A model study of the circulation in the Pearl River Estuary (PRE) and its adjacent coastal waters:

1. Simulations and comparison with observations


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The Princeton Ocean Model is used to study the circulation features in the Pearl River Estuary and their responses to tide, river discharge, wind, and heat flux in the winter dry and summer wet seasons. The model has an orthogonal curvilinear grid in the horizontal plane with variable spacing from 0.5 km in the estuary to 1 km on the shelf and 15 sigma levels in the vertical direction. The initial conditions and the subtidal open boundary forcing are obtained from an associated larger-scale model of the northern South China Sea. Buoyancy forcing uses the climatological monthly heat fluxes and river discharges, and both the climatological monthly wind and the realistic wind are used in the sensitivity experiments. The tidal forcing is represented by sinusoidal functions with the observed amplitudes and phases. In this paper, the simulated tide is first examined. The simulated seasonal distributions of the salinity, as well as the temporal variations of the salinity and velocity over a tidal cycle are described and then compared with the in situ survey data from July 1999 and January 2000. The model successfully reproduces the main hydrodynamic processes, such as the stratification, mixing, frontal dynamics, summer upwelling, two-layer gravitational circulation, etc., and the distributions of hydrodynamic parameters in the Pearl River Estuary and coastal waters for both the winter and the summer season.


1. Introduction

The Pearl River is the third largest river in China. The Pearl River Estuary (PRE), located in the north shelf of the South China Sea near Hong Kong, is a dynamically complex estuary. It has a trumpet-like water area with 8 river gates (inlets) on its west bank (see Figure 1). These gates are, respectively, Humen, Jiaomen, Hongqili, Hengmen, Modaomen, Jitimen, Hudaomen and Yamen. The discharge passing through Modaomen is the largest. The second largest discharge is through Humen. Together, the Pearl River discharge totals about 4000 m³ s⁻¹ (minimum) in the winter and about 20000 m³ s⁻¹ (maximum) in the summer. There are two deep channels in the estuary from the mouth up to the head of the estuary and many small islands in its coastal waters. In this region, a number of forcing mechanisms including bottom topography, freshwater discharge, wind, tide and coastal current, operate in concert to control the circulation and water properties. Bottom topography is a strong constraint on flow patterns in shallow coastal regions through vortex stretching and squashing. Freshwater outflow from the Pearl River sets up a strong density gradient and results in a westward flowing coastal current. The water is strongly stratified in the summer but partially mixed in the winter. This area experiences alternating monsoons every year, the northeasterly monsoon in the winter and the southwesterly monsoon in the summer. The monsoons have multiple effects. They drive the local circulation. Moreover, the large-scale wind patterns set up sea level gradients on the shelf, which in turn generate coastal currents. The PRE is a micro tidal estuary with small tidal amplitudes. M₂ and K₁ are the two dominant tidal constituents. The tidal range is about 0.8 ~ 0.9 m near the Wanshan Islands, about 0.9 m near Neilingding Island [Lin and Liang, 1996], and about 1.7 m near Humen [Zhao, 1990]. In such a complex estuary system, it is common that several different circulation regimes coexist and various types of fronts form between the circulation regimes such as the coastal temperature front and the river plume front in the estuary.
The PRE has been one of the most interesting places attracting study from oceanographers. Chinese scientists have studied a great deal about its basic hydrographic features. Many literatures discussed about the sea level patterns [Zhang, 1985; Wu and Xu, 1997] and numerical simulations of the tidal elevation and tidal current in the PRE [e.g., Wang et al., 1992; He, 1984, 1986; Lin and Liang, 1996; Zhang, 1985; Ye and Preiffer, 1990; Ye et al., 1986; Peng et al., 1991]. Tian [1994] and Ying [1983, 1986] described the salinity and temperature distributions. Dong et al. [1985] and Huang [1984] described the observed circulation. Zhao [1990] had a detailed and systematic discussion on the salinity, circulation, and tidal phenomena in the estuary. Previous studies mostly focused on individual dynamic processes separately and focused on the inside the estuary processes. The 3D circulation in the PRE with respect to the combined forcing of tide, wind, river discharge, the frontal gravitational circulation, and, in particular, the coastal current, has not been well understood. We have integrated a three-dimensional, primitive equation, estuarine and coastal ocean model forward in time to obtain a quasi-equilibrium winter and summer circulation for the PRE and the adjacent coastal waters. The main question is whether the model can reproduce the realistic responses of such a complex hydrodynamic system to the external forcing and represent its seasonal variations? In this part, the model results are verified against the in situ observations from two field investigations in July 1999 and January 2000 [Chen et al., 2000]. In addition, the seasonal characteristics of salinity and the tidal effect on salinity distributions are also examined.

2. Data

The Pearl River Estuary Pollution Project (PREPP) carried out two field investigations of the PRE and adjacent coastal waters [Chen et al., 2000]. Figure 2a shows the location of sample stations from the summer cruise between 17 July and 27 July 1999. Observed hydrodynamic parameters included water temperature, salinity, turbidity, and current. There were a total of 48 survey stations, 7 time series stations (C1 to C7) yielding a total of 55 sets of temperature and salinity and seven velocity time series. The investigation period coincided with the spring tide.

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Figure 1. Bathymetry of the PRE and the coastal region. Depth contours are in meters.
There were 8 cross sections (EL, ML, WL, and H1 to H5) and 6 time series stations (C1, C2, C3, C5, C9 and TPD) as shown in Figure 2b. Available observations included YSI temperature and salinity data from the 8 cross sections, ADCP current data from the cross sections EL and H2, and ADCP current data at the 6 time series stations.

3. Model

The Princeton Ocean Model (POM) [Mellor, 1998] used in this study has been widely applied to coastal oceans and estuaries [e.g., Oey et al., 1985a, 1985b, 1985c; Signell et al., 1994; Skogen et al., 1995, Xue et al., 2000]. This is a fully nonlinear, prognostic model incorporating the free surface and the Mellor and Yamada [1974, 1982] level 2.5 turbulence closure scheme for vertical mixing. Horizontal mixing coefficients are calculated using the Smagorinsky's [1963] nonlinear formula in which they are related to the scale of motion being resolved in the model and to the local deformation field. POM uses orthogonal curvilinear coordinates in the horizontal and a sigma coordinate transform in the vertical, which is scaled by the height of the water column. A staggered finite difference scheme is used in both the horizontal and the vertical. The implicit scheme used in the vertical eliminates time constraints for the vertical coordinate and permits the use of fine vertical resolution in the surface and bottom boundary layers. Although the surface elevation is a prognostic variable in the model, POM saves computational time by means of mode splitting such that the external mode is separated from the internal modes by vertically integrating the governing equations. The external mode provides the surface elevation and vertically integrated velocities to the internal mode, while the internal mode provides momentum and density gradient integrals and bottom stress to the external mode.

3.1. Model Configuration and Initialization

The POM was configured in a domain that includes the Huangmaohai Bay, PRE (also known as Lingdingyang Bay), coastal waters of Hong Kong, Mirs Bay and Daya Bay and the adjacent shelf region to about 60 m depth (Figure 1). The domain was approximately 150 km in the offshore direction and 200 km in the alongshore direction. The bottom topography was interpolated from a data set provided by the Second Institute of Oceanography, State Oceanic Administration, China.

An orthogonal curvilinear grid was designed to map the domain in 161 by 211 points (Figure 3a) with variable resolution from approximately 0.5 km /C2 0.5 km within the estuary and around Hong Kong to about 1 km /C2 1 km offshore. There were 15 sigma levels in the vertical with finer resolution near the surface and bottom. Following Xue et al. [2000], single-cell-width channels were added to represent the major distributaries of the Pearl River. Time steps used in this study were 3 seconds s for the external mode and 36 seconds s for the internal mode.

Initial values of the subtidal elevation, three-dimensional velocity, temperature and salinity were obtained from the associated, larger-scale North Shelf Model of the South China Sea (NSMSCS) (Figure 3b), which encompassed the northern shelf region of the SCS from 19°N to 24°N and from 111°E to 117.5°E. The NSMSCS had a resolution of about 1 km inside the estuary and 4 km on the shelf. In

Figure 2. Location of the survey and time series stations (a) for the summer cruise in July 1999 and (b) for the winter cruise in January 2000.

Figure 3. Nested grid of the Pearl River Estuary (PREM) model showing the numerical model for (a) the PRE and (b) the North Shelf Model of the South China Sea (NSMSCS).
Table 1. Monthly Averaged River Discharge Ratio in the Summer Wet Season and in the Winter Dry Season

<table>
<thead>
<tr>
<th>River Discharge Rate, m$^3$ s$^{-1}$</th>
<th>Humen</th>
<th>Jiaomen</th>
<th>Hongqili</th>
<th>Hengmen</th>
<th>Modaomen</th>
<th>Jitimen</th>
<th>Hudaomen and Yamen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>3399</td>
<td>3558</td>
<td>1393</td>
<td>2444</td>
<td>5522</td>
<td>1425</td>
<td>2335</td>
</tr>
<tr>
<td>Summer</td>
<td>796</td>
<td>557</td>
<td>152</td>
<td>366</td>
<td>777</td>
<td>163</td>
<td>577</td>
</tr>
</tbody>
</table>

general, the influence of initial conditions weakens gradually as time advances and, eventually, effects of the surface and lateral forcing dominate in the model solutions.

3.2. Surface Condition

[10] In this region, northeasterly winds dominate during winter and southwesterly winds during summer. For the initial diagnostic calculation, the surface forcing was given by climatological, monthly averaged winds, 6.5 m s$^{-1}$, direction $70^\circ$ for the winter, 3 m s$^{-1}$, direction $230^\circ$ for the summer. In the verification experiments, the climatological winds in the diagnostic calculation were replaced by the observed wind time series from the Waglan Island Station provided by the Hong Kong Observatory.

[11] Net heat fluxes in the winter and in the summer were given by $Q = Q_{0w} - 40 \delta T(t, x, y)$ and $Q = Q_{0s} - 80 \delta T(t, x, y)$, respectively. Here $Q_{0w} = -200$ W m$^{-2}$ and $Q_{0s} = 105$ W m$^{-2}$ are the statistical means of the observed heat fluxes for the study area. $\delta T(t, x, y, 0) = T_{surf}(t, x, y, 0) - T_{mean}$ was introduced as an adjusting factor from the coastal water to the estuarine water; $T_{surf}$ denotes the calculated surface temperature and $T_{mean}$ denotes the mean temperature of the study area. During the winter, the ocean releases heat to the atmosphere, and the net upward heat flux increases from nearshore to the open ocean.

3.3. Lateral Boundary Condition

[12] The PRE model domain has three open boundaries as shown in Figure 3a. The wintertime westward coastal current entering from the eastern boundary can influence the circulation in the coastal waters surrounding Hong Kong and inside the PRE. The eastern boundary hence represents the most critical upstream condition to the simulation. On the other hand, diluted waters from the estuary exit mostly across the western boundary where the transport needs to be monitored to ensure proper mass balance in the model.

[13] The PRE model is embedded in the NSMSCS such that the NSMSCS affects the PRE and the adjacent coastal region by providing boundary conditions, but there is no mechanism by which the evolution in the PRE model can feed back to the NSMSCS. Such a procedure is called passive nesting, and the flow relaxation scheme of Martin sen and Engedahl [1987] has been successfully applied [e.g., Oey and Chen, 1992, Xue et al., 2000]. Following boundary conditions combining the gravity radiation condition with the flow relaxation scheme resulted in satisfactory simulations for the present study. A gravity wave radiation condition was applied to the velocity component perpendicular to open boundaries. An upwind advection scheme was applied to temperature, salinity, and the velocity component parallel to the boundary so that in case of inflow the boundary conditions derived from the NSMSCS were imported by the inward velocities.

[14] When the tidal forcing was added in the numerical experiments, simple cosine functions with specified frequencies, amplitudes, and phases were linearly superimposed on the tidal averaged elevation predicted by the NSMSCS along the open boundary. Four tidal constituents, namely, $M_2$, $S_2$, $K_1$ and $O_1$ with frequencies of $1.4052 \times 10^{-5}$ rad s$^{-1}$, $1.4544 \times 10^{-4}$ rad s$^{-1}$, $7.2921 \times 10^{-5}$ rad s$^{-1}$, and $6.7598 \times 10^{-5}$ rad s$^{-1}$ were included in the calculation. The original amplitudes and phases were obtained by optimal interpolation of the global tidal charts of [Schiwiderski, 1980, L. H. Kantha et al., Tides in marginal, semi-enclosed and coastal seas. part I: Sea surface height, http://www.cast.msstate.edu/Tides2D, 1994]. It was, however, necessary to make some adjustments to these amplitudes and phases in order to minimize the misfits between the modeled and the observed tides at tidal stations inside the PRE and coastal waters.

[15] Zhao [1990] listed the monthly averaged discharge from the Pearl River and the proportional contributions from the 8 inlets. River outflow exerts profound influence on estuarine dynamics. However, the model had a resolution about 0.5 km nearshore, which was not aimed at resolving dynamic processes in rivers. Thus a special treatment was needed to parameterize physical variables near the river mouth. Single-cell-width channels were added to the model (see Figure 3) to approximate the major distributaries of the Pearl River. Outflows were specified at the head of the rivers with the transport equal to the seasonal discharge rates listed in Table 1. The discharged water was assumed to have an initial salinity of 7 ppt, which gradually reduced to 2 ppt in one day.

3.4. Numerical Experiments

[16] Two schemes of model spin-up were used in the present study. The first scheme was used to calibrate the modeled tide, in which the water density remains unchanged. A steady tidal harmonic solution was obtained after integrating the model for 10 days. The output data after day 15 was used to illustrate the tidal behaviors in the PRE.

[17] The second spin up scheme was used for the rest of the experiments in which the water density changes with time and space. The model is still run forward in time with the forcing gradually ramping up to the prescribed climatological values. The domain-wide integrated kinetic energy increased by 79% from day 0 to the end of day 5, and by another 14% by the end of the 10th day. It, however, varied by only 0.15% per day from the end of the 10th day to the 60th day. The tidal residual solution was archived, including the surface elevation, temperature, salinity and currents. The small amount of the salinity change from the 30th day to the 60th day suggested that the subtidal circulation had reached an equilibrium state. Model results after the 60th day for all baroclinic experiments were thus analyzed to illustrate the simulated salinity and temperature fields, the plume front, and the circulations in the PRE.

[18] In particular, this scheme was also used in the verification experiments driven by the multifactors includ-
4. Results and Verification

4.1. Tide

Table 2. Comparison of Simulated and Observed Values of M2 Tides at Tidal Observation Station

<table>
<thead>
<tr>
<th>Stations</th>
<th>AMP (Observ)</th>
<th>PHS (Observ)</th>
<th>AMP (Model)</th>
<th>PHS (Model)</th>
<th>DAMP</th>
<th>DPHS</th>
</tr>
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<tbody>
<tr>
<td>1. Da Hengquin</td>
<td>38</td>
<td>287</td>
<td>33.38</td>
<td>285</td>
<td>4.62</td>
<td>2</td>
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<tr>
<td>2. Da Wanshan</td>
<td>40</td>
<td>271</td>
<td>34.3</td>
<td>279</td>
<td>5.7</td>
<td>8</td>
</tr>
<tr>
<td>3. 7070 Macau</td>
<td>47</td>
<td>289</td>
<td>46.84</td>
<td>306</td>
<td>0.16</td>
<td>7</td>
</tr>
<tr>
<td>4. 7071 Zhuhai</td>
<td>53</td>
<td>302</td>
<td>55.16</td>
<td>314</td>
<td>2.16</td>
<td>12</td>
</tr>
<tr>
<td>5. Nei Ling Ding</td>
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<td>298</td>
<td>57.42</td>
<td>312</td>
<td>3.58</td>
<td>14</td>
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<tr>
<td>6. 7073 Chi Wan</td>
<td>50</td>
<td>298</td>
<td>52.89</td>
<td>305</td>
<td>2.89</td>
<td>7</td>
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<tr>
<td>7. 7086 Wai Ling Ding</td>
<td>45</td>
<td>292</td>
<td>47.94</td>
<td>299</td>
<td>2.94</td>
<td>7</td>
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<tr>
<td>8. 7087 Wen Wenzhou</td>
<td>30</td>
<td>275</td>
<td>33.23</td>
<td>278</td>
<td>3.23</td>
<td>3</td>
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<td>46.73</td>
<td>294</td>
<td>1.73</td>
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<td>10. 7093 Tap Shek Kok</td>
<td>64</td>
<td>343</td>
<td>67.93</td>
<td>330</td>
<td>3.93</td>
<td>12</td>
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<td>11. 7094 Tsing Shan Wan</td>
<td>48</td>
<td>287</td>
<td>48.31</td>
<td>299</td>
<td>0.31</td>
<td>12</td>
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<tr>
<td>12. San Banzhou</td>
<td>61</td>
<td>323</td>
<td>58.85</td>
<td>311</td>
<td>2.15</td>
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<td>13. 7094a Tai Lam Kok</td>
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<td>13</td>
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<td>14. 7096a Chek Lap Kok</td>
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<td>38.18</td>
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<td>16. 7097 Tai O</td>
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<td>267</td>
<td>37.61</td>
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<td>17</td>
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<td>38.56</td>
<td>280</td>
<td>1.44</td>
<td>12</td>
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<td>297</td>
<td>39.95</td>
<td>283</td>
<td>0.95</td>
<td>14</td>
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<td>23. 7122 Waglan Island</td>
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<td>268</td>
<td>33.8</td>
<td>275</td>
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<td>7</td>
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<tr>
<td>24. 7129 Pak Chau O</td>
<td>39</td>
<td>256</td>
<td>34.42</td>
<td>273</td>
<td>4.58</td>
<td>17</td>
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<td>25. 7132 Tai Po</td>
<td>37</td>
<td>269</td>
<td>36.74</td>
<td>274</td>
<td>0.26</td>
<td>5</td>
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<td>26. 7133 Yan Chu Tong</td>
<td>39</td>
<td>258</td>
<td>34.51</td>
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<td>27. 7135 Ping Chau</td>
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<td>28. 7137 Tuong Nging-lie dao</td>
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<td>31.51</td>
<td>271</td>
<td>1.51</td>
<td>11</td>
</tr>
</tbody>
</table>

*The M2 amplitude (AMP) in centimeters and phase (PHS) in degrees from the observation data and as calculated by the model. The last two columns are their differences (D).

The semidiurnal lunar tide, M2, is the predominant tidal constituent in the PRE and nearby coastal waters [Zhao, 1990]. The second largest tidal constituent is K1. Table 2 compares the modeled amplitude and phase with tidal constants derived from the historical data at a total of 28 tidal stations within the study area (see Figure 4 for the locations). The RMS of relative errors of the tidal amplitude is about 7.0% and the absolute mean error of the tidal phase is about 7 degrees for M2 and 3 degrees for K1.

Figures 5a and 5b show the corange and cotidal charts of the modeled M2 and K1. The amplitude of M2 is about 25 cm near the open boundary. It increases gradually from the outside to the inside of the estuary, reaching 60 cm near the head of the estuary. The amplitude of K1 increases slowly from the eastern coastal area to the inside of the estuary. In the coastal region, M2 and K1 have similar amplitude, whereas in the PRE the amplitude of K1 is about one half of that of M2.

The cotidal lines of M2 in the PRE run from southwest to northeast (Figure 5a) suggesting that M2 propagates from southeast to northwest in the estuary. The difference in phase for M2 is about 60° from Dagan Islands to the head of the PRE. The propagating feature for K1 is similar to that for M2. However, the difference in phase for K1 is only about 10° from Mirs Bay to the head of the PRE. The modeled corange and cotidal charts agree well with the observed results of Zhao [1990].

Figures 5c and 5d show the vertically averaged tidal ellipses for M2 and K1. In the PRE, tidal currents are mainly rectilinear, and the major axis of the tide ellipses is basically parallel to the main axis of the estuary. However, in the coastal region tidal currents are mostly rotational. The magnitude of the tidal currents for M2 is much larger in the PRE than that in the coastal waters. Vertically averaged currents associated with M2 and K1 have similar magnitude in the PRE, while the former is about twice the latter in the coastal waters.

4.2. Salinity and Temperature

In winter, the Pearl River discharge is small, so that both the Coriolis force and the tide play important roles in determining the estuarine dynamics. Since all the inlets are located on the west bank of the PRE and the Coriolis force
also steers the fresh water toward the western side of the estuary, an apparent plume front can be found to extend from the surface to the bottom along the main axis of the estuary, which separates the diluted water on the western side from the shelf water on the eastern side of the estuary (Figures 6a and 6b). The surface shelf water with high salinity intrudes into the estuary along the eastern side. Near the bottom, freshwater is limited to the western side near the head of the estuary for more shelf water is driven into the estuary at lower levels. In particular, the shelf water can reach the head of the estuary along the bottom in the two deep channels (Figure 6b). The shelf water with high salinity occupies the coastal area east of Lantau Island. Salinity contours are smooth in the coastal waters and in

**Figure 4.** Location of the tidal stations.

**Figure 5.** (top) Corange and cotidal chart of the (a) M2 and (b) K1; (bottom) tidal current chart of (c) M2 and (d) K1.
most areas of the estuary, where the bottom bathymetry and the coastline are relatively smooth. The similarity between the modeled salinity (Figures 7a and 7b) and the observed salinity (Figures 6a and 6b) indicates that the model can successfully reproduce the frontal zone associated with the river plume. This is very important to further understand the 3D patterns of the plume frontal zone and the mechanisms controlling the plume front [see Wong et al., 2003].

[25] The sensitivity analysis shows that the prevailing northeasterly monsoon during winter can increase the intrusion of the surface shelf water and the downward vertical mixing between the surface water and the subsurface water. Furthermore, northeasterly winds can also reduce the width of the surface plume frontal zone.

[26] In the summer, dynamic features of the surface river plume are different from those in the winter because of the combined effects of larger freshwater discharges and the southwesterly monsoon. The surface diluted river water occupies almost the entire PRE (Figure 6c). It can spread southeastward and reach Mirs Bay under the influence of the southwesterly monsoon (Figure 6c). However, near the bottom the plume is restricted to the inside of the estuary because of the intruding shelf water at depth (Figure 6d). The near bottom salinity front during the summer is similar to that during the winter. This means that the gravitational circulation associated with the plume front plays a dominant role in controlling subsurface front in the estuary in both the summer and the winter. At the surface, however, the frontal zone is considerably modulated by the monsoons. Again, the modeled summertime salinity field (Figures 7c and 7d) agrees well with the observations obtained during the PREPP summer cruise.

[27] Figure 8 compares the observed and the simulated salinity/temperature profiles at survey stations of the 1999 summer cruise. The top panels show the stations along the main axis of the estuary, and the lower panels show the
stations around Hong Kong. The simulated profiles appear to agree well with the observed ones. In the coastal waters, an obvious halocline exists at about the 5 m depth level at station 26 (Figure 8e). There is also a thermocline at a similar water depth (Figure 8j). In the estuary, both a similar halocline and thermocline can also be found at about 4 m depth at station 55 (Figures 8o and 8t). The agreement between the observations and the simulated results seems better in the coastal waters than inside the estuary, and the maximum error occurs at those stations near the head of the estuary. This is most likely due to the use of climatological discharge rates in the model. Another factor might be the horizontal resolution in the model (500 m), which may distort the morphology to a greater extent near the head of the estuary where there are smaller-scale topographic features. The strength of the simulated halocline is a bit weaker than the observed halocline in the coastal region where the water column is relatively deep. This may be because the vertical resolution in the model (15 sigma layers) is coarser than that in the observation (about 1 m).

[29] The PRE is basically a stratified estuary. In particular, the typical two-layer estuarine structure can extend to its coastal waters during the summer (wet) season when the river discharge is large and the wind is mostly from the south and southwest. However, the coastal region can be well mixed during the winter when the river discharge diminishes and the northeasterly winds hold the surface diluted water in the bay. The stratification strength varies greatly from season to season. Figures 9a and 9b (9c and 9d) compare the observed and the simulated salinity (temperature) along section L (a section connecting the stations along the main axis of the estuary in Figure 2a) during the summer wet season. Figures 9e and 9f show the comparison between the observed and the simulated salinity along the section ML (Figure 2b) in the winter. The corresponding temperature comparison is not shown since the temperature is almost homogeneous in the winter. Instead, Figures 9g and 9h show the comparison of the observed and the simulated winter salinity at a transversal cross section (H3) in the estuary. The model clearly reproduces the vertical distributions of the temperature and salinity along both the main axis of the estuary and the transversal section.

[29] It is clear that during the summer both salinity and temperature are strongly stratified, and the salinity gradient is a bit stronger than that of the temperature (Figures 9a, 9b, 9c, and 9d). During the winter, the stratified area becomes smaller, limited to the upper western side of the estuary near the freshwater sources (Figures 9e and 9f). In this stratified zone, the gradient is strongest in the middle part of the water column (Figures 9e and 9f) most likely because of the effects of wind mixing near the surface and the tidal mixing near the bottom. The sloping isohaline (upward toward the sea) along the main axis of the estuary suggests the presence of a two-layer gravitational circulation driven by the density gradient in the stratified zone regardless of season. The surface flow of the gravitational circulation is seaward but the bottom flow is toward the head of the estuary. Figure 9g indicates that during the winter the stratified zone is within the plume on the western side of the estuary, and the water is almost homogeneous on the eastern side. Therefore the plume has apparent 3D characteristics in the PRE and it is asymmetric with respect to the main axis of the estuary.

[30] Satellite SST images often show that an upwelling zone exists along the coast east of the Lantau Island (Figure 10a) during the prevailing southwesterly wind in the summer, and that there is a sharp thermal frontal zone on the shelf parallel to the coast during the winter (Figure 10b). Both the coastal upwelling in the summer and the midshelf temperature front in the winter are reproduced in the present model (Figures 10c and 10d).

[31] Figure 11 compares the observed and the simulated time series of the temperature and salinity at the time series stations. C1 and C2 represent the stations in the summer...
survey and C9 and TPD represent the stations in the winter survey. All these 4 stations are located in the PRE. The simulated salinity agrees reasonably with the observations at the surface, middle, and bottom layer and the agreement is in both winter and summer.

The largest absolute error for the hindcast of salinity is 4 in the summer and the Root Mean Square (RMS) of the relative error for a total of 1995 samples is ~24%. For the hindcast of salinity in the winter, the RMS of the relative error for a total of 3410 samples is about 15%. The largest absolute error for the hindcast of summer temperature is 2°C and the RMS of the relative error is 4%. The largest absolute error for the hindcast of winter temperature is about 3°C and the RMS of the relative error is about 13%. The relative error

Figure 8. Comparison of the observed and simulated profiles of salinity/temperature at stations from the survey in July 1999: (a)–(j) salinity and (k)–(t) temperature. The number in each panel denotes the station number.
for salinity seems larger in the summer mainly since the error associated with using the climatological discharge is larger when the discharges rates are higher and the discharges have stronger variability. On the other hand, the relative error for temperature seems larger in the winter mainly because the error associated with using the climatological heat flux is larger when the variability of the net downward heat flux increases in the winter.

4.3. Currents

[33] Under the combined effects of tide, runoff, wind, heat flux and the coastal current, the velocity field inside the estuary is rather complicated. In general, the ebb flow predominates with stronger speed or longer duration throughout the estuary. On the western side of the estuary, the flood duration is much shorter than the ebb duration. During the high runoff period in summer, the ebb current can reach 2 m s\(^{-1}\) at the surface and the flood duration is only 3 hours. This means that both the tide and the runoff play important roles in controlling the circulation inside of the PRE. On the other hand, tide plays a minor role in coastal waters where the flow is primarily driven by the monsoon winds.

[34] Figures 12a–12h (12i–12p) show the modeled surface and near-bottom velocity field at four different tidal phases during the spring tide in the summer (winter). It is cautioned that the bottom velocity pattern is for that at the lowest sigma layer (shallower inside the estuary but deeper in the coastal waters). It is clear that 1) both the surface and near bottom currents are stronger inside the PRE than those in the coastal waters for both seasons; 2) the ebb currents are considerably stronger than the flood currents, especially for the summer case (Figures 12c and 12g), because of the river’s outflow being in the same direction as the ebb currents; 3) the maximum ebb current reaches \(24\) m s\(^{-1}\) at the surface (summer case) while the maximum near-bottom flood current is only about 0.2 m s\(^{-1}\). This large difference between the surface and bottom velocity implies that the vertical shear of the horizontal velocity is rather significant, especially inside the estuary. Generally, the vertical shear is weaker during the flood tide. The above discussion indicates that the tidal components (\(M_2\) and \(K_1\)) play an important role in the temporal variation of the current field within the PRE (Figure 12), especially for the winter case.

[35] In winter, currents are obviously stronger near the plume front during both ebb and flood, indicating the presence of a gravitational circulation associated with the front. The RMS of relative errors of the current magnitude is about 15% for a total of 13,825 samples at the two cross sections.
Figure 10. Comparison of the (a)–(b) satellite-derived and (c)–(d) modeled SST for the (left) summer and (right) winter. The modeled SST is output from NSMCS.

Figure 11. Comparison of the observed and the simulated salinity/temperature time series. (a) Temperature and (b) salinity and (c) temperature and (d) salinity are stations from the summer cruise in July 1999; (e) T and (f) S and (g) T and (h) S are stations from the winter cruise in January 2000.
Figure 12. Temporal variations of the surface and bottom currents over a $M_2$ tide cycle (a)–(h) in the summer and (i)–(p) in the winter. Time interval: 3 hour. Plot grid interval: 8 grids $\times$ 8 grids.
Figure 12. (continued)
sections, EL (Figure 13) and H2. The errors of the current direction are less than 60° in about 88% of the samples.

The observed data from nine time series stations (3 during the summer survey and 6 during the winter survey) with 245,515 samples are available for comparison with the model results. Shown in Figure 14 are the time series at TPD from the winter survey and the time series at C3 from the summer survey. The RMS of relative errors of the magnitude is also about 15%. The errors of the current direction are less than 60° in about 88% of the samples. Larger errors often occur in places where the current begins to change its direction. Finally, the model results appear to better match the observations for the winter simulation than those for the summer. In the winter, the river outflow plays a less important role in controlling the temporal variation of the velocity field and its influence on the tidal currents is less pronounced because of the small freshwater discharge. However, in the summer the river discharge becomes much larger and thus so is the error generated by using the climatological monthly river discharge. Observed winds from the Waglan Island have been used in several sensitivity experiments, which, however, appears to have little effects on the overall RMSE. The reason is probably that in an area with complex morphology such as the PRE, the wind record from Waglan cannot represent the rich spatial variability in the realistic wind field.

5. Discussion

Although the tidal amplitude is small in the PRE, tidal mixing plays a significant role in affecting the stratification, especially during the spring tide in the winter. Figure 15 shows the variation of the hydrodynamic parameters at a point near the Neilingding Island during winter from a neap tide to a spring tide. The maximum vertical difference of the salinity (about 16 ppt) and consequently the maximum stratification occur at the end of the neap ebb tide (Figure 15c). Minimum salinity difference (<1 ppt) and minimum stratification occur at the end of the spring flood. This implies that stratification is enhanced during the ebb portion of the tidal cycle. The surface salinity varies by almost 10 ppt over the course of a tidal cycle, while the bottom salinity remains nearly constant (~25 ppt) throughout the tidal cycle during the neap and midtide. As the tidal force increases and the tidally induced mixing becomes stronger, the upper layer water with low salinity is mixed downward and the deep layer water with high salinity is mixed upward so that the salinity near the bottom gradually reduces while the salinity at the surface increases. The stratification formed during the neap tide is eroded during the spring tide. The variation of the mixing strength with time can be found by examining the turbulence coefficient time series (Figure 15d). From the neap to midtide, $k_h$ is less than $10 \text{ cm}^2 \text{s}^{-1}$ and the water column is strongly stratified. The maximum value of $k_h$ can reach about $220 \text{ cm}^2 \text{s}^{-1}$ during the spring tide, and the water column becomes relatively well mixed.

In summer, the salinity is stratified even during the spring tide (Figure 15f). However, the stratification weakens as the tidal force strengthens. The maximum salinity gradient is about 5 ppt m$^{-1}$, which appears during the neap and midtide. The minimum salinity gradient, about 1 ppt m$^{-1}$, occurs at the end of the spring flood tide. During the spring tide, the salinity varies over a tidal cycle by about 5 ppt near the surface, about 10 ppt at 3 m, and about 10~12 ppt near the bottom. During the neap tide, the salinity variation over a tidal cycle is larger at middepths, but still less than 5 at all depths.

6. Summary and Conclusions

The 3D POM was used to simulate the circulation and the hydrodynamics of the PRE and the adjacent coastal waters. The model results were verified with the observations from the PREPP field survey in July 1999 and January 2000. Furthermore, the seasonal variation of the salinity and the tidal dynamics of the PRE as well as the tidal effect on the salinity distribution in the PRE were also examined.

The PRE model can successfully reproduce the main hydrodynamic features, and the seasonality that occurs in the PRE and its coastal waters. These physical characteristics include tidal dynamics, stratification and mixing, the winter river plume and the associated frontal zone, the summer river plume and coastal upwelling. In summary, the RMS of relative errors of the tidal amplitude is about 7.0% and the absolute mean error of the tidal phase is about 7 degrees for $M_2$ and 3 degrees for $K_1$; the RMS of relative errors of the current speed is about 15% and the absolute errors of the current direction are less than 60 degrees for about 90% of the samples; the RMS of relative errors of the water temperature is about 4% in summer and about 13% in winter; the RMS of relative errors of the salinity is about 24% in summer and 15% in winter. The temperature
hindcast is better in summer than in winter because the variability of the heat flux, which is lacking in the present model that uses the climatological heat flux, is larger in the winter. In contrary, the salinity hindcast is better in winter than in summer because the variability of the discharge, which is also lacking in the present model, becomes larger in the summer.

Furthermore, both the observations and the modeled results show that the PRE is a stratified estuary. In particular, the stratification is intensified during the summer, and

Figure 14. Comparison of the observed and the simulated time series of horizontal currents at different depths: (a)–(h) the winter case; (i)–(p) summer case; (left) E-W components of the velocity; and (right) N-S component of the velocity.
Figure 15. Temporal variation of the tidal elevation, N-S velocity component, salinity, and turbulence coefficient ($k_h$) (near the Neilingding Island) over tidal cycle: (a)–(d) the winter case (from neap to spring) and (e)–(f) the summer case (from spring to neap). TMC-Turbulence Mixing Coefficient.
it can extend into the coastal waters outside of the estuary because of the larger river discharge and the southwesterly monsoon wind. Although the tidal amplitude is small in the PRE, the tidal mixing plays a significant role in affecting the salinity distribution, especially during the spring tide in the winter. In winter, stratification is relatively strong during the neap tide when the surface-to-bottom salinity difference varies from 10 ppt to 15 ppt over the course of a tidal cycle. However, during the spring tide the stratification occurred during the neap tide is eroded and the salinity difference from the surface to the bottom is less than 2 ppt over a tidal cycle.

[42] In addition, the Pearl River outflow forms a plume and an associated frontal zone in the study area. In the winter, this frontal zone is inside the estuary from the surface to the bottom. In the summer, however, the subsurface front remains inside of the PRE, while the surface front moves out of the estuary because of the excessive freshwater discharge and the southwesterly wind. This means that the frontal dynamics plays a dominant role in controlling the subsurface hydrodynamics while at the surface wind-driven effects cannot be ignored. The vertical distribution of the isohaline along the main axis of the estuary indicates a two-layer gravitational circulation associated with the plume frontal zone. On the other hand, the isohaline distribution along the section transversal to the estuary shows that the stratified region is confined within the plume on the western side of the estuary, but the water column is almost homogeneous on the eastern side of the estuary. This implies that the dynamic features in the winter are asymmetry with respect to the main axis of the PRE and the estuarine dynamics have apparent 3D characteristics.

[43] Discussions above indicate that the PRE model can reasonably reproduce the spatial and temporal variations of the important dynamic features in the PRE. This is essential to the examinations of the stratification, upwelling, and frontal processes to be addressed by Wong et al. [2003]. Furthermore, the validated model can become a useful tool for model studies of how dynamical processes affect the distributions of the dissolved oxygen as well as nutrients in the PRE.

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