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

Tingting Zua, Dongxiao Wang a,*, Jianping Gana, Weibing Guanc

a State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou 510301, China
b Division of Environment & Department of Mathematics, Hong Kong University of Science and Technology, Kowloon, Hong Kong, China
c State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, State Oceanic Administration, Hangzhou 310012, China

A R T I C L E   I N F O

Article history:
Received 3 September 2013
Received in revised form 18 February 2014
Accepted 18 March 2014
Available online 25 March 2014

Keywords:
Mathematical models
River plumes
Energy budget
Vertical mixing
Pearl River Estuary

A B S T R A C T

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.

© 2014 Elsevier B.V. All rights reserved.

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-adected 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, 2001).
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, $R' = \sqrt{\frac{\beta}{f}}$), 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; Xu 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. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
model, Gan et al. (2009) revealed the interactive dynamic processes between the Pearl River plume and upwelling circulation over the Northern SCS shelf using a shelf circulation model. They found that the buoyant plume was advected and reshaped by the coastal current, while the current was also modified by the stratification and pressure gradient induced by the plume. The interaction between the plume and the coastal current establishes a new dynamic balance that shapes the shelf circulation. Zu and Gan (2009), as well as Luo et al. (2012), examined the wind, tide and Coriolis effects on the Pearl River plume by using idealized and realistic topography, respectively, in their numerical simulations. These studies, however, only qualitatively showed the responses of the plume to the forcing field. The quantitative contributions of wind and tide to vertical mixing and related plume structures in different dynamic regions in the wide PRE that receives a large amount of fresh water input remain largely unclear.

In this paper, we explore the spreading and structure of the Pearl River plume in response to upwelling favorable wind, tide, and buoyancy discharge through a high-resolution circulation model that resolves the estuary and part of the shelf sea. Numerical experiments are carried out with energy analysis to differentiate the roles of these physical forcing fields in different geographical regions. Model implementation and validation are described in Section 2. The responses of the plume structure and estuary stratification to different forcing fields are presented in Section 3. Mechanical energy analysis and salt balance are applied to quantitatively assess the relative contribution of wind and tide to vertical mixing and sub-tidal plume structures in Section 4 and 5, while Section 6 summarizes the study.

2. Numerical model and its validation

2.1. Model configuration

The Regional Ocean Modeling System (ROMS; Haidvogel et al., 2000; Shchepetkin and McWilliams, 2005) is used to set up the estuary-shelf circulation system around the PRE. ROMS has been widely used in simulating estuarine circulation and buoyant plumes in different regions all over the world (Hunter et al., 2010; Li et al., 2005; Liu et al., 2009; MacCready et al., 2009; Otero et al., 2008; Rong and Li, 2012; Warner et al., 2005). The model domain (Fig. 1) covers both the PRE and its adjacent shelf, and the bottom topography is obtained 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 average horizontal grid size is about 0.8 × 0.8 km², and a terrain-following s-coordinate (Song and Haidvogel, 1994) with 30 vertical levels and θk = 2.5, θ0 = 0.8 are chosen in order to have a higher resolution in both surface and bottom boundary layers. Mellor and Yamada’s (1982) level 2.5 turbulent closure scheme is used to parameterize the vertical mixing. Other turbulent closure schemes (e.g., k-kl, k-c) are also tested, and results show that the structure and spreading of the plume is not sensitive to these turbulent closure schemes compared to the physical forcing (figures not shown). The model starts from 1st June, 2000, and runs for 85 days. Numerous experiments show that it takes about 25 days for the salinity in the PRE to be adjusted to a quasi-steady state, and we use the results after 50 days for further analysis in the paper. The model is forced by time-dependent river discharge, wind, and eight major tide components (M2, K1, S2, O1, N2, P1, K2, and Q1), which are extracted from the SCS tidal assimilation model (Zu et al., 2008) (Fig. 2). The wind (obtained in the Waglan Island, shown by Station E in Fig. 1) and initial conditions (obtained by averaging the temperature and salinity profile from World Ocean Atlas 2001 over the shelf region outside the PRE) are applied horizontally uniform over the model domain. The heat and salt fluxes at the sea surface are disregarded in the simulation for simplicity as the aim of this study is to differentiate the roles of wind and tide on the plume. Other details of the model can also be seen in Zu and Gan (2014).

![Fig. 2. Time-dependent buoyancy, wind and tide forcing illustrated by (a) river discharge (m³ s⁻¹), (b) 12-h smoothed wind stress (Nm⁻²) observed at Station D (solid line: along-shore component; dash line: cross-shore component), (c) tidal elevation anomaly (m) at Station A (dots), superimposed with the model simulation (solid line), (d) inertial-period (~36 h) smoothed sea surface elevation anomaly (m) at Station A (dash-dotted line: observation), superimposed with the model simulation (solid line). The gray bands indicate 95% confidence intervals of observations.](image-url)

2.2. Model validation

The simulated sea surface elevations compare well with the observations at Stations A–H (marked in Fig. 1). Time series of the hourly sea surface elevation anomalies (Fig. 2c) and inertial period (~36 h) low-pass filtered sea surface elevation anomalies (Fig. 2d) in Station A show that the correlation coefficients of the observation and model results are larger than 0.9; the sub-tidal variation of the sea surface elevation is negatively correlated with the along-shore wind stress, which suggests that the wind- and tide-modified intertidal and sub-tidal sea surface elevation variations could be well reproduced by the model. The correlation coefficients of the sea surface elevation at other stations are all larger than 0.8, which show similar patterns as that in Station A; thus figures are not shown here for these stations. Instead, comparisons of the observed and simulated tidal harmonic constants of the two major tidal components (M2 and K1) at all these stations are listed in Table 1. Differences between their amplitudes and phase lags are calculated as distances following Foreman et al. (1993)

\[
d = \sqrt{(H_o \cos \theta - H_s \cos \phi)^2 + (H_o \sin \theta \sin \phi - H_s \sin \theta)^2},
\]

where (\(H_o, \theta_o\)) and (\(H_s, \theta_s\)) are the observed and modeled amplitudes and phase lags, respectively. The root mean square (RMS) error of the amplitude is

\[
\sqrt{\frac{1}{2N} \sum_{i=1}^{N} |H_o - H_i|^2},
\]
where $H_{Si}$ and $H_{Oi}$ are the simulated and observed amplitudes at Station $i$, and $N$ is the total number of observation stations. Generally, the tidal harmonic constants obtained from the model compare well with those from the observation; the RMS errors of the amplitude are only 1.67 and 2.97 for $M_2$ and $K_1$, respectively. The tidal waves are better reproduced over the shelf, as the $d$ is smaller than those inside the estuary, possibly because of more complicated tidal features and topography inside the PRE. Nevertheless, the tidal accuracy of the simulation is sufficient to evaluate the role of tide on plume structure.

Simulated salinity along the cross-shelf sections is compared with that observed during the first upwelling period between days 53 and 60 (Fig. 3). Observations show that the low salinity plume occupies the top 10 m about 50 km off-shore, and the high-salinity bottom water moves upward onshore. The model outputs are interpolated to the time and location of the observation stations, and then plotted. The model could reasonably capture the basic structure of the plume, but there are still discrepancies between the simulated and the observed plume. The discrepancies are not notably improved when we use different spin-up time, thus they are likely due to some simplifications utilized in the model implementation (e.g. spatially uniform wind forcing and initial condition, approximation of a constant ratio of the river discharge along the outlets of eight distributaries, and not considering the surface heat flux, etc.). Nevertheless, the model with simplification could reasonably capture the general structure and basic response of the plume (as shown by the simulated surface salinity and observed SeaWiFS Chl-a concentration in Fig. 5 in Zu and Gan (2014)). Hence, we have modest confidence in the model performance in reproducing the responses of the plume to wind and tide forcing, and will use the simulated results for further discussion and analysis.

| Station | $M_2$ | | $K_1$ | |
|---------|-------| |-------|------|
|         | Amplitude (cm) | Phase (deg.) | d | Amplitude (cm) | Phase (deg.) | d |
|         | Obs. | Model | Obs. | Model | Obs. | Model | Obs. | Model |
| A       | 43.8 | 42.1  | 306.2 | 303.9  | 2.4  | 41.7  | 42.2  | 331.6 | 338.4 | 5.0  |
| B       | 48.1 | 43.1  | 286.2 | 295.2  | 8.7  | 25.2  | 33.1  | 318.6 | 334.7 | 11.3 |
| C       | 58.2 | 55.1  | 326.1 | 335.7  | 10.0 | 42.1  | 49.6  | 334.5 | 377.0 | 7.8  |
| D       | 43.4 | 43.1  | 270.3 | 271.5  | 1.0  | 42.5  | 41.8  | 311.0 | 313.8 | 2.2  |
| E       | 36.4 | 35.1  | 268.3 | 272.8  | 3.1  | 42.1  | 43.4  | 313.2 | 311.6 | 1.6  |
| F       | 35.5 | 34.2  | 263.8 | 262.2  | 1.6  | 24.0  | 27.9  | 312.1 | 310.9 | 3.9  |
| G       | 33.3 | 32.1  | 254.6 | 253.4  | 1.4  | 23.6  | 25.1  | 309.0 | 308.2 | 1.5  |
| H       | 30.1 | 28.7  | 281.4 | 273.8  | 3.2  | 36.4  | 38.2  | 322.7 | 326.7 | 3.2  |
| RMS error | 1.67 | | 2.97 | |
2.3. Numerical experiments

To differentiate the roles of wind and tide forcing on the time-dependent features of the plume and stratification, two additional numerical experiments are carried out. They are the same as the standard case except for excluding either wind or tide forcing. The three cases discussed in this paper are named WRT, WR, and RT, respectively, in which “W” stands for wind, “R” stands for river, and “T” stands for tide.

3. Plume structure in response to wind and tide forcing

3.1. Horizontal shape of the plume

The horizontal shape of the plume is roughly denoted by the daily-averaged 32-psu isohaline, similar as that used in the Columbia River plume by Hickey et al. (1998), as it fits the edge of the fresh water plume well around the PRE region (Fig. 3 in this paper and Fig. 5 in Zu and Gan (2014)). And this is also because the time-dependent salinity variation of ambient shelf water is very small compared to that of the plume water. The model results averaged on days 52, 56, 60, and 67 are used to study the sub-tidal evolution of the plume under different forcing (Table 2). The shapes of the plume at the surface in WRT and WR cases (Fig. 4a, c) show greater variability compared to their shapes at bottom (Fig. 4b, d), as wind impacts the plume and current at the surface directly.

During neap tide on day 52 when the wind is weak enough to be disregarded, the plume spreads westward against the coast in all cases with no bulge formed (red lines in Fig. 4), and shows typical subcritical feature. On day 56, when the upwelling favorable wind and tidal amplitude start to grow stronger with the increase of river discharge, the plume at the sea surface (black lines in Fig. 4) is much larger in size and is advected southeastward by the surface Ekman current except for RT case. The shape and extension of the plume in WRT case resemble those of WR case, but differ from RT case, which suggests the more important role of wind forcing on the plume over the shelf in a sub-tidal frame.

On day 67, when the upwelling favorable wind relaxes to become a weak downwelling favorable wind and reduced river discharge on day 60, the wind- and tide-induced mixing is the strongest, and the plume (green lines in Fig. 4) shrinks to a narrow eastward spreading tongue. However, the plume tongue in the case without tide (WR case) spreads about 90 km further eastward than the standard case (WRT case). This indicates that strong tide could significantly affect the plume shape over the shelf. However, this does not mean that the shorter plume tongue in WRT case is directly caused by increased tidal mixing over the shelf. The difference is probably due to the modified plume properties (buoyancy and thickness) in the near-shore region (as reflected in the different shape of the plume at the bottom around the entrance of the estuary, and more low-salinity water is trapped in this region when the tidal mixing is included), which affects the plume shape in the offshore region (Fong and Geyer, 2001; Lentz, 2004).

During neap tide on day 52 when the wind is weak enough to be disregarded, the plume spreads westward against the coast in all cases with no bulge formed (red lines in Fig. 4), and shows typical subcritical feature. On day 56, when the upwelling favorable wind and tidal amplitude start to grow stronger with the increase of river discharge, the plume at the sea surface (black lines in Fig. 4) is much larger in size and is advected southeastward by the surface Ekman current except for RT case. The shape and extension of the plume in WRT case resemble those of WR case, but differ from RT case, which suggests the more important role of wind forcing on the plume over the shelf in a sub-tidal frame.

Table 2

<table>
<thead>
<tr>
<th>Day from 1st June</th>
<th>River discharge (m³/s)</th>
<th>Wind stress (N/m²)</th>
<th>Tide amplitude ratio (%)</th>
<th>Representative forcing</th>
</tr>
</thead>
<tbody>
<tr>
<td>52</td>
<td>11,080</td>
<td>0.001</td>
<td>-34</td>
<td>Very weak/no wind, weak tide</td>
</tr>
<tr>
<td>56</td>
<td>13,176</td>
<td>-0.07</td>
<td>-45</td>
<td>Moderate/strong UPW, moderate tide</td>
</tr>
<tr>
<td>60</td>
<td>9952</td>
<td>-0.09</td>
<td>-97</td>
<td>Strong UPW, spring tide</td>
</tr>
<tr>
<td>67</td>
<td>9602</td>
<td>-0.003</td>
<td>-30</td>
<td>Weak DFW, neap tide</td>
</tr>
</tbody>
</table>

The vertical structures of the salinity and vertical diffusivity (sdiff = \( \frac{K_v}{s} \)), in which \( K_v \) is vertical eddy diffusivity, \( s \) is salinity and \( z \) is the vertical coordinate, here we consider only the vertical component as the horizontal component is several magnitudes smaller. Along the axial section of the PRE (marked in Fig. 1) are shown in Fig. 5. The positive and negative values of sdiff indicate increasing and decreasing tendency of salinity, respectively. The large positive and negative values of sdiff appear vertically in pairs at places with strong vertical mixing and reflect the region with high mixing rate.

A large magnitude of sdiff appears in the middle and lower PRE when tidal mixing is stronger (Fig. 5b, c, i, k), and it shows distinct spring–neap variation inside the estuary for WRT and RT cases. Accordingly, the structures of the plume inside the PRE are similar for WRT and RT cases, and the plume front at the bottom advances and retreats during the fortnight cycle. Besides, a large magnitude of sdiff also appears at the upper layer over the shelf outside the entrance of the PRE, when the upwelling wind becomes stronger (Fig. 5b, c, f, g), which suggests a higher mixing rate and associated larger variability of plume there. The magnitude of sdiff is very small in the upper estuary, since it is well-mixed and the mixing rate is low. Over the shelf farther offshore, its magnitude is much smaller than that outside the entrance of the estuary during the upwelling period, since the variability of the plume over the shelf farther offshore is mainly associated with the wind-
driven shelf circulation induced advection processes (figures not shown here) rather than the mixing process.

Tide-induced mixing greatly weakens the stratification inside the PRE, and its influence on the plume is limited from upper estuary to the near shore region outside the PRE. The enhanced thickness of the plume by tidal mixing results in the reduced $\sigma_{d}$ over the near shore region (Fig. 5c, g) (i.e. the plume is less sensitive to the wind mixing during spring tide), however the combination of wind and tide effects lead to a more complex variability of the plume than that forced by only wind or tide.

The evolution of plume structure in different cases shown in Figs. 4 and 5 clearly demonstrate that the structure of the plume in the middle and lower parts of the PRE cannot be effectively simulated without tide forcing; tidal mixing is not negligible even if we only want to study the shelf process in this region, for the off-shore stratification and plume structure are influenced by its near-shore characteristics. The structure of the plume in the estuary is determined by the combination of the buoyancy forcing associated with river discharge and tidal mixing, and it varies with the spring–neap cycle in the middle and lower parts of the estuary. On the other hand, the vertical structure of the plume over the shelf is sensitive to the wind-induced mixing near the entrance of the estuary, but is highly influenced by wind-driven shelf circulation farther offshore.

3.3. Freshwater thickness

Freshwater thickness relative to the background salinity, $s_0$, is defined as the vertical integral of salinity anomaly ($s_0 - s$) / $s_0$. The

---

**Fig. 4.** Surface (left) and bottom (right) salinity of 32 psu of WRT (top), WR (middle), and RT (bottom) cases averaged on day 52 (red), day 56 (black), day 60 (green), and day 67 (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 5. Salinity (black contours) and vertical salinity diffusivity (shadings) along the axial section of the PRE for WRT (top), WR (middle), and RT (bottom) cases averaged on day 52 (first column), day 56 (second), day 60 (third), and day 67 (fourth). The numbers along the x-axis are the grid numbers from model’s southern boundary to the northern boundary, and those along the y-axis are the water depth.
freshwater thickness over the shelf is highly correlated with the direction and strength of the wind; it becomes thinner (thicker) due to upwelling (downwelling), as it is stretched and advected offshore (pushed and accumulated against the coast) (Chao, 1988b; Hetland, 2005). Here, we examine the freshwater thickness of the Pearl River plume in response to tide and wind by comparing the results of WRT, WR and RT cases averaged during two periods (shown by the gray bands in Fig. 2): one is forced by strong upwelling favorable wind and spring tide (i.e., strong mixing period), and the other one is forced by very weak wind and neap tide (i.e., weak mixing period). The river discharge averages during these two periods have similar values, about $1.1 \times 10^4$ m$^3$ s$^{-1}$ and $1.2 \times 10^4$ m$^3$ s$^{-1}$, respectively.

The thickness of the freshwater in the PRE mainly follows the isobaths, with the thickest part appears along the two narrow deep channels (Fig. 6a). There is not much variation of the freshwater thickness in the upper PRE, as the water is well-mixed and the mixing rate is low, and the plume is not sensitive to the change of wind- and tide-mixing. In the middle and lower parts of the PRE, the thickness of the freshwater shows significant variation between Period I and Period II, especially for the WR case. This suggests again that the more stratified plume is more sensitive to the change of the mixing and is prone to higher mixing rate.

The range and thickness of the freshwater over the shelf show more notable variation, as advection becomes stronger. During Period I, the range and thickness of the freshwater in the WRT over the shelf is the smallest (Fig. 6a), as more low-salinity water is trapped inside the estuary due to tidal mixing and the freshwater over the shelf is quickly advected away by the wind-driven circulation and is mixed with the high salinity shelf water. During Period II (Fig. 6b), when vertical mixing is significantly reduced and the wind-driven offshore transport is relaxed, the freshwater over the shelf becomes thicker.

Unlike those in the narrower estuaries that receive lower river discharge, the structure and response of the freshwater plume and related salinity diffusivity show distinct characteristics in different parts of the PRE and adjacent shelf system, which could be divided into upper, middle, lower estuary and shelf regions. And the contributions from wind-

![Fig. 6.](image-url)
and tide-induced mixing on plume structures in different regions are quantitatively evaluated through mechanical energy analysis in the next section.

4. Relative contribution of wind- and tide-induced mixing

Mechanical energy is required to advect and mix fresh water with saline water, and to change the stratification and thickness of the buoyant plume. In this section, we evaluate the relative importance of wind- and tide-induced mixing in different regions by comparing the mechanical energy terms in the three cases. Similar as MacCready et al. (2009), we extend their study by evaluating the energy terms in different simulations and by dividing the estuary into three regions to examine the function of the PRE in transforming fresh water into saline water. Unlike the Columbia River Estuary, the PRE has a bell shape and a wide entrance connecting to the open ocean. The river plume shows characteristics of buoyant coastal front inside the PRE (Dong et al., 2004).

Following Weisberg and Zheng (2003), Zhong and Li (2006), and MacCready et al. (2009), the mechanical energy budget could be written as (see Appendix A for detailed derivation):

$$dE = -advTE - PW + WW - Dbot - Dint + BUOY + R.$$  (4.1)

In which, $dE$ is local change of the total mechanical energy; $advTE$ is the flux of mechanical energy into the control volume by horizontal advection; $PW$ is the divergence of pressure work; $WW$ is the work done by sea surface wind stress; $Dbot$ is the energy dissipation due to bottom stress; $Dint$ is the energy dissipation by vertical shears of the horizontal velocity that is integrated in the interior portion of the selected region (i.e., vertically from the first model velocity grid point above the bottom); $BUOY$ is the buoyancy flux via vertical diffusion; $R$ is the residual term that includes calculation error, energy dissipation from horizontal shear of horizontal velocity and the energy contribution from horizontal diffusive fluxes of $TE$, which are relatively small.

We average Eq. (4.1) over Periods I and II as defined in Section 3. Period I is during a strong upwelling favorable wind with spring tide, representing a period of strong mixing. Period II is during an upwelling relaxation period with very weak wind and neap tide, representing a period of weak mixing. Each time interval includes six M2 tidal cycles. The local change rate of the energy, $dTE$, is smaller than the other terms. In order to compare the roles of wind- and tide-induced mixing on the structure of the plume, we mainly focus on the forcing terms ($PW$ and $WW$), dissipation terms ($Dbot$ and $Dint$) and buoyancy terms ($BUOY$) as MacCready et al. (2009) did. The horizontal distributions of the vertically-integrated terms during these two periods are shown in Figs. 7–11.

The divergence of pressure work, $PW$, of WRT case is positive inside the PRE and two smaller estuaries (Huang Mao Hai and Mo Dao Men), which are located on the west side of the PRE, during both periods (Fig. 7a, b). The maximum $PW$ during these two periods appears at the entrance of Huang Mao Hai and Mo Dao Men, and in the middle of the PRE. The $PW$ of the RT case has a structure similar to that of the WRT case, with a little difference (the value is almost zero) over the shelf (figures not shown here). For the WR case (Fig. 7c, d), $PW$ shows a totally different pattern from the cases with the tidal forcing: $PW$ is negative along the west sides of the estuaries when upwelling favorable wind is strong, but it is more than an order of magnitude smaller than that in the WRT and RT cases. This difference suggests that the tide-induced $PW$ plays a dominant role in the estuary regions, and the estuarine circulation gains kinetic energy from tide-induced $PW$ but loses energy to wind-induced $PW$. The volume-integrated $PW$ (Table 3) shows that it is a major forcing term (more than 10 times larger than the $WW$ term) for the WRT case, except during Period I over the shelf where $WW$ is larger than $PW$. This implies that $WW$ becomes more important over the shelf. The value of $PW$ decreases from Period I to Period
The amount of reduction is larger in the lower PRE and the shelf region (about 70%) than in the upper and middle PRE (about 50%) in the WRT and RT cases. The well-mixed plume in the upper estuary and the salt wedge structure at the entrance indicate that tide-induced $PW$ input mainly acts to mix the plume and enhance the potential energy (Fig. 5).

Wind stress does positive work in both estuary and shelf (Fig. 8) during period I, but it is close to zero during period II (Figures are not shown here). The $WW$ terms in the WR and WRT cases are similar, with a large value appears along the shallow coastal region and the plume region. It is relatively larger in the WR case than in the WRT case in both estuary and shelf regions (Table 3). This is probably because tide tends to decelerate the response of current to the wind by enhanced vertical mixing and reduced efficiency of the $WW$ term in the upper water column, thus inhibits the advection of the plume by wind-driven current. $WW$ is the major forcing term in the WR case, as it is about 5 times (10 times) larger than $PW$ in the PRE region (shelf region). $WW$ acts to advect and mix the plume by increasing both kinetic and potential energy.

Energy dissipation due to bottom friction, $D_{bot}$, is negative. In the WRT case, its distribution looks like that of $PW$, with the largest magnitude in the middle of the PRE (Fig. 9a, b). Like the $PW$ term, $D_{bot}$ in the RT case also shows a similar pattern and magnitude inside the estuary as the WRT case, and differs a little from the WRT case over the shelf (figures not shown). However, the magnitude of $D_{bot}$ inside the estuary in the WR case is more than two orders of magnitude smaller than that forced by tide, as tide is predominant for the bottom energy dissipation.

---

**Fig. 8.** Vertically-integrated wind stress work term (Wm$^{-2}$) of WRT (left) and WR (right) cases during Period I.

**Fig. 9.** Similar to Fig. 7, except for energy dissipation due to bottom friction, $D_{bot}$. 

---
in the estuary region. The distribution of interior dissipation by vertical shear of horizontal velocity, $D_{\text{int}}$, has a pattern similar to $D_{\text{bot}}$ (Fig. 10). Its magnitude is larger than $D_{\text{bot}}$ in the WR case, but is about 30–50% smaller than $D_{\text{bot}}$ in the WRT and RT cases during Period I, except for the shelf region in the WRT case, where it is notably increased and becomes larger than $D_{\text{bot}}$ when the wind forcing is considered (Table 3).
The strongest and positive buoyancy flux, BUOY, appears along the two channels in the middle and lower estuary in both WRT (Fig. 11a, b) and RT cases (figures are not shown), while large BUOY also appears in the plume region over the shelf in both WRT and WR cases (Fig. 11). The BUOY term in the WRT and RT cases is larger than that in the WR case inside the PRE, but smaller in the shelf region during period I (Table 3). It is greatly reduced during Period II, especially in the lower case inside the PRE, but smaller in the shelf region during period I

The mixing efficiency (BUOY/Dbot + Dint) (Figs. 12 and 13) increases from the upper PRE (about 1–5%) to the shelf region (about 10–40%) during period I, and interestingly it is enhanced during Period II when the physical forcing and related vertical mixing decrease. The mixing efficiency in the WR case is apparently larger than that in the WRT and RT cases. This implies that the plume in the upper and middle PRE could be mixed rather well with tide forcing, the structure of the plume to the change of wind- and tide-induced mixing gradually increase from the upper to the lower estuary and shelf, and from shallower coastal region to the deeper channels and off shore regions.

5. Discussion

The salt balance has been used to study the adjustment of estuarine circulation and stratification to the changes of river flow and tidal mixing by MacCready, (1999). His result shows that both stratified and well-mixed estuaries respond more rapidly to the change of forcing than the intermediate stratified ones, while intermediate estuaries are more sensitive to the change. Responses of the plume to the variation of wind and tide in different regions of the system could be further studied through the salt balance, as indicated by the mixing efficiency that the sensitivity of the plume to the mixing could vary significantly in space and time under different forcing.

The salinity equation is written as:

$$\frac{\partial s}{\partial t} + \nabla \cdot (us) = \frac{\partial}{\partial z} \left( \frac{K}{s_{adv}} \nabla^2 s \right) - \frac{\partial}{\partial z} \left( \frac{K}{s_{diff}} \nabla^2 s \right) . \tag{5.1}$$

in which s is salinity, u is velocity vectors (u, v, w), K is eddy diffusivity. It is clear from Fig. 14 that upper PRE is well-mixed and variation of the plume is dominated by the advection process, the plume is not sensitive to the change of vertical mixing. The $s_{adv}$ term becomes larger from upper PRE to the shelf, and $s_{diff}$ shows spring–neap variation in the deep channel of the lower PRE. However, advective-diffusive balance becomes dominant in the deep channel in the middle and lower PRE, thus the plume is not sensitive to the change of vertical mixing either. The domain averaged $s_{adv}$ is still dominant in the middle and lower PRE, because the estuary is shallow and well-mixed despite the two narrow deep channels. The variation of the plume is related to the estuarine circulation that is controlled by both the gravitational circulation and shelf upwelling intrusion (Zu and Gan, 2014). There are dramatic changes over the shelf, $s_{diff}$ shows the variation with the strength of upwelling favorable wind, and the plume is jointly controlled by the advection and diffusion processes.

6. Summary

A three-dimensional circulation model that resolves both the estuary and part of the shelf was used to simulate the sub-tidal responses of the plume to wind and tide forcing in the PRE and its

---

Table 3

<table>
<thead>
<tr>
<th>Energy term units: $10^6$ W</th>
<th>Period I</th>
<th>Period II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>U (1.7 km$^3$)</td>
<td>M (2.9 km$^3$)</td>
</tr>
<tr>
<td>WRT PW</td>
<td>55.8</td>
<td>225</td>
</tr>
<tr>
<td>WRT WW</td>
<td>40.0</td>
<td>7.5</td>
</tr>
<tr>
<td>WRT D$_{bot}$</td>
<td>-34.1</td>
<td>-130.2</td>
</tr>
<tr>
<td>WRT D$_{int}$</td>
<td>-18.8</td>
<td>-75.5</td>
</tr>
<tr>
<td>RT BUOY</td>
<td>0.3</td>
<td>3.5</td>
</tr>
<tr>
<td>RT WW</td>
<td>-0.8</td>
<td>-1.0</td>
</tr>
<tr>
<td>RT D$_{bot}$</td>
<td>5.1</td>
<td>7.6</td>
</tr>
<tr>
<td>RT D$_{int}$</td>
<td>-0.3</td>
<td>-0.6</td>
</tr>
<tr>
<td>RT BUOY</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>RT WW</td>
<td>57.8</td>
<td>232.8</td>
</tr>
<tr>
<td>RT D$_{bot}$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>RT D$_{int}$</td>
<td>-34.6</td>
<td>-131.6</td>
</tr>
<tr>
<td>RT BUOY</td>
<td>-16.9</td>
<td>-74.1</td>
</tr>
<tr>
<td>RT WW</td>
<td>0.4</td>
<td>4.2</td>
</tr>
</tbody>
</table>
adjacent shelf. The model shows moderate ability to reproduce the tide- and wind-induced sea surface elevation variation and the structure of the plume, when compared with the observation from the tide gauges and cruises. Mechanical energy analysis was carried out to evaluate the relative contributions from wind and tide to the mixing and structure of the plume. We expanded MacCready et al.’s (2009) study by including two more numerical experiments that are forced without either tide or wind, and dividing the PRE into “upper”, “middle” and “lower” parts, as the PRE is a bell-shaped and wide estuary.

Model results show the freshwater plume and associated mixing efficiency respond differently to the wind and tide forcing in different dynamical regions in the PRE. Specifically, wind is the dominant forcing of the plume over the shelf region, since it helps to spread and mix the plume through wind-driven coastal current. Tide plays a more important role in the estuary and shallower near-shore region, and mainly affects the vertical structure of the plume through enhanced mixing. The change of the near-shore plume structure by tide also influences its off-shore shape. Tidal mixing tends to trap more low-salinity water inside the estuary, while upwelling favorable wind tends to spread the low-salinity water seaward. The sensitivity of the plume to the change of the wind and tide forcing and related vertical mixing vary significantly in different times and regions in this system, as it is well-mixed in the shallower estuarine region, but stratified in the deeper channels and shelf. The two physical forcings act to increase the kinetic energy of the system through surface stress work and divergence of the pressure work. The appearance of maximum forcing and dissipation in the middle PRE and at the entrances of other smaller estuaries suggests that tidal mixing makes the middle PRE act like an estuarine entrance, where the transition of the river plume into a coastal buoyant current occurs.

Fig. 13. Vertically-integrated mixing efficiency of WRT (upper) and WR (lower) cases during Period I (left) and Period II (right).
This study also indicates that tidal mixing should not be disregarded even if we are interested only in the shelf process around this region, for the plume’s size and structure over the shelf are highly correlated with its near-shore structure that is determined by tide.

Acknowledgments

We are grateful for the two anonymous reviewers, who have provided many thoughtful comments and suggestions which led to great improvements of the manuscript. We also thank Zhiquiang Liu, Xiaopei Lin, Huijie Xue and Xiaohua Wang for their helpful discussions. The numerical simulation is supported by the high-performance computing division and Ms. Dandan Sui of the South China Sea Institute of Oceanology. This research work was jointly supported by the National Natural Science Foundation of China (41006012 and 91128204), the 973 program (2011CB403504), the Hong Kong’s Research Grant Council (GRF612412), the youth talent frontier field project of SCSIO, CAS (SQ201002), and the Guangzhou Municipal Science and Technology Project (12F084060027).

Appendix A. Mechanical energy equations

Following Weisberg and Zheng (2003), Zhong and Li (2006), and MacCready et al. (2009), we derive the energy equations from the momentum, incompressibility, and density equations:

\[ \frac{D\vec{U}}{Dt} = -f \times \vec{U} - \frac{1}{\rho_0} \nabla P + \nabla \cdot (K_M \nabla \vec{U}), \quad (A1) \]

\[ \nabla \cdot \vec{U} = 0. \quad (A2) \]

\[ \frac{D\rho}{Dt} = \nabla \cdot (K_M \nabla \rho). \quad (A3) \]

where \( \vec{U} \) is the horizontal velocity vector \((u, v)\). As the vertical velocity \(w\) makes little contribution to the kinetic energy, it is not included in the kinetic energy calculation here. \(D() / Dt = \partial() / \partial t + \vec{U} \cdot \nabla \) is the material derivative, \(f\) is the Coriolis parameter, \(P\) is pressure, \(\rho_0\) is constant background density \((1025 \text{ kg m}^{-3})\), and \(\rho\) is the full density. \(K_M\) is eddy viscosity (including both vertical and horizontal components). The equation of kinetic energy per unit volume, \(KE = (1/2)\rho_0 \vec{U}^2\) is obtained by taking \(\rho_0 \vec{U} \cdot (Eq. (A1)):\)

\[ \frac{DKE}{Dt} = -\nabla \cdot (\rho_0 K_M \nabla \vec{U}) + \nabla \cdot (\rho_0 K_M \nabla \vec{U}) - \frac{1}{\rho_0} \rho_0 K_M (\nabla \vec{U})^2. \quad (A4) \]

The equation of potential energy per unit volume, \(PE = \rho gz\), is obtained by taking \(gz\) (Eq. (A3)):

\[ \frac{DPE}{Dt} = \rho gw + \nabla \cdot (gK_D \nabla \rho) - gK_D \frac{\partial \rho}{\partial z}. \quad (A5) \]

Thus, the volume integral of the total mechanical energy \(TE = KE + PE\) could be obtained by combining the volume integrals of
where $V$ is the volume of a chosen geographical region, $S$ is the area of the lateral sides of the selected region, $A$ is the surface or bottom areas of this region, $\tau$ is stress, subscripts $s$ and $b$ denote surface and bottom, respectively, and $K_{sv}$ and $A_{sv}$ are the vertical and horizontal eddy viscosity coefficients, respectively.

The nine terms in (A6) are defined as follows.

1. is local change of the total mechanical energy, $dTE$;
2. is the flux of mechanical energy into the control volume by horizontal advection, \(advE\);
3. is the divergence of pressure work, \(PW\);
4. is the work done by sea surface wind stress, \(WW\);
5. is the energy dissipation due to bottom stress, \(Dbot\);
6. is the energy dissipation by vertical shears of the horizontal velocity that is integrated in the interior portion of the selected region (i.e., vertically from the first model velocity grid point above the bottom), \(Dint\);
7. is the buoyancy flux via vertical advection and diffusion, \(BUOY\);
8. is similar to (6), but is due to the horizontal shear of horizontal velocity; and
9. is the horizontal diffusive fluxes of $T$ into the selected column.

The buoyancy flux by vertical advection, $\rho gw$, converts between the kinetic and potential energy. When the full vertical momentum equation is used, $\rho gw$ would be canceled from $\mathrm{BUOY}$ term. Thus, in the discussion of the buoyancy flux, only the part caused by vertical diffusion is considered. The energy contribution from terms (8) and (9) is relatively small, if we combine them with the calculation errors into the residual term. $\Re$, Eq. (A6) could be rewritten as:

$$
\frac{\partial}{\partial t} T_{E} = -\text{advE} - PW + WW - Dbot - Dint + \text{BUOY} + \Re
$$

(A7)

References