainly caused by the mixture of salt water and fresh water. Its temporal and spatial variation is regulated obviously by tide. Meanwhile it is also affected by topographic condition and weather, but the regulation of tide is dominant.

Plum front is the most important salinity front of the Jiulong Estuary, which affects the process of biology, chemistry and hydrology in the Taiwan Strait, especially in the summer typhoon season and this becomes more significant.

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