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On the role of wind and tide in generating variability of Pearl River plume during summer in a coupled wide estuary and shelf system

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ABSTRACT

A numerical simulation of the buoyant river plume over the Pearl River Estuary (PRE) and adjacent shelf during a typical upwelling favorable wind period of the summer monsoon is utilized to explore the responses of the plume to wind and tide forcing. The model is forced with time-dependent river discharge, wind and tide, and it shows reasonable ability to capture the basic structure and responses of the plume. Additional numerical experiments that are forced without either wind or tide are used to evaluate the relative importance of wind and tide in generating plume variability. Results show that the vertical structure of the plume and the strength of the stratification in the estuary are determined by the combination of the buoyancy forcing associated with river discharge and tidal forcing, and vary with the advection process, while the horizontal shape and spreading of the plume over the shelf are highly influenced by the wind-driven coastal current, and are more susceptible to the change of vertical mixing. Mechanical energy analysis in each dynamical region (upper, middle, lower estuary, and shelf) reveals that this is because the system mainly gains energy from tide (wind) in the estuary (shelf), and loses energy to the bottom friction (internal-shear mixing) in the estuary (shelf). The largest forcing and dissipation terms in the middle PRE, and at the entrances of smaller estuaries such as Huang Mao Hai, are due to tidal forcing, which enables the middle PRE to serve dynamically as the entrance of an estuary, where the transition of the river plume into coastal buoyancy current usually takes place. In addition, the mixing efficiency increases from upper PRE to the shelf and from strong to weak mixing period, thus the plume in the well-mixed upper estuary is not as sensitive to the changes of wind and tide as that over the highly stratified shelf.

1. Introduction

The formation and evolution of a river plume over the continental shelf in an idealized numerical model without additional external forcing, such as wind, tide, or ambient flow, is characterized as surface-advected plume, with always a bulge of anticyclonic surface current formed near the estuary mouth (Chao and Boicourt, 1986; Fennel and Mutzke, 1997; Yankovsky and Chapman, 1997). In the Northern Hemisphere, after exiting from the estuary, the buoyant plume turns right into a coastal current with a width narrower than the bulge, and flows downstream in the direction of Kelvin wave propagation. This is also defined as a supercritical plume by Chao (1988a) and Kourafalou et al. (1996a), but not often observed in nature (Garvine, 2001). The more commonly observed plume has a slight or no bulge formed at the estuary mouth and the plume-induced coastal current has a similar width as the bulge, and it is defined as a subcritical plume (Chao, 1988a; Kourafalou et al., 1996a). This kind of plume and coastal current could be reproduced by an idealized simulation by adding downstream (in Kelvin wave sense) ambient coastal current or downwelling favorable wind, or when more realistic geometry is considered (Garvine, 2001).

River plume shows more complex and diverse structures under the influence of wind and tide forcing. During a period of upwelling favorable wind, the plume is advected offshore through Ekman dynamics and upstream (in Kelvin wave sense) by a wind-driven alongshore coastal current (Chao, 1988b; Choi and Wilkin, 2007; Fong and Geyer, 2001; Gan et al., 2009; Garcia-Berdeal et al., 2002; Kourafalou et al., 1996b; Lentz, 2004; Whitney and Garvine, 2005). The shape and spreading of the plume over the shelf vary and respond quickly (within a few hours) to the change of wind direction and strength. Patches of low-salinity water might be formed if reversal of alongshore current appears (Wolanski et al., 1999). Enhanced mixing by wind can influence the vertical and horizontal structures of the plume (Hetland, 2005; Xing and Davies, 1999). On the other hand, the stratification caused by the plume confines the depth of the wind effect in the surface layer and intensifies the Ekman drift within the plume (Gan et al., 2009). Tide also plays a significant role in changing the structure and spreading of the plume by straining and stirring effects and by tidally-modified residual currents (Chao, 1990; Guo and Valle-Levinson, 2007; Simpson,

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1997; Simpson et al., 1990; Zu and Gan, 2009). The plume advances and retreats with the tidal current during a tidal cycle. The greatly enhanced mixing by tide retards the horizontal spreading process, and increases the thickness of the plume, while plume induced stratification modified the tidal current in turn.

The structure and spreading of the plume is closely related to vertical mixing, which is greatly influenced by the variation of wind and tide forcing. Chao (1988b) pointed out two types of wind-induced vertical mixing on the plume: one is the enhanced vertical current shear by seaward or upwelling favorable wind, and the other is the advection of heavier (saltier) water atop lighter (fresher) water by landward or downwelling favorable wind. Hetland (2005) revealed the relationship of the structure of a river plume with vertical mixing by an idealized wind-forced river plume system, and evaluated the effects of wind-induced mixing on the plume at different salinity ranges. His results showed that wind mixing had the greatest effect on plume structure at the salinity range of 24–29 psu. MacCready et al. (2009) extended the study by quantitatively evaluating the wind- and tide-induced mixing effects on the Columbia River plume. They compared the relative importance of wind and tide in an estuary and plume region through a mechanical energy budget, and showed that the divergence of tidal pressure work is dominant in the estuary, while in the far field plume region, whether tide or wind works as the dominant forcing term depends on its strength during different periods. Their results demonstrated the need to include both forcing terms in the simulation of river plume in an estuary and shelf coupled system.

The buoyant plume around the Pearl River Estuary (PRE) has a similar situation as that around the Columbia River estuary in that both estuaries are located along shelves which are influenced by the downwelling favorable wind in winter and upwelling favorable wind in summer. The differences are that the large, bell-shaped PRE is about 50-km wide at the entrance and 60-km long in the axial direction (Fig. 1), the Pearl River has a large fresh water discharge through eight distributaries (four northeastern outlets discharge about half of the total river discharge directly into the PRE, and four southwestern ones discharge directly into the shelf region (Harrison et al., 2008)), and its lower part could be strongly affected by the coastal circulation (Zu and Gan, 2014). Then questions may arise: when the estuary is large (wider than the internal Rossby deformation radius, $R' = \frac{\sqrt{g'h}}{f}$), what is its function in maintaining the mixing rate in transferring fresh water into shelf water? What are the relative roles of wind- and tide-induced mixing in different parts of a large estuary? And how do the plume and related mixing efficiency inside the estuary and over the shelf respond to the change of physical forcing in such a wide estuary and shelf upwelling system? In this paper, we try to answer these questions by expanding the MacCready et al. (2009) study to the PRE region.

The circulation around the PRE and its responses to tide, wind and buoyancy discharge during the dry (winter) and wet (summer) seasons have been investigated numerically (Ji et al., 2011a,b; Wong et al., 2003a,b; Xue and Chai, 2001). However, there are only a few studies focusing on the responses of the river plume to the physical forcing in the PRE, compared to those carried out in other estuaries in the world. The plume shows a distinct seasonal variation (Dong et al., 2004), as it is influenced by a large river discharge (about 10,000–40,000 $m^3\ s^{-1}$) under upwelling favorable wind in summer and by a small discharge (about 1000–5000 $m^3\ s^{-1}$) under strong downwelling favorable wind in winter (Harrison et al., 2008). Hence, its pattern is much more diverse in the wet (summer) season than in the dry (winter) season. The Pearl River plume was characterized into four types, namely, offshore bulge spreading, west alongshore spreading, east offshore spreading, and western and eastern alongshore spreading, by Ou et al. (2007), according to the surface salinity distribution observed between 1978 and 1984. The offshore bulge spreading type seldom appears, and the other three types are observed often and are subcritical plumes. Further study by Ou et al. (2009) showed that the size of the plume was related with the river discharge, and wind played a significant role in changing the shape of the plume. Owing to the temporal and spatial limitation of the observation data, structures and responses of the plume could neither be captured well nor investigated without the aid of a numerical

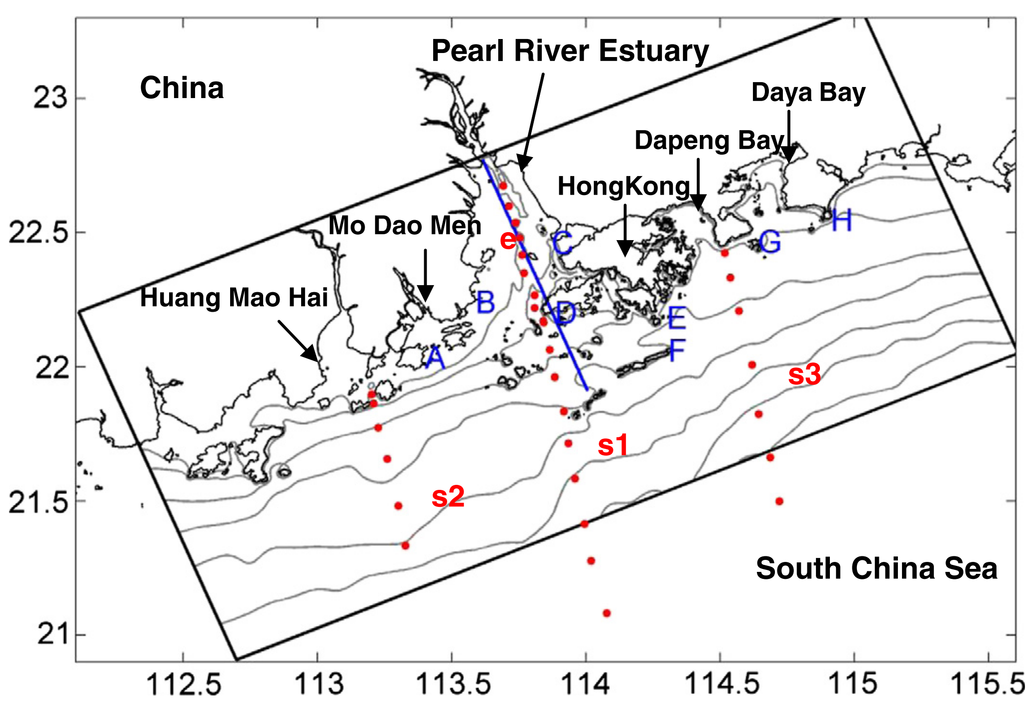

Fig. 1. Model domain (indicated by the rectangular box) and topography (contours for 5, 10, 20, 30, 40, 50, 60 and 70 m isobaths) for the Pearl River Estuary. The blue line marks the axial section of the PRE. Letters A–H indicate the tidal gauge stations used for model validation, and the red dots show the cruise sections s1, s2, s3, and e.