The Influence of Climate Change on the Fresh Water Plume in the Pearl River Estuary

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Abstract: In this study, a 3D mathematical model of Pearl River Estuary (PRE) and offshore is constructed. Numerical simulation is applied to study the mechanism of the plume of the PRE and the influence of future sea level rise. The model is verified by runoff and water elevation during the July 1999 flood season. The harmonic constants obtained from the simulation are compared with the existing results, and the results are in good consistency. The numerical simulation shows that the expansion of the plume is mainly affected by runoff, topography, Coriolis force, wind and sea surface height. The rise of sea level will make the salt isoline lines of the PRE move to upstream, but it does not affect the overall scope of the fresh water, the range of fresh water is mainly influenced by upstream flow. After the sea level rise the fresh water of the west coast of Guangdong Province appears to be expanded to the west in spring, summer and autumn. At the same time, the estuary circulation of the north-south is enhanced. The increased estuary circulation causes more fresh water flows out through the surface, which strengthened the westward expansion of the Coriolis force. In summer the special symmetrical structure of plume will be destroyed after sea level rise which is also the result of the change in the estuary circulation.

1 INTRODUCTION

The expansion of fresh water plume in the estuary has been a problem of great concern in the study of physical oceanography. The Pearl River is the second largest river in China. Saltwater intrusion has attracted widespread attention because of of its negative impacts on the water supply. However, the fresh water plume in water resource conservation status has not been correctly recognized. Runoff carries a lot of sediment, nutrients and other substances into the PRE and its adjacent sea area, it has a great influence on the physical, chemical and biological processes and the movement of sediment in the surrounding sea. Studying the law of motion and mechanism of the PRE plume has critical theoretical significance and practical value for the saltwater intrusion, freshwater erosion, water resource utilization, sediment transport and ecological environment in PRE. Research shows that: fresh water is mainly spread out of the sea in the form of plume flow, formation of low saltwater mass and saltwater fronts with pinnate distribution. The plume is mainly affected by runoff, topography, tide, wind, Coriolis force, baroclinic effect, background circulation, and sea level height.

In China research on freshwater plume is mainly based on field observation, satellite remote sensing, theoretical research, numerical simulation and numerical simulation combined with other methods. The research on the fresh water plume is mainly concentrated on the Yangtze River in China (Wang et al., 2012; Zhang et al., 2014). Before 2010, there were relatively few studies on the plumes of the PRE. Recently, with the richness of data and the improvement of technical means, the studies of fresh water plume in the PRE received many attetions. In the analysis of measured data, Dong et al observed

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the plume of Pearl River during the flood and dry seasons, the results showed that, high layer stratification of the plume, the estuarine surface forms plume flow, and the plume deflects eastward from the entrance under the south-west monsoon in the flood season, while during the dry season, the east of the estuary is a vertical and homogeneous high salt water and the plume is deflected westward under the action of geostrophic force (Dong et al. 2004). The surface temperature and salinity measurements in the northern South China Sea were analyzed (Sun et al., 2008), indicating that the southwest monsoon increased and more fresh water expands eastward, the sea level in the near shore is higher and the plume of the Pearl River is expanding westward (Pang 2006). Based on the measured data, the dynamic characteristics of the plume in summer were analyzed (Ou et al., 2009). Yang yang found that the plume of Pearl River will also extend to the western and esatren, specifically east can be extended to the center of the Red Bay, and the west can be extended to the east of Hailing Island. The plume expands to 21.2 °N driven by the southwest monsoon, and the plume is very obvious above the 10m depth (Yang and Meng et al., 2010). In the numerical simulation of plume, the hydrodynamic force of the plume in the PRE and the small scale circulation in the winter plume are studied by the POM model, that the plume of PRE formed by the river water and high brine of shelf, the deep plume is not part of the basic tidal, wind and river flow, while the tide and river flow affects the surface characteristics of the plume (Wong et al. 2003A; Wong et al. 2003B; Wong et al., 2004C). The interaction between the summer Pearl River plume and the upwelling of the south-west wind driven by the South China Sea is investigated by the measured and numerical simulation (ROMS) (Gan et al. 2009). In recent years, numerical simulation and the combination of numerical simulation and measurement have a lot of appearances (Lu et al. 2010; Wang et al. 2012; Shu et al. 2011; Pan et al., 2014; Lai et al. 2015; Zeng et al. 2015; Yan et al., 2015).The method of remote sensing inversion has also begun to be adopted by researchers (Lu and Zhan 2013; Zhaoyun et al. 2017; Qiu et al. 2017).

As far as we know, there is little research on the impact of sea level change on the plume of the Pearl River Estuary. Therefore, this research is 1) to study the rule of plume movement in the Pearl River Estuary, and 2) to understand the influence and dynamic mechanism of sea level change on the plume of the Pearl River Estuary.

2 DATA AND METHOD

2.1 Data and Model Description

The FVCOM developed by Chen changsheng and his team at University of Massachusetts was used in this research (Chen et al., 2003). Grid and water depth are shown in Figure 1 and 2. Based on the existing model (Chen et al., 2014; Chen et al., 2016), at the open ocean boundary, the model was forced by water elevation that was calculated by the harmonic constants of 8 main tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1) interpolated from the results in the South China Sea (Li et al., 2002). The measured river discharges (Figure 4) in every 6 hours from 6 major rivers(marked in red texts in Figure 3) were included to provide the freshwater input into the domain. The surface wind forcing is monthly average wind field around the world gained from National Oceanic and Atmospheric Administration . The initial thermohaline field is the monthly climate data from the South China Sea Marine Atlas (Editorial Board for Marine Atlas, 2006) with the existing observation data assimilated (Ji et al., 2015).

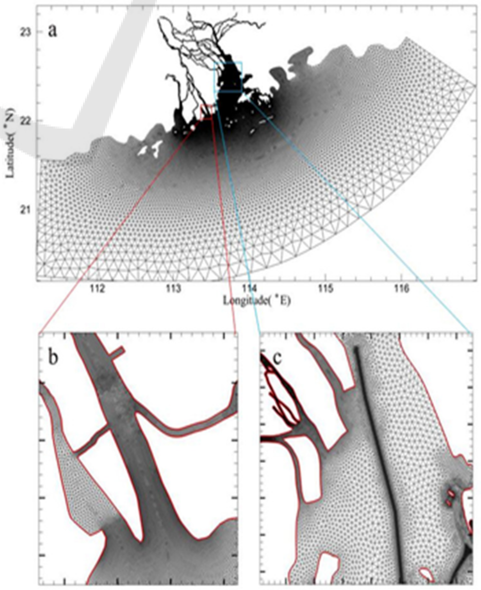

Figure 1: Model grid (a) and local grid (b Modalmen and c Lingdingyang).

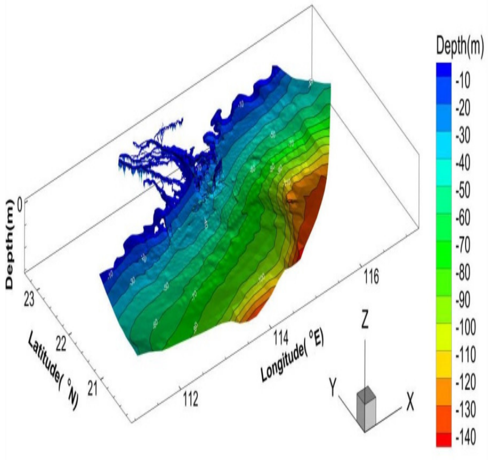

Figure 2: The 3D water depth of the study area.

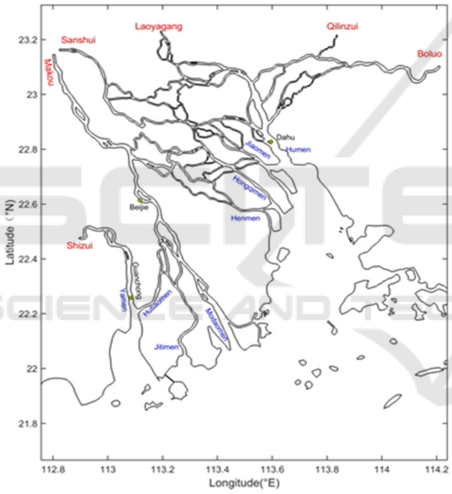

Figure 3: Upstream boundary, estuary and station in the study area.

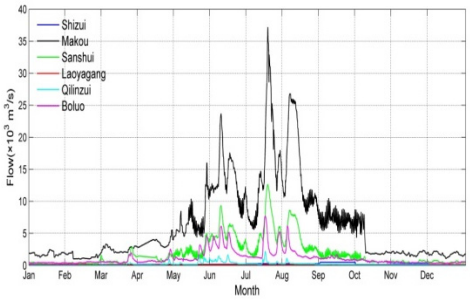

Figure 4: The measured river discharges in every 6 hours from 6 major rivers in 2006.

2.2 Model Validation

2.2.1 Verification of Water Elevation

The flow model validation salinity in previous studies have been published (Chen et al., 2016). This paper mainly studies the plume, and plume mainly in the summer wet period. Therefore verify the model by selecting some of the measured data during the July 1999 flood.

Figure 5, the rise of the water elevation caused by flood is very obvious, the water elevation is positive from Makou to Beijie in Xijiang river, it is no flood stream, the highest water elevation uplift to 6 m at Makou, and Beijie is close to 3 m. The water elevation in the whole river network area has been raised dramatically, the mesh of mode faces great pressure. To further quantify the accuracy of model results, we calculated the root mean square error (RMSE), relative error (RE), correlation coefficient (r), nash-sutcliffe efficiency coefficient (NSE), and a skill assessment parameter (Table 1). Although the RMSE of Makou reached 0.18 m, the simulation precision is acceptable (RE is 3.8%) compared with the actual elevation of 6 m, r values are larger than 0.85, and skill values are larger than 0.9. The simulation results can well reflect the changes of the water elevation in the river network during the flood period. Therefore, the model used in this paper can be adequate to deal with the flood. Further the model can be used for the next simulation of plume.

Table 1: RMSE, RE, skill, r, and NSE for modeled elevation.

Observation station	RMSE （m）	RE （%）	skill	r	NSE
Guanchong	0.09	15.6	0.97	0.96	0.93
Dahu	0.07	7.3	0.98	0.98	0.96
Beijie	0.05	0.5	0.97	0.97	0.92
Makou	0.18	3.8	0.91	0.99	0.70

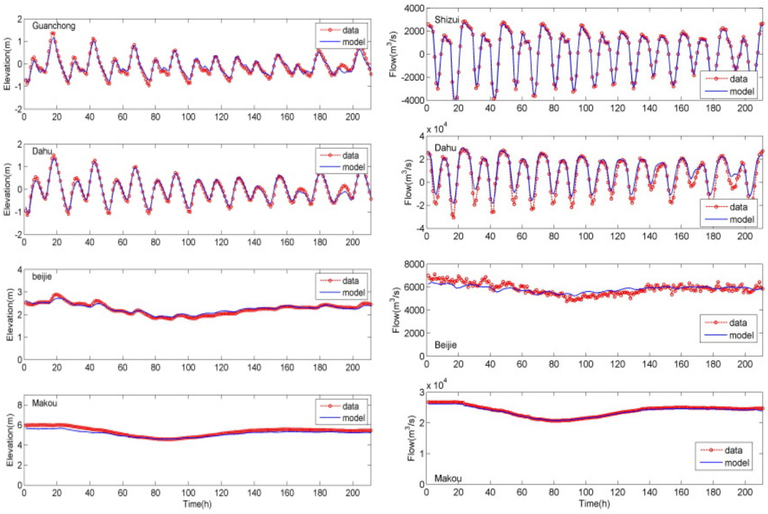

Figure 5: Water elevation (left) and flow (right) verification diagram (the actual red ring dotted line is the measured value, the blue line is the simulated value).

Table 2: RMSE, RE, skill, r, and NSE for modeled flow.

Section	RMSE(m^3/s)	RE(%)	skill	r	NSE
Shizui	121.6	5.1	0.99	0.99	0.99
Dahu	5050.8	3.6	0.96	0.97	0.87
Beijie	325.6	0.2	0.79	0.79	0.55
Makou	307.0	1.1	0.99	0.99	0.96

2.2.2 Verification of Flow

Table 2 is the RMSE, RE, skill, r, and NSE for modeled flow. The RMSE is larger near the Dahu entrance, but compared to the peak flow (40000 m^3/s), the RE is smaller, so the result is acceptable. The skill, r, and NSE are less than 0.85 in Beijie, this means the simulation results are close to the average value of the observations (RE is 0.2%), the measured value fluctuates greatly, possibly due to observation errors, and the overall results are reliable. The simulation results can well reflect the changes of the flow in the river network during the flood period. Therefore, the model used in this paper can be adequate to deal with the flood. Further the model can be used for the next simulation of plume.

3 RESULTS

3.1 Tide Harmonic Constants

The spread of the plume is very wide, the accuracy of the simulation results over the entire area is particularly important. Through the the numerical harmonic analysis of the simulation results, the amplitude and phase distribution of eight main constituents were obtained (Figure 6, list only K_1 and M_2). The results of this paper are compared with the existing results. The amplitude of the K_1 is about 0.28 m in the eastern part of the simulation area, and the amplitude increases gradually in the process of spreading westward, the maximum amplitude is 0.42 m (increased 50%). The amplitude of O_1 is between 0.24-0.34 m, and the amplitude of P_1 is between 0.09-0.13 m, the amplitude of Q_1 is located at 0.04-0.06 m. It can be found that the amplitude of P_1 is twice of Q_1. The phase of P_1 is equal to K_1, while the phase of Q_1 lags behind K_1. The amplitude of K_1 is 0.38-0.40 m, the amplitude of O_1 is 0.28-0.30 m, the amplitude of P_1 is 0.09-0.10 m, and the amplitude of Q_1 is 0.05-0.06 m in the Lingdingyang area.

The semidiurnal constituent in the simulated area is dominated by the M_2. The amplitude of M_2 increased significantly in the process of spreading westward (from 0.1 m to 0.65 m), this result is very close Wang Biao (0.12-0.56 m) (Wang, 2012). There is a low value of phase in the southeast corner (Figure 6), this indicates that the semidiurnal constituent from the open sea divides into two branches, and spreads westward and northeast respectively. This result is consistent with the existing research (Wang, 2012, Zhu et al. 2009). The amplitude of S_2 tide is about half of M_2, between 0.04 m and 0.28 m, the amplitude of K_2 is about 0.01-0.12 m, and the amplitude of N_2 is about 0.04-0.14 m. Overall, the amplitude and phase of M_2, S_2, K_2 and N_2 have great similarity in the distribution. M_2 is significant in the Lingdingyang sea, reach to 0.45-0.55 m, the amplitude of S_2 , K_2 and N_2 are 0.26 m, 0.06 m and 0.10 m.

3.2 Tide Constant

The tidal types are generally different for different estuaries. Dietrich defines the tidal coefficient F ($F=(K_1+O_1) / (M_2+S_2)$) (Dietrich, 1963). Tidal coefficient F less than 0.25 is semidiurnal tide type; 0.25-1.5 is mixed tide, and semidiurnal tide is dominant; 1.5-3.0 is mixed tide, and diurnal tide is dominant; greater than 3.0 is diurnal tide. The tidal coefficient F near the PRE is mostly between 0.8 and 1.5 (Figure 7). This indicates that the tidal type in the PRE is mixed tide dominated by semidiurnal tide, which is consistent with the result of Wang Biao (Wang, 2012). The tidal coefficient F increased to 2-3 in the river network. The tide change to mixed tide dominated by diurnal tide. This means that the influence of the diurnal tide is greater than semi-diurnal tide in the river network. The results of tide are consistent with the existing research results, the simulation results are reasinable for further research.

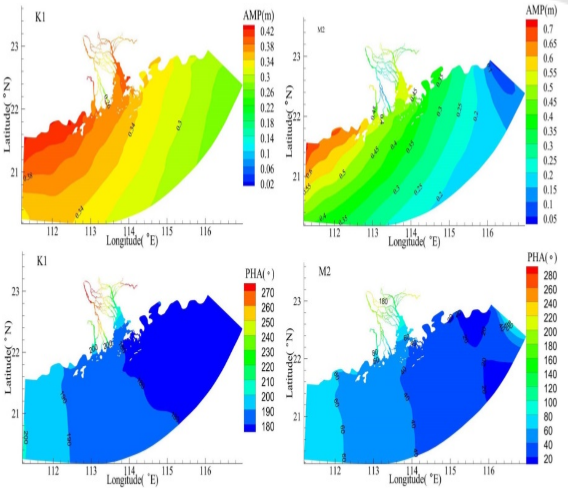

Figure 6: The harmonic constants of diurnal tide (left) and Semidiurnal tide (right) in PRE.

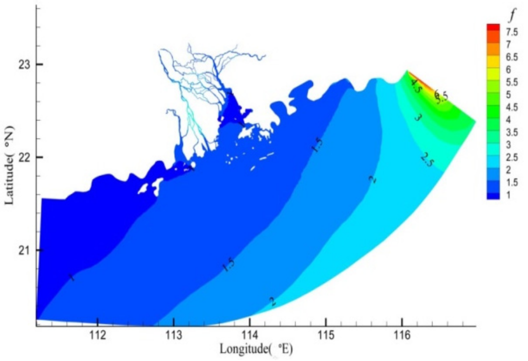

Figure 7: The distribution of tidal coefficient.

3.3 Analysis on the Law and Mechanism of Fresh Water Movement in the Pearl River Estuary

After the Pearl River flows into the sea, it mixes with the local seawater to form low salt water. This is the plume of the Pearl River. This paper uses the 32 PSU salinity line as the boundary between the fresh water plume and the high salt water in the open sea. The following will analyze the extending form and dynamic mechanism of the Pearl River plume during the season.

The main factors considered in this paper are five, tidal, wind, Coriolis force, runoff, and sea level. This section mainly considers the seasonal changes in sea level. The runoff is based on measured data at the upstream boundary. Tides are given by model predictions combined with measured data, which incorporate sea level heights for each season. The wind is downloaded from the Internet using the monthly average wind interpolated to the grid by region. Four experimental cases are set up for the plume, named as Case_1, Case_2, Case_3, Case_4. Case_1 is an actual case study, Case_2 is a case without wind, Case_3 is a case without Coriolis force, and Case_4 is a case without Wind and Coriolis force. At the same time, two sea level scenarios have also been considered. Base is the sea level scenario of 2006, P80 is scenario after sea level rises about 80cm. The results are monthly mean value. Through the comparative analysis of experimental results, the distribution of plume in the Pearl River Estuary during different seasons was ascertained. We will analyze the distribution of plume during each season and the influence mechanism of various factors of the PRE.

The simulation results of 2006 are compared with the observations of Yang Yang (Yang and Meng et al., 2010). The distribution results are consistent. Due to space limitations, this paper only lists summer results.

In spring, the surface plume of PRE is mainly westward along the coast. The plume can extend south to near 21.4 °N. The factors causing the westward expansion of plume include Coriolis force, northeast monsoon and sea level height. The Coriolis force is the main driving force of west expansion. The northeast monsoon will cause the Ekman effect to significantly restrict the outward expansion. The bottom plume is also mainly west-expanded, except that the area of plume is significantly smaller than the surface layer.

In summer. The surface plume area of the PRE reaches the maximum in the whole year, mainly because the runoff reaches the maximum value throughout the year. At the same time, the plume echibits a unique symmetrical structure (Figure 8, Black box), the main reason is the Ekman effect of the southwest monsoon. The summer surface plume extends westward and eastward simultaneously, The driving force for the expansion to the west is the Coriolis force and sea level, and the driving force for the expansion to the east is the southwest monsoon and sea level. The bottom plume still extends to the west, and the monsoon has no effect on the distribution of the plume at the bottom.

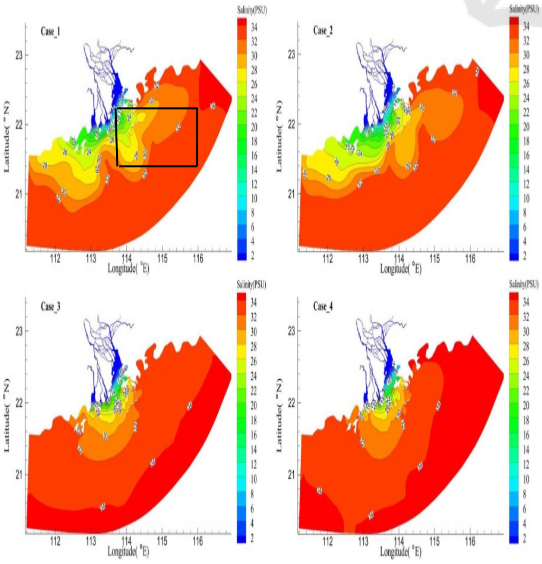

Figure 8: The plume distribution in the four cases under Base scene in summer.

In autumn, the runoff weakened significantly, the monsoon began to change, and the northeast wind gradually strengthened. The northeast monsoon and the Coriolis force restrict the spread of plume into the open sea. The surface plume constrict to the coast and form a significant northeast-southwest plume. At this time, the Pearl River plume is mianly westward. The dynamic factors for westward expansion include Coriolis force, northeast monsoon and sea level height. Although the northeast monsoon hindered the eastward expansion of the plume, there is still an isolated low-salt center in the outside of Daya Bay. This center is the remnant of the eastward plume in summer, which is separated from the body of the plume after the autumn monsoon shifts to become an isolated water mass.. There is also a low-salt center at the bottom of the east of Daya Bay, which is smaller than the surface and closer to the shore. The bottom plume still expands to the west, and the main driving force is the Coriolis force. The monsoon has no effect on the bottom.

The surface plume of the PRE are mainly west expansion under the influence of the northeast monsoon and Coriolis force in the winter, and is limited to shallow water areas along the western coast of Guangdong. The main factors of western expansion are Coriolis force, northeast monsoon, and sea level height. The range of plume is smallest throughout the year in winter.

3.4 Prediction and Mechanism Analysis of the Impact of Sea Level Rise on the Fresh Water of the Pearl River Estuary

The previous section analysed the law and dynamic mechanism of the plume in the PRE. This section focuses on the analysis of the effects of sea level rise on the plume in the PRE. Figure 9 is the plume distribution of Case_1 under Base and P80 scene in summer.

In spring, the plume of the PRE will move to north as a whole after the rise of sea level, and the range does not change much. The westward extension of the plume on the western coast of Guangdong is slightly strengthened.

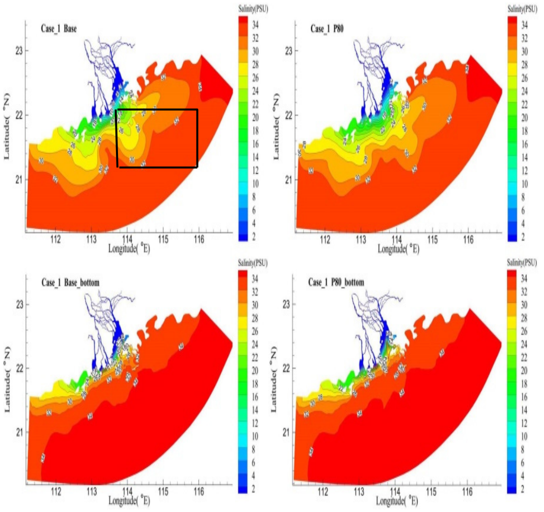

Figure 9: The plume distribution of Case_1 under Base and P80 scene in summer.

The most obvious effect of sea level rise on surface plume in summer is destruction of the original symmetrical distribution structure (Figure 9). The reason is the strengthen of north-south estuarine circulation in PRE, more fresh water flow into the open sea through the surface after sea level rise. The range of eastern expansion of the plume in the summer does not change much after the rise of the sea level. However, the easternmost position has shrunk slightly to the west. The westward expansion of the plume in the western coast of Guangdong has shown a trend of increasing westward expansion.

In autumn. The isohalines outside the estuary are obviously moving northward after the sea level rise, the isohaline of 32 psu extend slightly eastward. The low-salt center in the eastern coast of Guangdong appears to move west, the size of the water mass does not change. The western plume of the western coast of Guangdong has seen a phenomenon of west expansion, and the longest distance to the southward expansion has also increased. At the bottom, the original low-salt water mass disappeared. The range of the bottom plume decreases slightly after sea level rise. Because the plume area is inherently small, sea level rise has not affected the range of winter plume.

4 DISCUSSIONS

Sea level rise is a long-term process. For ease of study, this paper does not consider long-term change in runoff, topography and other factors. Previous study has found that sea level rise will affect the tide, salinity, saltwater intrusion, and estuary circulation in the PRE (Chen et al., 2016). It also affects the plume of this paper. The most fundamental reason for these effects is that the sea level rise has changed the WSS (Water Surface Slope) of the river. The decrease of WSS means that the water level gradient on the upstream and downstream is reduced, and the runoff suppression force is weakened. Runoff and tide have always been a shifting relationship at the estuary. Runoff suppressing force weakens, and tidal action will strengthen in the river channel. Previous research has found that tidal range and current will increase and come earlier in the river channel after sea level rise, the more obvious the upstream (Chen et al., 2016). The results of the harmonic analysis also illustrate this situation (Figure 10). Of course, the impact of sea level rise on tide is limited to the river channel and estuaries that are affected by tide. There is almost no impact on the open sea. The Pearl River estuary has a north-south estuarine circulation, high-salinity seawater upstreams from the bottom layer under tidal action, and fresh water flow out from the surface. After the sea level rise, the tidal effect increases, and more high-salinity seawater upstream from the bottom. Although the runoff suppressing force weakens, more freshwater flows out from the surface. This enhances the north-south estuary circulation. More freshwater float on high-salinity seawater after rushing out of the estuary, continue to expand outwards due to inertia and Coriolis force. This breaks the unique symmetrical structure of the summer and also resulted in the westward expansion of the plume to strengthen.

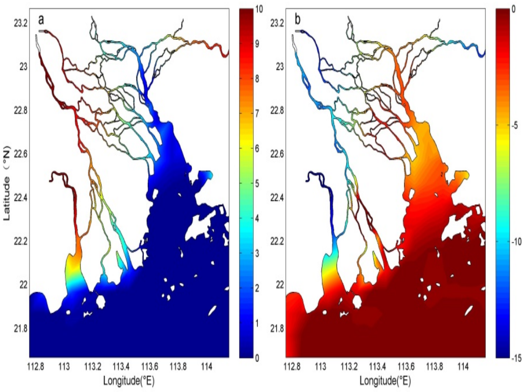

Figure 10: Difference of M2 tidal amplitide(a, cm) and phase lag(b, °) between the Base and P80.

5 CONCLUSIONS

The factors causing the westward expansion of plume include Coriolis force, northeast monsoon and sea level height in spring. In summer, the plume echibits a unique symmetrical structure, the main reason is the Ekman effect of the southwest monsoon. The summer surface plume extends westward and eastward simultaneously, The driving force for the expansion to the west is the Coriolis force and sea level, and the driving force for the expansion to the east is the southwest monsoon and sea level. The dynamic factors for westward expansion include Coriolis force, northeast monsoon and sea level height in autumn. Although the northeast monsoon hindered the eastward expansion of the plume, there is still an isolated low-salt center in the outside of Daya Bay. The surface plume of the PRE is mainly west expansion under the influence of the northeast monsoon and Coriolis force in the winter, and is limited to shallow water areas along the western coast of Guangdong.

Sea level rise will cause the salt isohaline lines of the PRE to migrate to the upstream, but it will not change the overall extent of the plume, and the range of plume is mainly affected by the upstream runoff.

The plume on the coast of western Guangdong appears to have expanded westward in the spring, summer, and autumn seasons after the sea level rise. In the summer and autumn, the plume's eastward expansion distance decreased. The unique symmetrical structure of summer plume will be destroyed. The reasons for these changes are the decrease of the WSS and the strengthening of the estuary circulation after sea level rise.

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