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A numerical study of coupled estuary–shelf circulation around the Pearl River Estuary during summer: Responses to variable winds, tides and river discharge

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ABSTRACT

The mean (sub-tidal) circulations in the Pearl River Estuary (PRE) and over the adjacent shelf are interactive. They are driven by multi-forcing of winds, tides, and the buoyancy of river discharge. Utilizing a validated three-dimensional, high resolution numerical model, we find that the circulation in the PRE during summer is dominated by an advective gravitational two-layer circulation in the upper estuary and the landward part of the lower PRE, where the surface flow pattern also varies with the upwelling winds. The circulation in the seaward part of the lower PRE is governed by both gravitational circulation and geostrophic intrusive current from the shelf. The pattern and intensity of these circulations are largely modulated by variable wind forcing. The cross-shore upwelling shelf circulation off the PRE enhances the water exchange rate between the shelf and the PRE, but the net intrusive transport into the PRE is negatively correlated with the intensity of upwelling-favorable wind stress. Relatively strong water exchange rate between the shelf and estuary occurs during upwelling, which reduces the flushing time of the estuary. Although the ebbing/flooding tide strengthens/weakens the eastward alongshore upwelling current, tidal effect on the upwelling circulation and on the net transport between the shelf and estuary is not significant over the sub-tidal period. The shelf influences the estuary mainly through the intrusions of the shelf waters at the western bank and along the two navigation channels of the PRE; and they are governed by geostrophic cross-shelf upwelling circulation and by gravitational intrusive currents due to pressure gradients, yielded by the alongshore variation of the upwelling shelf circulation and by the buoyancy forcing of the river plume, respectively.

1. Introduction

The Pearl River Estuary (PRE) is located along the coast of Guangdong province in China between 21°N and 23°N, 113°E and 115°E (Fig. 1). It links the Pearl River, the world's 13th largest river with annual mean discharge rate: $\sim$10,000 m^3 s^{-1}, with the continental shelf in the Northern South China Sea (NSCS). The river has 8 inlets, and 4 of them constitute more than half of the total discharge. These 4 inlets are located within the PRE along its western shore. The bell-shaped PRE has an axial length of $\sim$60 km with a narrow head of only several kilometers in the upper estuary near Hu Men (HM). It has a relatively wide seaside entrance of $\sim$50 km in the lower estuary between Hong Kong (HK) and Macau (MC) (Fig. 1). The estuary is characterized by a wide flat western bank less than 5 m deep, and by a relatively deep eastern valley. Two distinct deep channels of $\sim$20 m in the central and eastern parts link the lower and upper PRE with the adjacent shelf. Over the shelf, the isobaths are approximately parallel to the coast with a strong cross-shelf gradient on the shelf to the west of the PRE. In contrast, the shelf slope farther offshore is steeper to the east of the PRE. In addition, the coastline is extremely complex around the PRE and adjacent shelf with many islands scattered around the entrance and many coastal bays. All these geometric and topographic features greatly modulate the circulation in both the estuary and the adjacent shelf.

Tides are mainly semi-diurnal (M2) and diurnal (K1) around the PRE region and have $\sim$1.0 m magnitude inside the PRE. They are amplified and modulated as they propagate back and forth in the PRE with spatially variable water depth. Tides form a counter–clockwise tidal residual circulation (Mao et al., 2004) and may affect the estuarine circulation in both tidal and sub-tidal frequencies. With the seaward freshwater from Pearl River discharge, they lead to a gravitational circulation in the PRE and exhibits as a salt wedge estuary in the wet season (Lu and Gan, 2015).

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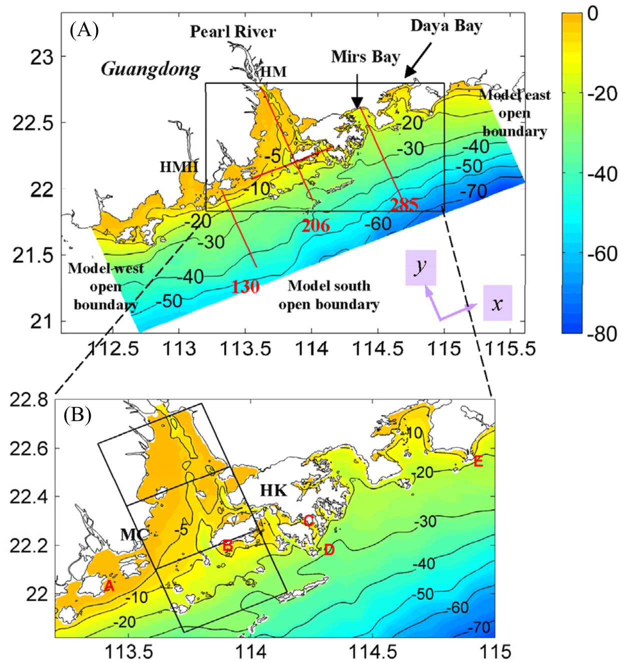

Fig. 1. (A) The model domain and bathymetry (m, color contour with black contour lines). The red lines denote the sections along the axial of the PRE (central), western and eastern shelves, as well as along the entrance of the PRE; (B) zoomed topography around the PRE and Hong Kong waters. The black boxes define the regions of upper, lower estuary and the shelf in the discussion. "A, B, C, D, E" represent the location of the tidal gauge in Sanzao, Shekpik, HK-B, Waglan, and Gangkou respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

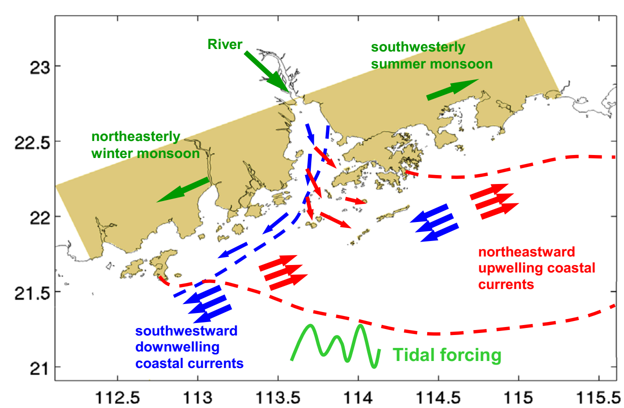

Fig. 2. Sketch of the river plume and coastal currents in the PRE and adjacent shelf in winter (blue dashed lines and arrows) and summer (red dashed lines and arrows), drawn based on the results from previous studies. Monsoon wind directions are also marked in the land points and the dashed lines refer to the outer edge location of the river plume. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Besides the tidal forcing and buoyancy from river discharge, the circulation in the PRE is also forced by the winds and it interacts with the shelf circulation. The seasonal circulation and associated forcing in the PRE and adjacent shelf can be summarized based on the previous studies (e.g. Xue et al., 2001; Wong et al., 2003a,b; Su, 2004; Dong et al., 2004; Ou et al., 2007; Gan et al., 2009a,b; Sheng et al., 2010; Ji et al., 2011a,b), as shown in Fig. 2. Driven by the East Asia summer monsoon, coastal upwelling with the northeastward along-shore currents forms along the coast off the PRE. This wind-driven coastal current closely interacts with the estuarine circulation in the lower part of the PRE (Dong et al., 2004). Shelf water intrusion into the estuary occurs during the upwelling season (Zu and Gan, 2009). The intrusion may alter circulation in the PRE and the water exchange rate between shelf and estuary. Although the tidal circulation plays an important role in the water exchange over the tidal cycle, sub-tidal circulation ultimately determines the net water exchange. The specific characteristics of these processes and the dynamics of the intrusion over the sub-tidal period remain largely unknown.

In addition, the fresher water exiting from the estuary forms a buoyant plume over the shelf. It spreads eastward or southeastward in response to the southwesterly monsoon during summer. The interaction of plume and wind-driven shelf circulation alters the intensity and pattern of the coastal upwelling circulation (Gan et al., 2009b) that, in turn, modulates the intrusion of shelf water into the PRE.

This study presents the processes and dynamical rationalization for variable responses of coupled estuary–shelf circulation in the PRE to the multi-forcing of wind, tide, river discharge and shelf circulation.

2. Ocean model

In this study, we use the free-surface, stretched terrain-following, hydrostatic, primitive-equation Regional Ocean Modeling System (ROMS) (Haidvogel et al., 2000; Shchepetkin and McWilliams, 2005). The model domain covers both the PRE and the adjacent shelf in order to link the two systems (Fig. 1A). The western and eastern boundaries are approximately normal to the isobaths over the shelf and extend about 150 km offshore from the coast. The southern open boundary is roughly along the 50 m isobath, about 100 km offshore from the PRE. We obtain the bottom topography by combining water depth data from the Hong Kong Maritime Department and water depths digitized from the high resolution navigation charts published by the China Maritime Safety Administration. The topography is slightly smoothed to reduce truncation error and the minimum water depth was set equal to 2 m. We adopt a horizontal curvilinear grid with 400×200 grid points on the x-axis (alongshore) and y-axis (cross-shore). The grid forms an average horizontal grid size of about 0.8 km. We use the terrain-following s-ordinate (Song and Haidvogel, 1994) with 30 levels in the vertical axis and with higher resolution in both the surface and bottom boundary layers.

We initialize the model with horizontally uniform temperature and salinity profiles obtained from the World Ocean Atlas 2001 (WOA01; Boyer et al., 2005) at 114.5°E, 21.5°N, which resembles the conditions found during a field cruise that carried out in July 2000. The initial sea surface elevation and current velocity are set to zero. We apply a temporally variable wind stress that was measured from July 1 to August 1, 2000 on Waglan Island (marked by D in Fig. 1B). Owing to the relatively weak spatial variation of wind forcing in the PRE region, the wind stress is applied uniformly throughout the whole model domain. The time series of wind contains two ~10-day typical upwelling periods separated by one ~8-day upwelling relaxation or weak downwelling period (Fig. 3). The time series represents the typical variation in the southwesterly monsoon wind in the region. The wind stress is calculated using Large and Pond (1981), and is low-pass filtered using a 12-h filter to reduce spurious noise in the numerical solution.

We use tidal harmonic constituents of 8 major components (M_2, K_1, S_2, O_1, N_2, P_1, K_2, and Q_1) extracted from the South China Sea tidal assimilation model (Zu et al., 2008) to provide the tidal elevation and currents on the model's open boundaries. We apply an observed time-dependent river discharge rate at the eight main river exits during the simulation period (Fig. 3B). The volume of discharge is uniformly distributed in the water column with river water temperature and salinity set to be 29.5 °C and 3 psu. The