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A model study of the effects of river discharges and interannual variation of winds on the plume front in winter in Pearl River Estuary

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ABSTRACT

A three-dimensional numerical model, Estuarine, Coastal and Ocean Modeling System with Sediments (ECOMSED), is employed to study the mechanism of plume front in the Pearl River Estuary (PRE) in detail. The model is forced by winds, tides and river discharges. The modeled results of tidal elevation, current velocity and salinity are in reasonable agreement with observational data in the PRE. By analyzing momentum and saltwater transport balance equations, it is found that the wind stress term, the pressure gradient term and the local time derivative term of velocity are dominant in the momentum equation, while the local time derivative term, the horizontal advective term and the vertical mixing term of salinity are dominant in the salinity transport equation. The residual current at surface along the plume front is seaward and stronger, whilst that in the bottom layer is mainly landward. A series of sensitive experiments is also run to examine the responses of plume front to changes of river discharges at different inlets in Lingdingyang Bay and interannual variation of northeast winds in winter. The location of plume front responds differently to the change of river discharge at different inlets. An increase in the river discharge at Dahu inlet seems to affect the location of plume front most among the four river inlets, it makes the plume front move eastward and southward wholly; the variation of river discharge at Nansha or Fengmamiao inlet on the location of plume front is more local and weaker; whilst the variation of river discharge at Hengmen inlet has little effect on the plume front. The location of plume front also changes in response to the interannual variation of northeast winds in winter, the stronger or the more eastward the winds are, the more westward the plume front moves, and only in the northern PRE, the response of plume front to the variation of wind speeds is largely different from that to the variation of wind directions.

1. Introduction

The Pearl River Estuary (PRE) is one of the most complex estuaries in the world, it is characterized by eight river discharge inlets, i.e., Humen, Jiaomen, Hongqili, Hengmen, Modaomen, Jitimen, Hutiaomen and Yamen (Fig. 1). It has two longitudinal channels, namely, the west and east channels. The east deep channel is mainly affected by tidal currents offshore, while the west shallow channel is mainly influenced by low salinity discharges from every river mouths (Lin and Liang, 1996). As the Changjiang River or Columbia River which has a significant influence on the hydrography and ecology along the coast and adjacent sea (e.g., Zhu, 2005; Liu et al., 2009), the PRE also plays a similar important role in coast of the northern South China Sea (e.g., Ou et al., 2009).

Fronts, especially those with a consistent position, are often thought of as dividing the ocean into different regimes with separate water masses (Simpson and James, 1986; Wang et al., 2007). There are some studies on hydrodynamics and plume front in the Lingdingyang Bay. Ying (1994) discusses the variation of fronts in the PRE within a tidal period and suggests that the front is related with tidal currents. North of the Neilingding Island, isohalines run from northeast to southwest with the salinity on the eastern side of the estuary being higher than that on the eastern side (Yang et al., 1995). By a numerical model, Wong et al., (2004) suggest that the plume front is formed by the salinity gradient between the riverine water and the higher salinity shelf waters, the density-driven current that is associated with frontal dynamics plays a dominant role in modifying the dynamic behavior of the circulation. Dong et al. (2004) describe the distribution of plume

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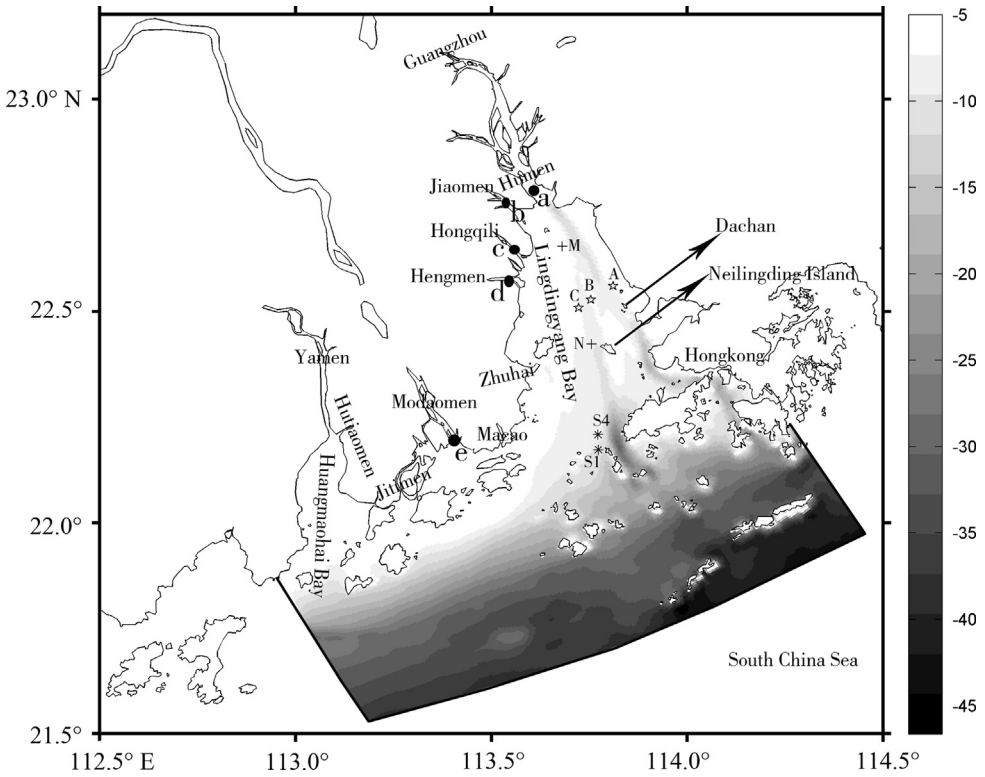

Fig. 1. Topography of the PRE and adjacent coastal waters (where "●" at a, b, c, d and e stand for the inlets at Dahu, Nansha, Fengmamiao, Hengmen and Denglongshan, respectively, these river discharges are prescribed in the model. "+" at M and N stand for the locations where currents are observed, and "*" at S1 and S4 stand for the locations where salinity are observed, and "☆" at A, B and C are the sites chosen for analyses in the text). The strong solid lines are the open boundaries where the tidal harmonic constants are prescribed.

front in both wet and dry seasons, and show that the estuary is nearly in geostrophic balance in the cross-estuary direction by analyzing momentum balance. Ji et al. (2011) demonstrate that a large-size estuarine plume occupies the PRE and the mean circulation in the PRE is characterized by a two-layer estuarine circulation in the vertical direction, with a sharp salinity front near the mouth of the estuary in the wet season. Zhou et al. (2012) find that the saltwater intrudes further during spring tide than during neap tide under different freshwater outflows, the river discharge is a dominant factor in controlling the vertical salinity structure and the length of saltwater intrusion; the northeast monsoon in winter can increase the salinity intrusion in the PRE.

However, some problems remain unsolved, e.g., in the cross-estuary direction, is the estuary nearly in geostrophic balance as suggested by Dong et al. (2004) based on a simple two-dimensional numerical model? In fact, the scale of the estuary might be too small to reflect the Coriolis effect and keep in the geostrophic balance. And what about the saltwater transport balance? There are four major river discharge inlets, Humen, Jiaomen, Hongqili and Hengmen, but which one is the most key factor affecting the location of plume front? And finally, does the interannual variation of northeast winds affect the plume front? Is the plume front more sensitive to the variation of wind speed or direction? In this paper, a three-dimensional numerical model, Estuarine, Coastal and Ocean Modeling System with Sediments (ECOMSED), is employed to study these problems.

This paper is organized as follows. First, the model description and data are presented in Section 2. Second, the model is validated by in situ observational data in Section 3. Third, analyses of model results in tidal dynamics, momentum and salinity transports balances are addressed in Section 4. Fourth, in Section 5, a series of sensitivity experiments under different physical conditions is carried out to study the effects of river discharges at different inlets and interannual northeast winds on the plume front, and finally, the conclusions are summarized in Section 6.

2. Model description and data

2.1. Model description

ECOMSED is a three-dimensional numerical model of hydrodynamic, wave, sediment and contaminant transport processes in shallow water (Blumberg, 2002). The computational domain includes the Huangmaohai Bay, the PRE, coastal waters of Hong Kong and the adjacent shelf region where the water depth is less than 45 m (Fig. 1). An orthogonal horizontal curvilinear grid is designed to map the domain in 250×250 grids with variable resolutions from 375 m $\times$ 370 m within the estuary to 970 m $\times$ 1000 m offshore. There are 6 sigma levels with an equal thickness of each layer in the vertical direction. The eight river inlets and the east, west and south boundaries are set as open boundaries. Time steps used in this study are 0.5 s for external mode and 30 s for internal mode. The observational monthly mean river discharges at eight river inlets, i.e., Dahu (Humen), Nansha (Jiaomen), Fengmamiao (Hongqili), Hengmen, Denglongshan (Modaomen), Huangjin (Hutiaomen) and Guanchong (Yamen) in winter (Table 1) are prescribed at the open boundaries. The initial salinity and temperature data are prescribed according to the observational data in winter of 2001, and the winds are obtained by interpolating the monthly averaged data of QuikSCAT/NECP blended wind data. At the east, west and south open boundaries, harmonic