Circulation and transport in the Pearl River Estuary and adjacent shelf:
observational and modeling studies

by

SUN Ran

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This is to certify that I have examined the above MPhil thesis and have found that it is complete and satisfactory in all respects, and that any and all revisions required by the thesis examination committee have been made.

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Abstract

Circulation, hydrographic features and associated transports in the Pearl River Estuary (PRE) as well as over the adjacent shelf are controlled by multi-forcing of the river discharge, tides, and winds. Data from in situ measurements and from a validated three-dimensional, high resolution numerical model have been utilized to investigate the sub-tidal and intra-tidal hydrodynamics in the PRE and the estuary-shelf interaction in different seasons. Our observation results indicate that in summer, freshwater from Pearl River covers the entire estuary in the surface and upper estuary in the bottom. The river plume is formed after the freshwater spreads to eastern part of the shelf by the southwesterly wind-driven coastal current. In winter, discharge from a relative small runoff from the river flows along the west bank of the estuary under Coriolis effect and northeasterly wind forcing. Tidally-driven currents dominate axial circulation in the estuary and greatly modify the transports between the estuary and adjacent shelf. It is found that flood current starts from the bottom at the eastern side of estuary while the ebb current exists at the western side. The strongest stratification occurs in the lower estuary where the river water encounters sea water and the tidal straining effect intensifies during the ebb tides when tidal mixing is relatively weak.

Both the model and observation show that the circulation in the PRE is a salt-wedge estuary with a typical two-layer estuarine circulation in summer, and a partially mixed estuary in winter, as a result of seasonal variation of the river discharge. Our analyses based on the process-oriented modeling study show that the heat transport between the estuary and adjacent shelf is mainly determined by the volume transport due to small cross-shore temperature gradient, while the salt flux is controlled by both the transport and the cross-shore salinity gradient. Tidal prism varies considerably, due to highly variable ratio of river discharge to tidal volume, which affects strongly the exchanges between the estuary and the adjacent shelf, especially in winter. It is shown that there is an obvious spring-neap variation in the volume, heat and salt transports between the estuary and shelf. The stronger transports occur during neaps. Numerical sensitivity studies indicate that the river discharge plays an important role in controlling the net volume and heat transports between the estuary and the shelf, while the tidal forcing has the largest effect on salt transport in both summer and winter. Monsoonal wind forcing modulates the shelf circulation and affects the seasonal transports between the estuary and shelf as a result of the interaction between the estuarine and shelf dynamic regime.
CHAPTER 1 INTRODUCTION

1.1 Hydrodynamics in the Pearl River Estuary (PRE) and adjacent shelf

1.1.1 Physics of estuary and estuarine circulation

An estuary is a semi-enclosed coastal body of water which has free connection to the open sea and links to a river upstream as far as the limit of tidal influence. The sea water is measurably diluted with fresh water derived from land drainage [1].

Physically, estuaries form a transition zone between river, land and ocean, where fresh water from land meets and mixes with salt water from the ocean, and are subject to both oceanic and coastal physical processes, such as river plume, coastal currents, winds and tidal effects, which is shown schematically in Figure 1.1. Both fresh water and seawater are important factors that influence the circulation and thermohaline distribution in and outside the estuary.

Estuarine circulation was first introduced by Pliny the Elder (1st century A.D). He found that flow varied vertically in estuaries from fishermen's nets and provided the first written documentation. Pritchard [2] linked estuarine circulation to forcing arising from the horizontal density gradient between freshwater and seawater. He also pointed out that tidal currents were much stronger than residual currents in the circulation. Estuarine circulation varied and may be controlled by the inflow of rivers, tides, precipitation and evaporation, winds, and other oceanic events in the adjacent coastal waters such as upwelling, eddy, storms etc.

Hansen and Rattray [3] suggested that the estuarine residual circulation obtained by tidal averaging was a gravitational flow forced by horizontal salinity gradient. It can be dynamically expressed in a steady state as

$$\frac{1}{\rho_0} \frac{\partial p}{\partial x} + \frac{\partial}{\partial z} \left[ A_z \frac{\partial u}{\partial z} \right] = 0$$

(1.1)

where $u$, $p$, $\rho_0$ and $A_z$ are the horizontal velocity, pressure, mean density, and vertical eddy viscosity coefficient, respectively, and the overbar denotes a tidal average. Equation (1.1) states that water pressure gradient force that drives the gravitational circulation is balanced by vertical mixing. The intensity of estuarine circulation can affect residence time and exposure time of waters in the estuary.
Studying the estuarine circulation is not only important for understanding the estuary itself, but also essential to study the estuary-ocean exchange, as the estuary and adjacent shelf are dynamically coupled by the river plume and oceanic processes. Estuarine circulation also determines the heat and salt transports between the estuary and shelf.

1.1.2 Circulation in PRE and adjacent shelf

The Pearl River Estuary (PRE) is a bell-shaped semi-enclosed sea located along the south coast of mainland China at 113.5°~ 114.1°E and 22°~ 22.8°N. The coast has a NE–SW orientation and the adjacent shelf is 150–250 km wide (Figure 1.2). It is a subtropical estuary with an annual rainfall from 1,600 to 2,300 mm [4]. The topography of the PRE has mixed features of channels, shoals and tidal flats. Water depth in the estuary varies from 2 to 5 m over the western side to ~15 m over the eastern side. Most of the PRE is quite shallow and the average depth is about 4.8 m. There are two longitudinal deep channels along the PRE. The east channel with a water depth of about 10 m passes around the northeast tip of Lantau Island connects to the shelf via East Lamma Channel. The other west channel runs down the PRE and connects to Lantau Channel, which is shallower. The area of the PRE is about 1900 km². All these geometric and topographic features greatly modulate the circulation and salt and heat transport in both the estuary and the adjacent shelf.

The Pearl River is the third largest river in China with a total drainage area of 4.5×10⁵ km². The river discharge is ~4,000 m³/s in winter and peaks with ~20,000 m³/s in summer. The annual average discharge is ~10,000 m³/s [5].

Circulations in the PRE and coastal shelf have following general features based on the previous studies [1, 6, 7]. In summer, the circulation exhibited a two-layer pattern with seaward currents in the upper layer and landward currents in the bottom layer due to large river discharge and mostly southerly wind. In general, currents at the surface are stronger than bottom. The mean currents are always stronger in the northwest than in the northeast part with four river inlets in the northwestern part of the PRE. In the region outside of PRE, the residual currents are eastward. However, in winter, the relatively low river discharge obviously can maintain a classical partially mixed estuarine circulation only in the upper reach of the PRE during the
northeast monsoon. The residual currents are much weaker than in wet season. In the lower part of estuary and shelf, the circulation assumes a typical pattern of a coastal current. The strong northeasterly monsoon winds produced a northeastward flowing Guangdong coastal current and the current may intrude into PRE.

Hydrographic features in the PRE and shelf also vary with seasons. In wet season, the entire surface layer of the PRE is filled up with fresh water. Seawater intrusion from bottom and forms the salt wedge estuarine circulation [1]. Upon exiting from the PRE, the river plume spreads eastward by the southwesterly-driven upwelling currents [8]. In the dry season, the salt water can intrude a long way into the upper estuary with runoff reducing [9]. A front separated the upper fresh river water from seawater in the mid-estuary and the PRE is a partially or well-mixed estuary [10]. In the shelf region, the river plume spread to the west under northeast wind and Coriolis effect. This coupled estuary-shelf system in winter and summer can be summarized in Figure 1.3.

Circulations and hydrographic features associated with river, wind and tidal forcing have been studied observationally and numerically by other researchers. Wong et al. [11, 12] examined the PRE estuarine plume and the associated frontal dynamics in response to the seasonal discharge of the Pearl River and monsoon winds based on the observations and numerical results. Mao et al. [1] examined the tides and tidal currents in the PRE from field observations. Larson et al. [13] studied the circulation and salinity distribution in the PRE by forcing a numerical circulation model with tides and time-invariant freshwater discharge from four eastern-most inlets. Harrison et al. [4] summarized the influence of physical, chemical and biological factors in the eutrophication in the PRE. Gan et al. [14] examined the interaction of an estuarine plume produced by the Pearl River discharge with coastal waters in the northeastern SCS. Zu and Gan [15] numerically studied estuary–shelf circulation responses to variable winds, tides and river discharge around the Pearl River Estuary during summer.

Basic estuarine circulation features and its adjacent shelf have also been studied numerically and observationally in other estuary of the world’s ocean. For example, Chao and Boicourt [16] found that under the Coriolis effects, the two-layer estuarine circulation was modified as outflow offshore distributed on the west surface and inflow shoreward on the east bottom
compensating surface current. Chen and Stanford [17] studied that moderate down-estuary winds enhance the exchange between estuary and shelf while up-estuary winds always reduce it in Chesapeake Bay.

1.1.3 Tides and tidal currents in PRE

Tides and tidal currents play a key role in estuarine circulation. They are main source of energy for turbulence and mixing as well. They also affect the movement of dissolved, particulate material and vertical stability of water column.

Tides in the PRE mainly arrive as tidal waves propagating from the Pacific Ocean through the Luzon Strait [18] and East China Sea [19]. The mean tidal range is between 1.0 and 1.7 m. M2 is the dominant semi-diurnal tidal constituent, followed by K1, O1, and S2. The (K1+O1)/M2 constituent amplitude ratio is usually used to reveal the tidal pattern, and the ratio in the PRE ranges from 0.94 at Humen, to 1.77 at Wanshan Islands, south of Hong Kong [20]. The tides in PRE are characterized as mixed diurnal tide [1].

Wong et al. [21] had found that the amplitudes of M2 and K1 increased gradually from the outside to the inside of the estuary. In the coastal region, M2 and K1 have similar amplitudes, whereas in the PRE the amplitude of K1 is about one half of that of M2. M2 and K1 propagate from the southeastern to the northwestern estuary. The difference in phase for M2 is about 60° from Dangan Islands to the head of the PRE while K1 is only about 10° from Mirs Bay to the head of the PRE.

Mao et al. [1] investigated the variability in tidal levels and tidal currents in PRE during summer and winter in 1998. They found that the averaged tidal range increased gradually from offshore towards the estuary with larger amplitude increment in semi-diurnal tides than diurnal tides. The distribution of the mean current in the estuary depicted an anti-clockwise circulation in the estuary. Tidal currents were larger in the east than in the west, which was also found by Xu [22]. Zhao [20] also found that under the Coriolis effects and prevailing easterly winds, ebb currents exited the estuary from the western side of the estuary and flood currents intruded into the estuary from the eastern side, as shown in the schematic Figure 1.4.
1.2 Transports in PRE and PRE-shelf exchanges

Exchange flow between estuary and shelf is the key characteristic of tidally averaged circulation and stratification in an estuary. Macready and Geyer [23] showed that the tidally averaged circulation of many estuaries had two extraordinary features: one is that the bottom layer of water always flow landward (Figure 1.5); and another is that the volume flux of the exchange flow is often many times greater than river discharge alone.

Salt transport

Salt transport largely controls the saltwater intrusion, longitudinal and lateral density gradient and baroclinic circulation in an estuary. These in turn determine the transport of sediment, nutrients and contaminants, and thus affect water quality and ecosystem of the estuary [24]. Salt transport is generally divided into a seaward advection of salt due to the net outflow and two landward salt transports, estuarine exchange flow (gravitational circulation) and tidal dispersion (also called tidal oscillatory flux) [3, 23, 25-29]. A steady balance in which volume is conserved has volume fluxes \( Q_1 = Q_2 + Q_R \) (1.2), (Figure 1.5), where \( Q_1 \) represents volume transport flow out of the estuary through the mouth, \( Q_2 \) and \( Q_R \) are water transport flow in through the estuary mouth and river discharge, respectively. If salt flux through the mouth is dominated by the exchange flow acting on the tidally averaged salinity, the net salt balance is \( V \dot{s}_1 = Q_2 s_2 - Q_1 s_1 \) (1.3) where \( V \) is the volume, \( \dot{s}_1 \) is the volume-averaged salinity, and subscript \( t \) is the time derivative [23].

The saltwater intrusion dynamics, in response to changes in river discharge and tidal mixing in the Modaomen Estuary (Figure 1.6), have been studied by Gong and Shen [24]. They revealed that the salt is imported into the estuary during neap tides mainly through exchange flow induced steady shear transport, and is exported from the estuary during spring tides.

For the intra-tidal part, based on previous studies, Gong et al. [24] found that the two major components of salt transport flux are quite different at different stations along the estuary during a dry season at Modaomen estuary. The tidal salt flux is the primary component of landward transport at the station where the salt intrusion limit occurs, whereas the advective salt flux is more important at the station in the mesohaline region and at the estuary mouth during neap tide, while the advective salt flux becomes more important during meso and spring tide.
**Heat transport**

Temperature plays a key hydrodynamic, ecological, and morphological role within an estuary and the annual temperature cycle is important in determining the range of fauna and flora [30]. Heat exchange in estuary takes place across water-atmosphere, sediment-water and estuary-shelf interfaces at different states of tide. Heat balance responds to local processes and advection. Locally, heating process is dominated by incoming solar radiation while cooling is mainly due to outgoing long-wave radiation and latent heat fluxes. Adveective heat fluxes occur due to thermal gradient in the moving waters, which are difficult to quantify because of large spatial gradients in both temperature and velocity.

The rate of heat transport in estuary depends on the advection and mixing of estuarine and coastal waters across the mouth of Pearl River. Surface and horizontal exchanges in the water column can rapidly increase or decrease by several centigrade degrees during inundation by flooding winter and summer tidal and coastal currents, respectively.

There are little studies on heat fluxes in estuary especially the advective heat fluxes. This study will assess the advective heat fluxes across the section at the mouth of PRE in order to investigate the interactive role between the PRE and the adjacent shelf.

1.3 Objectives

Many studies on circulations in PRE have been conducted by both observational and modeling. However, these studies were mainly focusing on the tidal circulation, the sub-tidal circulation associated with wind and buoyancy forced current as well as coastal current intrusion have not been well understood. Meanwhile, huge uncertainties remain regarding to the salt and heat transport, exchanges around the PRE, especially over the intra-tidal and seasonal time scales.

Questions such as how the salt and heat fluxes changes in different seasons and during different tidal phases and how they response to the fresh water discharge, wind and tidal forcing are not adequately studied, particularly comparing to those carried out in other estuaries in the world. Unlike other estuaries, the mouth of PRE is so wide that it acts like a coastal sea, namely, the coastal processes take effect inside the lower part of the estuary [7]. The dynamics and thermodynamics of the PRE are unique and are largely unclear.
The main objectives of this study are:

1. To investigate basic seasonal, intra-tidal and subtidal circulation in the PRE and the adjacent shelf;
2. To study seasonal salt and temperature distribution and variability in the PRE;
3. To utilize observation data and model results to investigate water exchanges, salt and heat fluxes between the estuary and the adjacent continental shelf;
4. To identify dominant factors that control the transports and fluxes in response to forcing of river discharge, wind and tides.
Figure 1.1 Schematic of an estuary and its controlling factors.

Figure 1.2 Map of the Pearl River Estuary. The thick dashed lines are the survey sections and the color shaded and contours show the bathymetry (m). The red dot denotes the Gaoyao hydrological station.
Figure 1.3 Sketch of the river plume and coastal currents in the PRE and adjacent shelf in winter (blue dashed lines and arrows) and summer (red dashed lines and arrows), drawn based on the results from previous studies. Monsoon wind directions are also marked in the land points and the dashed lines refer to the outer edge location of the river plume. (Adopted from Zu and Gan [7]).

Figure 1.4 Sketch of the tidal currents in the PRE. Ebb currents (blue arrows) and flood currents (red arrows), show the bathymetry (m). The results are based on the results from previous studies (e.g. Zhao [20] and Q. Mao et al. [1]).
Figure 1.5 Definition sketch of an idealized partially mixed estuary, showing the tidally averaged circulation highlighting the exchange flow. (Adopted from MacCready et al. [23])

Figure 1.6 Geometry of the Modaomen Estuary. (Adopted from W. Gong et al. [24])
CHAPTER 2 METHODOLOGY

Field measurements and numerical modeling are utilized to study general circulation, hydrographic features and the associated transports in the PRE and the adjacent shelf. Due to spatial and temporal limitations in measurements, it is necessary to use a three-dimensional numerical model for spatiotemporal interpolation and extrapolation of the observed results.

2.1 Observation

Monthly field surveys were conducted in the PRE from March 2010 to March 2011. In addition, two large-scale surveys that covered both PRE and its neighboring coastal waters were carried out in August and December of 2012.

Hydrographic data were collected by a ship-boarded SBE-25 SEALOGGER Conductivity-Temperature-Depth (CTD) profiler with a vertical resolution of around 0.5 m at a sampling rate of 8Hz. The system was calibrated by the manufacturer just before the field survey (Sea Bird Electronics, Inc.). The accuracy of the CTD profiling system is 0.0021C, 0.0003S/m, and 0.1% of full scale range for temperature, conductivity, and pressure, respectively, and there solution is 0.00031C, 0.00004S/m, and 0.015% of full scale range, respectively. The CTD profiling system was lowered and raised in the water column at a rate of ~0.2 m/s. The current velocity was measured by a WHS-300 Workhorse Acoustic Doppler Current Profiler (ADCP) system (Teledyne RD Instruments) at a vertical resolution of 0.5m with a working frequency of 300 kHz.

In 2010-2011 cruises, the field observations focused on sections B, L, and C inside PRE (Figure 1.2). Two or three stations were sampled along transect B and five stations each along transects L and C. All the stations for each transects measured T, S and current during both ebb and flood period. In August and December 2012, forty-four fixed stations along transects P, A, B, L, C and F and fifty-eight stations along transects A, D, L, E, C and F were set up for summer and winter cruise, respectively (Figure 2.1 and Figure 2.2). Moored measurement of T-S and velocity time series were conducted at a shelf station as shown in Figure 2.1 and Figure 2.2 during these two surveys. The spatial intervals of sampling along transects were ~7 km along section A and ~5 km along the other sections. Section C was sampled twice for ebb and flood period in the summer cruise.
For presenting PRE and adjacent shelf circulation and other features, we started with two big cruises in summer and winter, 2012. Both of the two cruises did measurement with a large area extending to shelf region. In order to analyze the intra-tidal characters, we picked out three cruises of July, August in 2010 and August 2012 representing summer condition. Data of December in 2010, January and February in 2012 cruises showed winter condition for PRE and coastal area. We can conclude some common features and find different circulation conditions varying with tidal phases. Details will be provided in CHAPTER 3.

The variation of the Pearl River discharge during this period was represented by data collected from the Xijiang River (a.k.a. West River, one of the most important tributaries of the Pearl River), which represents ~68.5% of the total Pearl River discharge. Daily flow rate was obtained from the Information Center of Water Resources (Bureau of Hydrology, the Ministry of Water Resources of PR China) (http://xxfb.hydroinfo.gov.cn/EN/eindex4winter.jsp). The fresh water discharge from the upper four outlets (Humen, Jiaomen, Hongqimen, and Hengmen) can be estimated as ~53% of the total Pearl River discharge [5].

And the wind forcing time series data come from four automatic weather station Hong Kong Observatory (Figure 2.3). The data's time interval is one hour.

The river discharge and wind forcing condition are introduced here. In summer, Pearl River discharge reaches its yearly maximum. The runoff from the upper four outlets was about 12,000-15,000 m$^3$/s in 2012 (Figure 2.4a) during cruise periods. Figure 2.4(b) presents the observed wind stress in Lau Fau Shan (LFS), Sha Chau (SC), Tai O (TO) and Cheung Chau (CCH). LFS locates at the middle part of the estuary. SC and TO are in the lower part and CCH is outside the estuary-southeast of Lantau Island. Wind forcing over the PRE and adjacent water is prevailing southwesterly monsoon in the wet season from Jul 30th to Aug 3rd in 2012.

In the winter cruise, the river discharge from the upper four outlets was reduced to 2000~2500 m$^3$/s (Figure 2.5a). PRE and the shelf were under the influence of northeasterly monsoon forcing (Figure 2.5b). The river water is the main source of freshwater transport running into the estuary.

Both of buoyant plume and wind affect the offshore transport in the surface layer and the concomitant compensating shoreward current (or weakened offshore transport) beneath it.
Tidal forcing is obtained from observational data and model predicted results. The observational data is from historical records by Hong Kong Observatory around the tidal gauge stations in Hong Kong (Figure 2.3). Two model results are predicted by Tidal Model Driver (TMD, L. Padman & S. Erofeeva) and extracted tidal signals with model output data by function T_TIDE. The description of TMD and T_TIDE and methods to derive tidal information are provided in subsection 2.3-2.4.

2.2 Model and model description

2.2.1 Ocean model and implementation

The Regional Ocean Modeling System (ROMS) [31] is used in this study to understand temporal and spatial variability of estuary-shelf coupled processes. ROMS is a three-dimensional, free-surface, stretched terrain-following, hydrostatic, primitive-equation ocean model widely used in the oceanographic community. The Boussinesq approximation, that density variations are neglected in the momentum equations except in their contribution to the buoyancy force in the vertical direction, is also considered. The ROMS has been successfully implemented on the studies of river plume and estuarine circulation by MacCready and Geyer, Hetland, Warner et al., Choi and Wilkin [32-35] in various estuaries around the world and by Zu and Gan [7] in the PRE.

The model domain is a parallelogram, with a trapezoid PRE connecting to a parallelogram Northern South China Sea (NSCS) shelf. PRE is approximately 65 km long and 62 km wide at its southern entrance and the shelf part of the domain covers area of about 334 km long and 75 km wide. There are 400 × 200 horizontal grid points with corresponding grid size of about 0.8 km. The model has 30 vertical terrain-following s-level with resolution varying from about 0.03m in both surface and bottom boundary layers to 2.4m in the interior of the water column. The realistic topography in the PRE and its adjacent coastal waters were utilized.

The model is initialized with horizontally uniform temperature and salinity profiles obtained from the World Ocean Atlas 2001 (WOA01; Boyer et al. [36]) at 114.5°E, 21.5°N, which resembles the conditions found during a field cruise that carried out in July 2012. The initial sea surface elevation and current velocity are set to zero. We used tidal harmonic constituents
of 9 major components (K1, P1, O1, Q1, K2, S2, M2, N2 and M4) extracted from the South China Sea tidal assimilation model [19] to provide the tidal elevation and currents on the model's open boundaries. In these process-oriented experiments, we applied a constant river discharge rate and uniform wind stress in all cases. The volume of the river discharge is uniformly distributed in the water column with river water climatology data of temperature and salinity set to be 29.5°C and 3 psu. Model runs for 50 days and bihourly outputs are used for analyses. The buoyancy forcing caused by heat and salt fluxes between the atmosphere and the sea surface are neglected in all cases for simplicity.

We have conducted several numerical experiments (Table 2.1) with different forcing schemes to identify the dominant forcing process in the region. Results from the eight runs are presented and discussed in the following Chapters. Among them, Case 1-4 represented summer conditions and were forced with upwelling favorable wind and river discharge in summer. Case 5-8 represented winter conditions and were forced with downwelling favorable wind and the corresponding river discharge. Cases 1 and 5 (SC) are standard cases for summer and winter, respective, and they considered all the forcing including river discharge, tide and wind. Cases 2 and 6 (HR) halved river discharge of those in the respective Cases 1 and 5. Cases 3 and 7 (NT) are similar to Case 1 and 5, respectively, except that the tides were turned off. Cases 4 and 8 (HW) halved wind stress of those in the respective Cases 1 and 5.

<table>
<thead>
<tr>
<th></th>
<th>River discharge (total) m³ s⁻¹</th>
<th>River discharge (upper four outlets) m³ s⁻¹</th>
<th>Tidal forcing</th>
<th>Wind stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 1(SC_S)</td>
<td>18400</td>
<td>9830.9</td>
<td>Yes</td>
<td>0.025 (SW)</td>
</tr>
<tr>
<td>Case 2(HR_S)</td>
<td>9200</td>
<td>4915.4</td>
<td>Yes</td>
<td>0.025 (SW)</td>
</tr>
<tr>
<td>Case 3(NT_S)</td>
<td>18400</td>
<td>9830.9</td>
<td>No</td>
<td>0.025 (SW)</td>
</tr>
<tr>
<td>Case 4(HW_S)</td>
<td>18400</td>
<td>9830.9</td>
<td>Yes</td>
<td>0.0125 (SW)</td>
</tr>
<tr>
<td>Winter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Case 5(SC_W)</td>
<td>4800</td>
<td>2564.6</td>
<td>Yes</td>
<td>0.1 (NE)</td>
</tr>
<tr>
<td>Case 6(HR_W)</td>
<td>2400</td>
<td>1282.3</td>
<td>Yes</td>
<td>0.1 (NE)</td>
</tr>
<tr>
<td>Case 7(NT_W)</td>
<td>4800</td>
<td>2564.6</td>
<td>No</td>
<td>0.1 (NE)</td>
</tr>
<tr>
<td>Case 8(HW_W)</td>
<td>4800</td>
<td>2564.6</td>
<td>Yes</td>
<td>0.05 (NE)</td>
</tr>
</tbody>
</table>

Table 2.1 Sensitivity experiment with 8 cases in model results.
2.2.2 Tidal Model Driver (TMD) and T_TIDE

TMD is a Matlab package for accessing the harmonic constituents developed by Oregon State University [37]. TMD includes two components: (1) a graphical user interface (GUI) for quickly browsing tide fields, zooming in on regions of interest, and selecting points and time ranges for predictions of specific variables; and (2) a set of scripts for accessing tide fields and making predictions [37].

T_TIDE is a package of routines that can be used to perform classical harmonic analysis with nodal corrections, inference, and a variety of user specified options [38]. Predictions can also be made using the analyzed constituents. There are several novel features in T_TIDE. First, although the harmonic analysis algorithm with nodal corrections is not original, it is implemented in MATLAB, an analysis package widely used by oceanographers. This allows for easy use within the framework of a complete analysis involving plotting of raw data, scatter plots, and so forth. Second, the code is written directly in matrix terms and thus relatively easy to understand and modify if required. Finally, in order to differentiate between true deterministic (line) frequencies and broad-spectrum variability, confidence intervals for the estimated tidal parameters are computed using one of several user-selectable algorithms.

2.2.3 Derivation of observed subtidal currents

Unlike other estuaries in the world, PRE has a wide mouth connected to NSCS which makes it more difficult to conduct in situ measurements. Since our observation data was collected from fixed station data, sampling time was different at each station. To overcome this temporal inconsistence of the observed data, we derived tidal information for each station from model results. Our approach included:

1. Model validation: We have 4-year (2010-2013) time-series tidal data collected in four tidal gauge stations around Hong Kong (Figure 2.3) provided by Hong Kong Observatory (HKO). The model tidal data were validated with the tidal gauge measurements (Figure 2.6).

2. Spatial interpolation: The model results are spatially interpolated to the sampling stations during the cruises.
3. Tidal velocity: We used T_TIDE function to extract tide components for all the model results at the observational stations to obtain time-series tidal currents.

4. Temporal interpolation: After steps 1-3, we then interpolated the model data to the exact sampling time for each station.

5. Residual currents: Residual currents were obtained by subtracting model tide currents from observed (total) currents. The deduction was done by $u$, $v$ components in respective $x$ (eastward) and $y$ (northward) directions, respectively.
Figure 2.1 2012 summer cruise stations distribution.

Figure 2.2 2012 winter cruise stations distribution.
Figure 2.3 Wind and tidal gauge stations distribution for HKO data.
Figure 2.4 River discharge (a) and wind stress (b) in Lau Fau Shan (LFS), Sha Chau (SC), Tai O (TO) and Cheung Chau (CCH) in the summer, 2012. Blue solid line is cross-shore wind stress component and red dash line is along shore wind stress component. Positive values direct northward and westward, respectively. Areas within black dash line are sampling period.
Figure 2.5 Same as Figure 2.4, but for the winter 2012.
Figure 2.6 Comparison of the hourly sea surface elevation anomaly between simulated results and tidal gauge observation data in Shekpic, Tsim Bei Tsui, Tai Miu Wan and Waglan respectively. The simulated and observed results are shown by the blue and redlines respectively. The number shown in each figure is the correlation coefficient. Left column is summer value and right is winter.
CHAPTER 3 RESULTS

3.1 Observational study

3.1.1 Circulation and hydrographic features

The PRE is influenced by subtropical monsoon. The estuary circulation is controlled by a number of factors, such as river discharge, tidal currents, wind and topography. The seasonal circulation and hydrographic features are discussed using data collected from the summer and winter cruises in 2010 and 2012.

Summer pattern

Figure 3.1 shows the depth-averaged currents in the estuary and costal area. The velocity patterns differ inside and outside PRE. At the head of the estuary, total currents were landward, due to residual current mainly contributed by flood tide. The currents along the center line were southwestward. Although wind during this period was southwesterly, the magnitude was very small. So the southwestward currents were the results of interaction of buoyancy-driven gravitational circulation and tidally-driven current. Outside the estuary, the total (mean) currents were seaward in the shelf area under the combined effects of southeasterly wind, tidal and gravitational forcing. Due to its large area, measurements over the entire PRE lasted ~7 day, during which stations were at different tide stages.

To extract the corresponding tidal currents in Figure 3.1 (c) and thus the sub-tidal current, a model-derived tidal current (see Section 2.3) were used. In order to avoid predicted errors in model velocity, tidal currents from model were extracted at the time when tidal elevation from model results matched with that in during the sampling time at each station (Figure 3.1 (d)). And the total currents were obtained from the measurement data. If one station had two data of ebb and flood, the total current for this station has been averaged.

It was flood tide during the head measuring period, which led to the landward currents. The largest tidal currents were in the mid-part of the estuary. It agrees with the previous study by Mao, et al. [1]. While over the shelf, it experienced a weak ebb tide during the sampling period. Subtracted of total measured velocity vectors by tidal currents, we obtained sub-tidal currents
and they had a similar pattern with the total measurement currents. Overall, the circulation exhibited a pattern that river water flowed out from west side of the estuary and spread eastward and seawater intruded into the estuary from the east part of the estuary mouth. It formed a small cyclonic circulation at the estuary mouth. Evidently, inside the estuary, river discharge dominated the estuary circulation and shelf pattern is affected by wind in summer.

The water mass properties are presented in Figure 3.2. In wet season, the river water occupied whole estuary. The salinity varied from 0 to 34 psu with lower salinity inside the PRE region and higher salinity in the shelf. Estuarine water is warmer than ocean water in summer. Temperature range was quite small, from 26 to 30°C. The density was mainly determined by the salinity. So overall the shelf water was denser than estuarine water. From the salinity and temperature distribution (Figure 3.3), the diluted water almost filled the entire estuary and the river plume spread eastward as exiting the estuary. The near-surface salinity varied from ~2 psu in the PRE to ~30 psu in the shelf. The surface salinity front located near the mouth of the PRE. In the bottom layer, the salinity front moved shoreward. For the temperature distribution, the surface water was with higher temperature than the bottom. The range of temperature variation was small from the head of PRE to the shelf. The western part of the shelf was colder than the eastern part.

**Winter pattern**

The depth-averaged mean currents in winter showed that currents inside estuary were affected mainly by tidal currents due to small river discharge. Most of PRE measurements were conducted during flood period (Figure 3.4 (c, d)) and the mean currents were mainly directed shoreward. Relatively strong upstream currents occurred in the mid-part of estuary. Currents over shelf were directed westward, mainly due to the combination of tide and wind-driven currents.

The properties of water mass properties in the winter are presented in Figure 3.5. The salinity varied from 6 to 34 psu with lower salinity inside the PRE region and higher salinity in the shelf. Estuary water with lower temperature varied from 20 to 22°C and shelf water had a wider range from 19 to 24°C. River water was colder than seawater in the winter.
Because the runoff was reduced, the seawater with higher salinity intruded a long way into the river in the dry season. Since all the fresh water outlets were located on the west bank of the PRE and the Coriolis force also steered the river water toward the western side, an apparent freshwater plume front extended westward from the surface to the bottom (Figure 3.6(a) and (b)). From the temperature distribution, it showed similar pattern that cold river water concentrates on the western side of the estuary. There was also a cold and high salinity bulge to the south of Hong Kong. The cold river plume veered to the west with the westward downwelling favorable wind. Where did the cold water bulge come? It was likely due to the eastward veering during the episodic eastward wind during the downwelling season. And this was a massive bulk of water so that the cold water center touched the bottom layer.

3.1.2 Tidal effect on seasonal and intra-tidal features

Previous parts indicated that tide plays a very important role in the circulation in the region, particularly in the estuary. PRE is an estuary with a large area with ~60 km length along its central axis. Our observations and previous studies, M2 and K1 tides in the PRE propagate from southeast to northwest in the estuary. There is phase lag about 90° for M2, S2 and 40° for K1 and O1, respectively, which means time lag is about 3 hours from Dangan Islands to the head of PRE [1].

**Tidal effect on summer circulation**

Figure 3.7a shows the currents along section A (Figure 1.2) in the summer. The corresponding tidal elevation is presented in Figure 3.7b. The black, red and blue curves in Figure 3.7b refer to tidal elevation at Sta.A1, A6 and A9, which located in the head, middle and mouth of the estuary respectively. A1-A4 was sampled during the flood period while A5-A8 during the ebb period. A9 and A10 were also in the phase of high tide during flood. The total currents along section A are shown in Figure 3.7a. Tidally-driven currents obviously dominated circulation along section A. During ebb period, currents in Station A5-A8 showed strong seawater trend and surface current was stronger than the bottom one. During flood period, stations A1-A4 and A9-A10 showed landward currents. At the head of PRE, surface currents were stronger, while at the mouth of estuary (Stations A9 and A10) the mid-layer currents were the largest. This phenomenon suggested that the seawater intrusion was mostly from the middle layer.
The PRE is basically a stratified estuary. Particularly, the typical two-layer estuarine structure can extend to coastal waters during summer when river discharge is large and wind is mainly from the south or the southwest. Figure 3.7(c) and (d) shows the observed salinity and temperature along section A during the wet season. It is clear that both salinity and temperature were strongly stratified, and the salinity and temperature gradients existed around A7 and A8 (Figure 3.7c and d). It should be noticed that the stratification was largest during ebb tide (Stations A6, A7 and A8). This temperature and salinity structures, however, were the typically response in the estuary, regardless than the observational tidal phase [10]. One key reason is that the river runoff and seawater met at this region where the turbidity maximum occurs. Another factor maybe there was considerable variation of stratification during the tide, which is called tidal straining [39]. Because of shear in the velocity profile, the surface water travels faster with a larger trajectory of motion than the bottom water. During ebb tide, the fresher water is displaced over the saltier water and the stratification increased. Thus there is a faster decrease of surface water salinity than near the bottom layer. The surface to bottom salinity difference increases.

The section at the mouth of estuary is the boundary of estuary and shelf and related to exchange and transport between them. Three cruises observational data in summer, July, August in 2010 and August in 2012 are used to demonstrate the intra-tidal responses at the boundary. Figure 3.8 shows the tidal elevation for Section C in three cruises. Figure 3.8(a), (b) and (c) stand for cruises in July 2010, August 2010, and August 2012 respectively. Generally, they can be divided into two cases: the big-ebb-small-flood pattern (Case I) and the big-ebb-big-flood pattern (Case II). Although the mouth of PRE is wide, the measurement period for each section was within 4 hours to reduce the tidal phase difference. So each cruise along section C captured the ebb (Figure 3.9) and flood (Figure 3.10) conditions.

During the ebb, currents occurred mainly in the western part of the section (west of station C4). The strongest ebb current was found at the low-low tidal phase, or C4, C2-C3 and C2-C2 for cruises 1 (Case I), 2 and 3 (Case II), respectively. Station C5 was sampled at the phase transition time between the ebb and flood (as defined in the station in Figure 3.8). As a result, the landward currents existed at station C5. Vertical distribution of salinity showed that lower salinity river
water existed in the section in corresponding to the larger ebb current. Since the tidal circulation is cyclonic in the estuary, it is expected that the fresher water was observed in the western side of the estuary. And the fresh water with salinity <16 psu extended through entire water column in the eastern side. Similarly, the highest temperature occurred when ebb current was the strongest.

During flood, currents should be mainly landward. However, in Case I, due to the smaller flood amplitude, weaker seaward currents were still seen across section C. The landward current started to appear in the bottom in the eastern channel and the surface freshwater from the ebb tide was erased and became thinner. In general, the water was saltier than that during the ebb. The thickness of freshwater less than 16 psu was ~3m due to more seawater intrusion from bottom. For Case II, the amplitude of the flood tides was stronger and the landward current occupied across the entire section. However, the freshwater and relatively high water temperature from previous ebb west of station C3 remained visible during these low high tide period (Figure 3.9). It is obviously, the strongest current always appears at the late ebb/flood period during spring tide. Tidal currents, just like tides, are affected by the different phases of the moon. [40] However, the tides’ influence on current flow is much more difficult to analyze.

The vertical profiles of velocity, salinity and temperature of 4-5 stations in Figure 3.9 and Figure 3.10 were used to compute instantaneous volume, salt and heat fluxes across the section C. The transport, salt and heat flux can be calculated with equations below.

\[
Q_v = \iint v \, dx \, dz, \quad (3.1)
\]
\[
Q_S = \iint S \rho \, v \, dx \, dz, \quad (3.2)
\]
\[
Q_h = \iint \rho C_p \, \theta v \, dx \, dz, \quad (3.3)
\]

where \(v\) is instantaneous velocity normal to the cross-section; \(z\) is the vertical coordinate; \(S\) is salinity; \(C_p\) is water heat capacity which is a function of salinity, pressure and temperature \(\theta\). I have assumed that \(v, S, \theta\) have been filtered to remove turbulent fluctuations shorter than a couple of minutes.

Transport results are shown in Figure 3.11. Ebb transports are shown in blue blocks and flood in red. For ebb tide, three cruises show similar results and the volume transport, salt and heat
fluxes were seaward, and their values were -$5.25\times 10^4$ m$^3$/s, -$9.92\times 10^8$ Kg/s, -$6.12\times 10^{12}$ J/s, respectively. The seaward fluxes were mainly contributed by those in the surface layer, over the west channel and the western side of the section C. And the mean flood transports were $3.96\times 10^4$ m$^3$/s, $1.11\times 10^9$ Kg/s, $4.44\times 10^{12}$ J/s. For Case I during the low-high-tide of the flood pattern, current profile was still seawater, except in the bottom layer along west channel. Thus, the volume transport and heat flux were still seaward. The salinity was high along west channel bottom where the currents were landward, salt transport was landward across Section C. For Case II, the seawater intruded from the mid-layer and surface over west channel and thus the transport of salinity and temperature were landward, respectively.

**Tidal effect in winter**

In the winter cruise of 2012, the field measurement extended to A15, 130 km away from the head of PRE (Figure 2.2). Figure 3.12 presents the current, salinity and temperature distribution along section A and its corresponding tidal elevation. It took almost 2 days to conduct the survey along the section and each sampling stations were at different tidal phases. In Figure 3.12b, black line stands for tidal elevation at station A1, red and blue lines stand at A9 and A15. Tidal phase lag was smaller over the shelf than inside the estuary. The tidal phase for each station should locate at the line of its nearest station. It indicated that tide played a key role in circulation in the estuary and adjacent shelf. As the runoff was greatly reduced and the water was well mixed by the northeasterly winds in the dry season, the estuary was usually considered to be partially mixed in winter [20, 22]. As shown in Figure 3.12, water is well mixing along the axial section. Diluted water with salinity < 16 psu reached station A4 in the upper estuary. In contrast, salinity < 16 psu was at station A8 at the lower estuary on the surface and at A6 in the bottom. The salinity over the shelf was all above 32 psu.

As for cross-estuary section at the mouth of estuary, it can also be divided into 2 cases (Figure 3.13), the small-ebb-small-flood (Case I), and small-ebb-big-flood (Case II). During the ebb tide (Figure 3.14), since river discharge was the lowest in the dry season, it is obviously that river water exited the estuary from the western side. The magnitude of varied with tidal phase during the sampling, so did the salinity and temperature.
The flood tide (Figure 3.15), the strongest tidal current occurred in stations C2-C3 according to the tidal phase during the sampling. Low salinity/cold temperature river waters were inversely correlated with the magnitude of the flood current along the section at the entrance of the estuary. Combined with flood and ebb current during both winter and summer (Figure 3.9, Figure 3.10, Figure 3.14 and Figure 3.15), it can be concluded that the flood current started from the bottom at the eastern side of estuary while the ebb currents existed at the western side. Salinity and temperature across the section were linked with the intensity of the tidal currents. The stratification was stronger during ebb tide than flood tide both in summer and winter.

Transport results are shown in Figure 3.16. The mean ebb transports of volume, salt and heat in winter were \(-2.61 \times 10^4\) m³/s, \(-7.62 \times 10^8\) Kg/s, \(-2.10 \times 10^{12}\) J/s respectively. And the mean flood transport was \(3.82 \times 10^4\) m³/s, \(1.23 \times 10^9\) Kg/s, \(2.98 \times 10^{12}\) J/s. Compared to summer, it is easy to understand that the outflow of the estuary reduced due to decrease of the river discharge, and the inflow during flood tide also declined under this condition in the dry season.

3.1.3 Seasonal variation of transport

Extracting the residual flux due to freshwater flux alone can be difficult because of the small ratio of freshwater flux to instantaneous tidal flux [41], so net transports were calculated roughly by averaging the ebb and flood values. Results are shown in Figure 3.17. Small flood periods in two seasons are in orange blocks, and big flood periods are in red and purple ones. They differ in cases for summer and winter. The net transports, salt and heat flux are affected much by the relative ebb and flood period. In Case I, the transport and flux showed outflow due to the remaining seaward currents during small flood period in both seasons. The volume transport magnitude reached to \(-3.25 \times 10^4\) m³/s in summer. It was a third more than winter of \(-2.24 \times 10^4\) m³/s due to river discharge difference. However, the net salt flux in winter with a transport of \(-6.50 \times 10^8\) Kg/s was larger than summer of \(-4.28 \times 10^8\) Kg/s. Both velocity and salinity oscillations contributed to the variation in baroclinic salt transport across the section. It was obvious that water in winter was much saltier than summer according to the salinity profile in Figure 3.15b. The heat transport showed a similar trend with volume transport with a much higher temperature distribution in summer.
For Case II, the net transports both presented an intrusion trend in two seasons. The average volume transport for two cruises of Case II was $11.84 \times 10^4$ m$^3$/s in winter, which was almost twice than that of $6.58 \times 10^4$ m$^3$/s in summer. The intrusion in winter was much larger than in summer. As for salt and heat fluxes, the average magnitude for salt flux in winter was about $4.00 \times 10^8$ Kg/s which was nearly a quarter more than that in summer of $3.05 \times 10^8$ Kg/s. The net heat flux for summer and winter were at a transport of $6.77 \times 10^{11}$J/s and $8.40 \times 10^{11}$J/s respectively. The difference was also about a quarter. The results indicated that seawater intrusion was stronger in winter than summer. Using salinity or temperature as a conservative tracer reduced the intrusion difference between salt and heat flux. Compared to the ebb-flood flux in Figure 3.10, the approximate subtide flux was much smaller than instantaneous tidal flux. The ratio of subtide and intra-tide flux was about 0.1, which suggests that tide plays a significant role in water exchanges between PRE and its adjacent shelf.

3.2 Model results

Although there are some observation results in the previous chapters, the data insufficient in time-series and errors of instruments are not negligible. In this part, we adopt a three-dimensional numerical model to study transports in this area. The circulation and hydrographic features associated with transports in PRE and adjacent shelf are introduced in the section with observation-model comparison first. Then the volume, salt and heat transport are discussed in the last section.

3.2.1 Observation-model comparison

The simulated salinity horizontal distribution during summer and winter is compared with the observed data in 2012 cruises and the results are presented in Figure 3.18. The left panel shows the surface salinity distribution in summer. And the right panel is in winter. In the estuary, river water occupies almost the entire PRE in summer resulting from large diluted water. The salinity front exists at the mouth of the estuary in observation and model. Over the shelf, the fresh water spreads to the east in summer. While in winter, the salinity front orients northeast to southwest appears in the west part of the estuary. The plume is restricted to the inside of the intruding shelf water with small river discharge. The simulated results appear to agree well with the observed ones on the basic features in general.
For the intra-tide part, the observational and model results are compared in Figure 3.19. Same transects in model results as Section C in observation are examined here. The model results are consistent with observation. During ebb tide in summer, fresh water with salinity less than 12 psu are mainly in west part of section C and the salt water are in the bottom layer along west channel. During flood, water is much saltier with seawater intruding on the surface. In winter, the observation and model results also show similar pattern that river water is in the west part of the estuary. And they both show that the stratification during ebb is stronger than flood due to the tidal straining effect.

Volume transports for intra-tide and net (roughly-calculated subtidal) in the observed data and simulated results are compared in Figure 3.20. We selected time periods with similar tidal phase in model to the observed tide during section C measuring period in different cases. The model results agreed qualitatively well with observation. The maximum transport occurs in summer during ebb period of big-ebb-small-flood case both in observation and simulated results. The transports for big-ebb-big-flood case in summer and small-ebb-small-flood case in winter show a good tidal symmetry with a relatively small net transport. The maximum seaward transport is in big-ebb-small-flood case and the maximum intrusion appears in small-ebb-big-flood case. The results above indicate that the net transports depend on the flood situation. The transports comparison shows that model results have a good agreement with the observation data qualitatively.

Differences of observation and model are mainly generated by using the climatological river discharge and wind stress. In-situ winds and river discharge vary much with time. Although four wind stations shows similar wind condition around PRE in general (See Figure 2.4 and Figure 2.5), they still could not represent the rich spatial variability in the realistic wind field especially in the west side of the estuary and shelf.
3.2.2 Characteristics in estuary and over the shelf

The observed features in estuary and shelf are analyzed in the previous parts. The simulated results with climatological forcing conditions are presented in this section in order to reveal the basic circulation and hydrographic features in the idealized model.

Summer pattern in model

There is largest river outflow at $9830 \text{ m}^3\text{s}^{-1}$ from the upper four outlets in summer. A uniform alongshore wind stress is $0.0230\text{Pa}$ toward east, which is upwelling favorable wind and cross-shore wind stress is $0.0098\text{Pa}$ to north. Circulation in PRE and shelf are affected more by river and wind. PRE is a stratified estuary especially in summer. Model results shows obviously that currents are different in the surface and bottom layer. Surface currents are all seaward due to large river flow (Figure 3.21a). Strongest currents at about $0.6\text{m/s}$ are over the shelf under the combination effect of Ekman transport and river. In the bottom, the magnitude of subtide currents is quite smaller than surface. Landward currents are observed at the mouth of the estuary, and they are stronger along west and east channel. This two-layer circulation structure reveals that exchange flow driven by density gradients plays an important role in summer. The salinity and temperature structure indicates large fresh water fills upper estuary from surface to bottom (Figure 3.22). River plume spreads to the east on the shelf surface. Water is much fresher and warmer in the east than west shelf due to the Lantau Island. Seawater intrudes from the west and east channel which agrees with the currents distribution. The salinity and temperature front at the mouth of the estuary shows that river water and seawater meet in this area and the stratification is the strongest.

Winter pattern in model

In winter, the Pearl River discharge is small, so that wind and Coriolis effect play important roles in determining the subtidal estuarine dynamics. Strong alongshore wind stress is $0.0921\text{Pa}$ toward west, which is downwelling favorable wind and cross-shore wind stress is $0.0391\text{Pa}$ to south. Inside the estuary, currents are in the same direction with westward wind due to water depth is shallow in this region. Over the shelf, large coastal currents are still to the west under eastern wind. There is landward intrusion at the mouth of estuary in both surface and bottom.
Bottom residual currents are less than 0.1m/s and show a cyclonic circulation at the mouth. Seawater flows into the estuary from the east part of Lantau Island and flows out near the west bank (Figure 3.23b).

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 orienting northeast to southwest which agrees with the observed results. The front separates the diluted water on the western side from the shelf water on the eastern part of PRE (Figure 3.24). The temperature distribution is consistent with salinity. Most part of the shelf water are occupied with seawater.

3.2.3 Seasonal, sub-tidal and intra-tidal volume, heat and salt transports

The basic circulation and hydrographic features in PRE and shelf are studied in previous part. In the last part of this chapter, the sub-tidal and intra-tidal exchanges will be discussed, thus we focused on Section C—the boundary of estuary and shelf which relates to exchange and transport between them. And volume transport, salt and heat transports for different seasons and tidal periods will be studied. We analyzed results of standard cases here, and then the other cases are discussed in the forcing part next chapter.

In the PRE, various types of physical forcing, including river discharge, monsoon winds, tides, coastal currents and the gravitational circulation associated with a density gradient to control the water and transport in the estuary. It varies with seasons and tides.

Base on Eqts (3.1), (3.2) and (3.3), volume transport, salt and heat flux are calculated across section C. Inflow and outflow are calculated individually in this part. Inflow is calculated by the equations below.

\[ Q_{v\text{-inflow}} = \int \int v_{in} dS, \]  
\[ Q_{S\text{-inflow}} = \int \int \rho \sigma_v v_{in} dS, \]  
\[ Q_{h\text{-inflow}} = \int \int \rho C_P \theta v_{in} dS, \]

Outflow values are the results of the same way, but for variables seaward.
Sub-tidal transports

The sub-tidal variables of currents, salinity and temperature are obtained by T\_TIDE, which is introduced in section 2.2.2. The transports in Table 3.1 are results of mean value during steady state period from 30 to 48 days. In summer standard case, river discharge from the upper four outlets is \( \sim 9830.9 \text{ m}^3/\text{s} \). The net transport across Section C reaches to \( 1.09 \times 10^4 \text{ m}^3/\text{s} \), which means \( \sim 1000 \text{ m}^3/\text{s} \) outflow transports are driven by other effects. In summer, PRE is under the influence of southwestern wind mainly, it is deduced that the Ekman transports are the main source. Combined with the subtidal profiles across section C in Figure 3.25, it shows that inflow is in the bottom layer in the west part and along east channel. The outflow concentrates on the surface above west channel reaching \( 1.97 \times 10^4 \text{ m}^3/\text{s} \). While in winter, the outflow and net transport are half of that in summer due to reduced river discharge. The inflow is also smaller than summer which indicates that buoyancy-driven gravitational circulation is enhanced by the increasing river discharge. From the velocity profile, landward currents are mainly in along west channel and seaward currents peak at the west side of the section. It should be noticed that transports from inlets are \( \sim 2564.6 \text{ m}^3/\text{s} \); while the net value reaches \( \sim 5600 \text{ m}^3/\text{s} \). North wind stress is 0.0921Pa and east wind stress is 0.0391Pa. North wind plays a more important role here. Due to the depth is shallow in this area, surface water is more likely in the same direction as wind, which leads to more seaward transport. This reveals that winds bring larger impact on circulation PRE in winter than summer.

In summer, seawater with higher salinity and lower temperature intrudes from the bottom layers. Much fresher and warmer river water flows out on the surface, especially in the west side of the section. This process leads to a salt flux of \( 1.2 \times 10^8 \text{ Kg/s} \) and heat flux of \( 1.2 \times 10^{12} \text{ J/s} \) from estuary to shelf. In winter, river water with lower salinity and temperature exits to the shelf in the west side. Saltier and warmer seawater are in the east part couple with upstream currents. The net outflow heat flux in summer is twice of winter similar to volume transport due to the temperature ranging small. Both velocity and salinity oscillations contribute greatly to the salt transport across the section.

33
Intra-tidal transports

In this section, we will talk about two kinds of intra-tidal variations on transports in model. One is transports for ebb and flood tide, and the other is spring-neap variation.

Based on the observation part, tidal forcing plays an important role in modifying the circulation and transport in the estuary. Here we still focus on the estuary and shelf interface-section C. Ebb and flood periods are determined by tidal elevation of section C and all values are averaged from 30 to 48 days. Volume, salt and heat transport are shown in Table 3.2. It shows that transports are all inflow during flood. Based on cross-shore current profiles during ebb tide (Figure 3.26a,b), ebb currents occupies across the entire transports over the whole section. Transports are seaward with strongest currents in the east side. The largest velocity appears on the surface above west channel in summer due to large runoff and wind effect. While in winter, the ebb currents maximize at two places, one is in the west side exporting river water and the other is in the east side exporting the mixture of seawater and freshwater. And seaward currents in winter are stronger than that in summer overall, which results in larger seaward transport. During flood tide, landward currents take up the whole section. Likewise, landward currents are strongest over west channel during flood. Unlike during ebb tide, flood currents maximize at the mid-layer both in west and east side which means seawater intrudes mainly from mid-layer in summer. And weak seaward currents are observed over east surface in summer and over west surface in winter where the river flows out. Compared the result in Table 3.2 with Table 3.1, it can be found that transports for intra-tide are much larger than that of subtide. In summer, intra-tidal volume and heat transports are more than 7 times of that for subtide.

<table>
<thead>
<tr>
<th></th>
<th>Volume transport (×10^4 m^3/s)</th>
<th>Salt flux (×10^8 Kg/s)</th>
<th>Heat flux (×10^12 J/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inflow</strong></td>
<td>0.87</td>
<td>2.29</td>
<td>0.93</td>
</tr>
<tr>
<td><strong>SUMMER</strong></td>
<td><strong>Outflow</strong></td>
<td>-1.97</td>
<td>-3.49</td>
</tr>
<tr>
<td><strong>Net</strong></td>
<td>-1.09</td>
<td>-1.20</td>
<td>-1.20</td>
</tr>
<tr>
<td><strong>Inflow</strong></td>
<td>0.52</td>
<td>1.79</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>WINTER</strong></td>
<td><strong>Outflow</strong></td>
<td>-1.08</td>
<td>-3.42</td>
</tr>
<tr>
<td><strong>Net</strong></td>
<td>-0.56</td>
<td>-1.63</td>
<td>-0.52</td>
</tr>
</tbody>
</table>

Table 3.1 Subtidal volume, salt and heat transport of summer and winter in model. Results are averaged from 30 to 48 days.
winter, this value is raised to more than 15 times. And for salt flux, the ratio is even larger, reaching up to 15 times in summer and ~20 times in winter. The above results reveal that tidal prism varies considerably, bringing about significant changes in the ratio of river flow to tidal volume and affect much on exchanges between estuary and shelf, especially in winter.

<table>
<thead>
<tr>
<th></th>
<th>Volume transport</th>
<th>Salt flux</th>
<th>Heat flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUMMER Flood</td>
<td>7.25 (×10⁴ m³/s)</td>
<td>18.58 (×10⁸ Kg/s)</td>
<td>7.73 (×10¹² J/s)</td>
</tr>
<tr>
<td>SUMMER Ebb</td>
<td>-9.06</td>
<td>-19.49</td>
<td>-9.76</td>
</tr>
<tr>
<td>WINTER Flood</td>
<td>8.14 (×10⁴ m³/s)</td>
<td>27.90 (×10⁸ Kg/s)</td>
<td>7.80 (×10¹² J/s)</td>
</tr>
<tr>
<td>WINTER Ebb</td>
<td>-9.35</td>
<td>-31.46</td>
<td>-8.92</td>
</tr>
</tbody>
</table>

Table 3.2 Volume, salt and heat transport during ebb and flood period in summer and winter in model. Results are averaged of ebb and flood period from 30 to 48 days.

The spring-neap cycle in estuarine circulation is the most conspicuous and consistent signal of low-frequency estuarine variability. Spring-neap tide cycles control sedimentation and seaward escape of suspended sediment. This phenomenon was first documented by Haas[42] on the basis of a set of observations in sub-estuaries of Chesapeake Bay. Geyer & Cannon[43] noted a factor of two variations in the strength of the exchange flow at the entrance to Puget Sound, with maximum exchange flow occurring during the neaps and minimum during the springs.

Here we examine the spring-neap variation in PRE of standard case for summer and winter. In order to see the spring-neap variation clearly, transports and fluxes are smoothed by 36 hours. A spring-neap variation is seen obviously in the volume, salt and heat transports (Figure 3.27). Figure 3.27(a) (b) present tidal elevations for section C. In summer, Day 33 to Day 36 is neap tide and Day 41 to Day 44 is spring tide. The largest net volume transports appears in Day 33 which is during neap tide and low net outflow transports are in Day 41 to Day 45 with small fluctuations during spring tide. Net heat flux shows similar pattern with the greatest rate of loss at 9.8×10¹¹ W on Day 33. Because of the flow temperature has a nearly constant value of 26.1±0.5°C (See Figure 3.25c), the heat flux variations are caused mostly by transport variations. This variability gives the fundamental importance of tidal mixing as a controlling variable for estuarine stratification. Salt flux presents a different pattern form volume and heat transport that during neap tide, salt transport shows an inflow during neap tide and the greatest salt loss appears during spring tide. Both velocity and salinity oscillations make a great
contribution to the variation in summer. To illustrate this phenomenon, current profile of the section coupled with salinity profile is presented in Figure 3.28. It is found that stratification is stronger during neap than spring (Figure 3.28a,b). Much stronger intrusion currents with higher salinity from bottom and a wider range of upstream currents with much fresher river water are observed during neap tide, which explains salt inflow. During spring tide, seawater in the bottom shows weaker landward currents and less saltier while the seaward currents extend to the mid-layer. So the outflow peaks at the spring tide. In winter, it shows that both salt and heat transports are caused mostly by transport variations. The exchange flow peaks during neap tide and reaches minimum during spring tide. Geyer and Cannon [43] hypothesized that increased mixing during spring tides results in reduced exchange flow. Our results confirm their analysis. A number of subsequent researchers have documented spring-neap variations in circulation consistent with the influence of enhanced mixing (e.g., Nunes & Lennon, Monismith et al., Griffin & LeBlond, Geyer et al. [44-47]). It appears that the variations of mixing are more important than advective nonlinearities in PRE, leading to a tendency for stronger exchange flows during neaps than springs.
Figure 3.1 Depth-averaged velocity vectors (a-c) and tidal elevation (m) (d) in the summer, 2012. (a)-(c) stand for total, sub-tidal and tidal currents, respectively.
Figure 3.2 The temperature ($\theta$,$^{\circ}$C)-salinity (T-S) diagram showing the water masses in the entire survey area in the summer 2012.

Figure 3.3 Salinity and temperature distributions in the summer 2012. The upper panel is salinity distribution and the lower column is temperature. (a) (c) are surface distributions and (b) (d) are for bottom distributions.
Figure 3.4 Same as Figure 3.1, but for the winter 2012.
Figure 3.5 Same as Figure 3.2, but for the winter 2012.

Figure 3.6 Same as Figure 3.3, but for the winter 2012.
Figure 3.7 Axial section (A) total currents (a), tidal elevation (b), salinity profile (c), and temperature profile (d) in the summer 2012. Positive value stands for landward currents. The black, red and blue curves in (b) refer to tidal elevation at Sta.A1, A6 and A9 respectively.

Figure 3.8 Tidal elevation (m) along section C in the summer 2012. (a), (b) and (c) are cruises in July 2010, August 2010, and August 2012. (a) is tidal elevation for big ebb, small flood period; (b) and (c) are big ebb, big flood period.
Figure 3.9 Velocity normal to section C (a)-(c), salinity (d)-(f) and temperature (g)-(i) distribution along the section C during ebb period in summer. (a), (d) and (g) were sampled during the cruises in July, 2010; (b), (e) and (h) were sampled in August, 2010; (c), (f) and (i) were sampled in August, 2012. Positive value stands for landward currents.
Figure 3.10 Same as Figure 3.9, but for flood period.
Figure 3.11 Volume, salt and heat transports for July 2010 (left column), August 2010 (middle column) and August 2012 (right column). Blue and red bars are for ebb and flood tide, respectively. Positive value stands for inflow.
Figure 3.12 Same as Figure 3.7, but for winter in 2012.

Figure 3.13 Tidal elevation (m) along Section C during sampling period in winter 2012. (a), (b) and (c) are for cruises in Jan 2011, Dec 2010, Feb 2011, respectively. (a) is tidal elevation for small ebb, small flood period. (b) and (c) are small ebb, big flood period.
Figure 3.14 Velocity normal to section C (a)-(c), salinity (d)-(f) and temperature (g)-(i) distribution along the section C during ebb period in summer. (a), (d) and (g) were sampled during the cruises in Jan, 2011; (b), (e) and (h) were sampled in Dec, 2010; (c), (f) and (i) were sampled in Feb, 2011. Positive value stands for landward currents.
Figure 3.15 Same as Figure 3.14, but for flood period.
Figure 3.16 Volume, salt and heat transports for Dec 2010 (left column), Jan 2011 (middle column) and Feb 2011 (right column). Blue and red bars are for ebb and flood tide, respectively. Positive value stands for inflow.
Figure 3.17 Net volume, salt and heat transports for three cruises in summer and winter. Yellow bars are for Case I; red and purple bars are for Case II. Positive value stands for inflow.
Figure 3.18 Observation (a)(b) and model (c)(d) comparison on surface salinity in summer and winter.
Figure 3.19 Observation-model comparison of Section C salinity profile during ebb and flood in summer and winter. Large figures are observation results and the small ones are model's.
Figure 3.20 Comparison of volume transports (m$^3$/s) for Case I and II in observation and model data. Small figures on the right top are the observed (blue line) and the simulated (red line) tidal elevation. Positive value stands for inflow.
Figure 3.21 Tidally-averaged currents on the surface (a) and bottom (b) distribution in model results in summer. Plot grid interval: 8 grids × 8 grids.

Figure 3.22 Same as, but for the winter.
Figure 3.23 Salinity (a) and temperature (b) distribution in model results in summer.

Figure 3.24 Same as Figure 3.23, but for the winter.
Figure 3.25 Normal velocity, salinity and temperature profile for summer (upper panel) and winter (lower panel) in model.

Figure 3.26 Cross-shore current profile over section C for ebb and flood period in summer and winter. All values are averaged from 30 to 48 days.
Figure 3.27 Volume, salt and heat transport across section C in summer (left panel) and winter (right panel). Tidal elevation for section C in summer (a) and winter (b) are in the first row. Transports and flux are smoothed by 36 hours. Shading parts are spring and neap periods. Positive value stands for inflow.
Figure 3.28 Current and salinity profile during neap and spring tide period in summer. Neap period is the mean value from Day 33 to 36 corresponding to Figure 3.28 and spring period is mean value from Day 41 to 44.
CHAPTER 4 DISCUSSION

4.1 Salt and heat balance analyses

In this section, we are going to examine the salt and heat budget and analyze the salt and heat fluxes across section C at the entrance of the estuary. We simplified the salt and heat flux equations by regarding density and heat capacity term as constant. The factor \( \rho C_p \) is essentially a constant equal to \( 4.09 \times 10^6 \text{ W} \cdot \text{°C}^{-1} \cdot \text{m}^{-3} \) [48]. MacCready [49] presents the calculation of salt flux decomposition. Methods are described briefly as below. Here, we used the classical Eulerian method for decomposing the tidally averaged salt flux through a cross section of estuary. This gives rise to the river, exchange flow, and tidal fluxes. Following Lerczak et al. [27], the subtidal salt flux \( F \) through a section is given by

\[
F_S = \langle \iint u S dA \rangle, \tag{4.1}
\]

in which the angle bracket represents a low pass subtidal filter (25 hours), \( u \) is axial velocity, \( S \) is the salinity and \( A \) is the cross-sectional area of integration. The cross-sectional integral within the angle bracket represents the instantaneous salt flux. \( u \) and \( S \) are decomposed into tidally and cross-sectionally averaged \( (u_0, S_0) \), tidally averaged and cross-sectionally varying \( (u_1, S_1) \), and tidally and cross-sectionally varying \( (u_2, S_2) \) components. The tidally averaged area properties are defined by

\[
A_0 \equiv \langle \int dA \rangle, \quad dA_0 \equiv \langle dA \rangle, \tag{4.2}
\]

The sectionally and tidally averaged velocity and salinity are then

\[
u_0 \equiv \frac{\langle udA \rangle}{A_0}, \quad s_0 \equiv \frac{\langle sdA \rangle}{A_0}, \tag{4.3}
\]

And the sectionally varying tidally averaged terms are defined by

\[
u_1 \equiv \frac{\langle udA \rangle}{dA_0} - u_0, \quad s_1 \equiv \frac{\langle sdA \rangle}{dA_0} - s_0, \tag{4.4}
\]

The sectionally and tidally varying remainders are

\[
u_2 \equiv u - u_0 - u_1, \quad s_2 \equiv s - s_0 - s_1, \tag{4.5}
\]

The subtidal salt flux are decomposed into three parts (river, exchange, and the tidal) as

\[
F_S = \langle \iint (u_0 + u_1 + u_2) (S_0 + S_1 + S_2) dA \rangle \\
\approx \langle \iint (u_0 S_0 + u_1 S_1 + u_2 S_2) dA \rangle, \tag{4.6}
\]
Here, we eliminated the other six of nine terms in Equation (4.6) by the properties
\[ \int u_1 dA_0 = 0, \int S_1 dA_0 = 0, \langle u_2 dA \rangle = 0, \text{ and } \langle s_2 dA \rangle = 0, \]
Then the equation turns into \( F_S = F_0 + F_E + F_T \).
\[ (4.7) \]
The left term \( F_S \) is the storage of salt. The first term \( F_0 \) on right side is the salt flux owing to subtidal cross-sectionally averaged transport, including the salt loss due to winds Chen and Sanford [17]. This term removes salt from the estuary generally. The second term \( F_E \) is the subtidal shear dispersion resulting from gravitational circulation. The third term \( F_T \) is the tidal oscillatory salt flux. \( F_E + F_T \) adds salt to the estuary.

In this thesis, we also decomposed the tidally averaged heat flux at a cross section following the same method with salinity term replaced with temperature. The results in summer and winter are shown as below.

Figure 4.1 shows the salt flux decomposition at section C in summer and winter based on the numerical model outputs. In summer, the subtidal barotropic \( F_0 \) is negative with daily fluctuations, indicating that salt loss due to river runoff. The salt flux \( F_E \) resulting from the two-layer estuarine circulation flows is positive thus supplies salt into the estuary. In order to better identify the fluctuation, \( F_T \) is smoothed by 25 hours and presented in red solid line. \( F_T \) is always positive so that tidal pumping supplies salt into PRE. And \( F_T \) dominates over \( F_E \) during spring tide period. The salt storage term shows a similar pattern with \( F_E \). Therefore, the salt balance at a cross section between the estuary and shelf is maintained by the competition between the salt loss due to river discharge and the salt gain due to estuarine exchange flows and tidal pumping, as documented in other partially mixed estuaries by Simpson et al. and Lerczak et al. [27, 50]. In winter, salt balance across section C shows similar pattern with that in summer. While in winter, \( F_0 \) is still negative but smaller than that in summer with decreasing runoff. The salt flux balance is a competition between gravitational circulation, tidal pumping and river. The total effect is salt outflow. Compared with Figure 4.1(a) and Figure 4.1(b), it can be found that subtidal shear dispersion \( F_E \) is much stronger in summer which indicates that enhancement in river discharge contributes to exchange flow, which results in salt gain during neap tide period in summer. Meanwhile, it can be found from the red dashed lines that tidal oscillatory salt flux fluctuates significantly although the total effect is positive.
Heat flux decomposition at section C presents a different story. The barotropic subtidal flux $F_0$ is much larger than the other terms and dominates the storage of the heat flux in summer and winter (Figure 4.2). In summer, river water is warmer than seawater thus heat flux $F_E$ resulting from exchange flow is negative thus causes heat loss from the estuary. $F_0$, which is mainly contributed from river discharge and subtidal heat flux due to winds, dominates the storage of heat flux in the estuary ($F_0/(F_E + F_T) \approx 10$). In winter, seawater with higher temperature transports heat flux into estuary by estuarine exchange flows and tidal pumping. Heat loss is mainly caused by river flow term ($F_0/(F_E + F_T) \approx 3$).

4.2 Forcing process in the transport

In previous section, we decomposed the tidally averaged salt and heat flux through C section. To understand how different physical processes including tide, river and wind affect the volume transport, salt and heat flux, we conducted several simulations (Table 2.1) with different forcing schemes to identify the dominant forcing process in the region. Results from the eight runs are presented and discussed in this section coupled with currents, salinity and temperature profile along section C under different forcing conditions in summer and winter respectively.

Results of the eight cases averaged over 30 to 50 days are presented and for the convenience of comparison among different cases, the fields with same variables of 8 cases are listed in each row. The structures of the section C current field, salinity and temperature profile are greatly affected by tidal forcing, river discharge and wind.

In summer, tide is turned off in Cases 3 and 7 (NT) for winter and summer respectively. In the horizontal distribution, the seaward movement and the position of the plume are determined by tidal forcing [8, 11, 12]. Here we focus on the section connecting with estuary and shelf. Compared with Figure 4.3 (a)(e)(i) and (b)(f)(j), the river outflow concentrates near the surface and seawater is in the bottom layer when tide is absent (Figure 4.3f, j). River water from upstream is transported above west channel under the westerly wind. The seaward currents on the surface and landward currents in the bottom are both reduced (Figure 4.4b). In Cases 2 and 6 (HR), river discharge is reduced in half. Less fresh water piles up at the head of the estuary and the axial pressure gradient decreases, as a result, the seaward currents are slower than
standard case. Meanwhile, the plume intrusion at the bottom slows down. It is clear to see that the mean salinity is higher and temperature is lower, especially in the surface layer. In Cases 4 and 8 (HW), we halved the upwelling favorable wind stress. It shows that the intrusion currents are slightly weaker in the bottom at the west part (Figure 4.3d). And the other features are almost same as the standard case, which indicates halving the wind stress has little effect on the circulation and hydrographic features of section C in summer.

In winter, seaward currents are in the west side of the estuary and sea water intrudes only from the east side along west channel of PRE (Figure 4.4a). The seaward currents are weaker than that in summer. River water concentrates along the west side (Figure 4.4e, i). In the no tide case, Coriolis and wind effects dominate the circulation in the estuary and shelf. The head of the plume is located in a much shoreward position at the entrance of the estuary with tide [8]. More salt water occupies the eastern part of the estuary and the shelf near the coast. River decrease in winter causes weak seaward currents in the west shore, but it has little effect on landward intrusion in the east shore. Salinity and temperature across section increase due to less fresher and colder water from river (Figure 4.4g, k). And wind diminishment causes larger river runoff with Ekman effect decreasing across the section compared to the standard case.

The tidally averaged volume, salt and heat transport are presented in Figure 4.5.

\[ \Delta \varphi = \varphi_{standard\ case} - \varphi_{test\ case}, \]

\( \varphi \) stands for an arbitrary variable of volume, salt or heat transport. In summer, volume and heat transport are affected greatly by the change of river. It is not surprising that river runoff is imported from upstream and should export from the mouth to maintain the volume balance in the estuary. Change in river takes directly effect on the net volume transport. And temperature has a small range of <3°C (Figure 3.2). The change of heat transport is similar to volume transport. Salt flux turns to be inflow when river is halved. Based on Figure 4.3(c)(g), much saltier water appears in the middle and bottom layer where currents is landward, which can illustrate the phenomenon. When the tide is turned off in Case 3 without other forcing changing, volume, salt and heat transport outflow increase, which shows that tide induces inflow across the section. Especially, salt transport outflow increases significantly. As stated above, landward currents in the middle and bottom layer reduce greatly when tide is absent. The salinity profile
shows a great difference with less vertical mixing. The ratios of the no-tide case and the standard case are ~17% for volume and heat transport, while this value reaches ~600% for salt flux. Wind changes for Case 4 take the smallest effect on the transports and hydrography across the section. Halving wind stress causes slightly more outflow which is reflected in Figure 4.3 (h) (i). The ratios of the halving wind and the standard case for volume and heat flux is ~2% while for salt flux is ~33%.

In winter, it is clear that change in tides affect the three transports most. Similar to summer, more transport is exported to the shelf across section when tide is absent and heat loss is mainly due to volume transport in the no-tide case. The difference of heat and volume transport between the no-tide case and the standard case takes up over 60% of the standard case. However, salt flux has nearly doubled when tide is absent, which results in the large seaward currents in the west shore. Lower river discharge has little effect due to minimal runoff in winter. When wind is halved in winter, it takes little effect on volume and heat transports while salt flux difference ratio is about 26%. The wind decrease in winter takes opposite effect on the three transports to summer. Decrease in northeasterly wind stress causes outflow transport reduction. We found seaward transport decreasing mainly in the middle part of the estuary which results in this reduction.

4.3 Currents intrusion controlled by variable winds in summer

In this section, we will discuss the currents intrusion controlled by variable winds combined with observation and model results in summer. Time-series of current velocity data were collected at TS station (Figure 2.1) for five days from August 6th 2:00 am to 11th 2:00 am, 2012. Wind stress at Tai’O station during the measuring time and subtidal cross-shore current velocity are shown in Figure 4.6. Subtidal velocity is extracted with the T_TIDE [38].

In summer, the shelf area was under influence of southwesterly wind, which is upwelling favorable. Long-shore eastward wind causes offshore transport of surface waters due to the Coriolis force associated with the earth rotation. Continuity of mass requires deeper water must rise to replace that which is driven offshore. This region of divergence is an upwelling region and is associated with cooler water near the surface. This motion of water in the offshore direction leads to a pressure gradient perpendicular to the shore which drives a longshore,
eastward current. Upwelling regions are important to the coastal ecosystem that brings nutrients to the surface from deeper water. Semidiurnal relaxation events occurred when the southwesterly wind relaxes. Landward currents are observed at sub-surface layer between 4-6 m or even deeper after the along-shore wind relaxation period. To have a better understanding, we conducted a numerical experiment to examine the effect of relaxation of upwelling wind on the variability of the cross-shore transport. In this experiment, along-shore wind is relaxed in the way similar to the observation in Tai’ O station. And other forcing in this case are the same as Case 3 in Table 2.1. We found that a response similar to observation is found in the model result (Figure 4.7), which shows an intrusion in the sub-surface layer at ~5m after upwelling favorable wind relaxation. The velocity and stratification of coastal buoyancy currents are influenced by wind forcing [50]. Upwelling favorable winds produced cross-shelf pressure gradient. The pressure gradient force (PGF) was established between fresher water near the coast and seawater offshore. The response of the buoyancy current was sensitive to the variation of upwelling favorable wind. So we inferred that the relaxation of alongshore wind leads to decreasing Ekman transport. T. Zu and Gan [7] found that the net landward transport across the entrance section strengthens during upwelling relaxation and weakens during upwelling with surface Ekman transport compensates the intrusive bottom current. And the water exchange rate between the shelf and estuary increases during upwelling. To get a better understanding of the controlling factor for the intrusion at subsurface at T-S station, forcing mechanisms are studied in next part.

**Dynamic analysis**

To identify the forcing process, we use the time series of the depth-averaged momentum term balances from Equation (4.9) and Equation (4.10) as well as depth-dependent momentum term balances from Equation (4.11) and Equation (4.12).

The forcing mechanisms involved at time-series station in summer are analyzed by the depth-averaged along-shore (x-direction in the model) and cross-shore (y-direction in the model) momentum Equation (4.9) and Equation (4.10)

\[
\frac{\partial U}{\partial t} = fV - \frac{1}{\rho_0} \frac{\partial P}{\partial x} + \frac{1}{\rho_0 D} \tau_s^x - \frac{1}{\rho_0 D} \tau_b^x - NL, \tag{4.9}
\]
\[
\frac{\partial V}{\partial t} = -fU - \frac{1}{\rho_0} \frac{\partial P}{\partial y} + \frac{1}{\rho_0 D} \tau_\gamma^y - \frac{1}{\rho_0 D} \tau_\delta^y - NL. 
\] (4.10)

where \((U, V)\) are depth-averaged barotropic velocity in \((x, y)\); \(f\) is the Coriolis parameter; \(\rho_0\) is the reference density; \(P\) is depth-averaged pressure; \(D\) is the total water depth; \((\tau_\alpha^x, \tau_\alpha^y)\) are the surface wind stress components; \((\tau_\beta^x, \tau_\beta^y)\) are the bottom wind stress components; and NL stands for the nonlinear horizontal advection and viscosity terms. The term at left side of the equal sign is acceleration term (accel). The first term at the right side is Coriolis force (cor); the second one is pressure gradient force (PGF); the third one is surface wind stress (sstr); the fourth one is bottom stress (bstr). The sum of first and second term at right side is the ageostrophic term (ageo). The barotropic dynamics at T-S station in summer are presents in Figure 4.8.

We also use depth-dependent momentum Equation (4.11) and Equation (4.12) to analyze the balance at ~5m depth. The depth-dependent momentum equations are

\[
\frac{\partial u}{\partial t} = f v - \frac{1}{\rho_0} \frac{\partial p}{\partial x} + (vvis) + (hadv + vadv), \] (4.11)

\[
\frac{\partial v}{\partial t} = -f u - \frac{1}{\rho_0} \frac{\partial p}{\partial y} + (vvis) + (hadv + vadv). \] (4.12)

where \((u, v)\) are depth-dependent velocity; \(p\) is depth-dependent pressure; \(vvis\) is vertical velocity; and \((hadv, vadv)\) are horizontal and vertical momentum advection. Other terms are analogous to those in Equation (4.9) and Equation (4.10). Horizontal viscosity is neglected here.

From the depth-averaged along-shore momentum balances in Figure 4.8, a positive cor, or the landward quasi-geostrophic current, forms in a few hours after along-shore wind relaxation in \(x\)-direction. The cross-channel PGF is formed as a result of the cross-shore gradient of dynamic height induced by river plume and Ekman transport. This term is balanced by the negative cor in \(y\)-direction, which indicates an eastward current. After water piles up at a certain level, mass continuity generates a sub-surface landward currents.

In order to analyze the balance more clearly, a depth-dependent momentum term balance at ~5m is presented in Figure 4.9. In the cross-shore balance, a negative Coriolis force balances the positive PGF associated with the onshore flow at ~5m depth. PGF peaks at the lowest point of along-shore wind. The balance turns into a geostrophic balance, in which a northward PGF forms an eastward along-shore geostrophic current during upwelling. The geostrophic balance
forms around largest along-shore cor point while it relaxes as along-shore wind increases. accel has a similar variation with ageo term. The upwelling is clearly seen from the hadv term and it is balanced by vadv compensation from bottom layer. The northward current can be driven by positive PGF which is set up by the upwelling wind forcing over the shelf.
Figure 4.1 Salt flux decomposition at section C in summer (a) and winter (b). $F_E$, shear dispersion due to baroclinic exchange flow; $F_T$, tidal pumping; and $F_0$, subtidal barotropic transport. Red solid line is $F_T$ smoothed by 25 hours.

Figure 4.2 Same as Figure 4.1, but for the heat flux.
Figure 4.3 Averaged currents (upper panel), salinity (middle panel) and temperature (lower panel) distribution of section C from Day 30 to 50 in summer. (a)(e)(i) are standard case; (b)(f)(j) are no tide case; (c)(g)(k) are half river case and (d)(h)(l) are half wind case respectively.
Figure 4.4 Same as Figure 4.3, but for the winter.
Figure 4.5 Averaged volume, salt and heat transport from Day 30 to 50 and the differences between the specific case and the standard case in summer (a)(b)(c) and winter (d)(e)(f).
Figure 4.6 Time-series of (a) wind stress at Tai’O station and (b) subtide cross-shore velocity of T-S station from August 6th to 11th, 2012. The x-axis is Julian hours starting from August 6th 2:00. Positive value stands for landward.

Figure 4.7 Time-series of (a) wind stress and (b) subtide cross-shore velocity of T-S station in model from Day 40 to 45. Positive value stands for landward.
Figure 4.8 Time-series of terms (m/s²) in (a) along-shore (x) and cross-shore (y) depth-averaged momentum balances at T-S station in summer (shown in Figure 2.1). The x-axis is the number of hours from Day 40 in model. Positive value stands for landward.

Figure 4.9 Time-series of terms (m/s²) in (a) along-shore (x) and cross-shore (y) depth-dependent momentum balances at water depth of ~5m for T-S station (shown in Figure 2.1). The x-axis is the number of hours from Day 40 in model.
CHAPTER 5 SUMMARY

PRE is the 2nd largest estuary in China with mixed bathymetric features of channels, shoals and tidal flats. There are two deep channels in the estuary, which modulate the circulation and become the main channel to link PRE water with adjacent shelf. We investigated circulation, hydrographic features and associated salt, heat transports using *in situ* field measurement and process-oriented numerical modeling. We also examined the dominant physical processes that control the transports and fluxes in response to forcing of river discharge, wind and tides.

Our study showed that the PRE circulation is jointly controlled by Pearl River runoff, tidal currents, wind and buoyancy-forced current. It is also largely regulated by the bathymetric features in the region. In summer, fresh water from Pearl River occupies the entire estuary in the surface and upper estuary in the bottom. The river plume is formed after freshwater spreads to eastern part of the adjacent shelf by the southwesterly wind-driven current. A salinity front appears near the entrance of PRE between the freshwater and seawater. PRE is highly stratified and is a salt wedge estuary in summer. In winter, the relative small discharged freshwater flows along the west bank of the estuary under Coriolis effect and northeasterly wind forcing. It forms an apparent salinity front oriented NE-SW from the surface to the bottom in the estuary. The PRE is considered to be partially mixed in winter. The circulation and hydrographic features are generally consistent with previous studies.

Tides greatly modify the circulation, hydrographic features and transports in PRE. According to the observation data, tidally-driven currents are dominant in the axial section of the PRE. Based on the *in situ* observational data, we demonstrated the intra-tidal responses across the boundary between estuary and shelf. Two scenarios with different tidal patterns of big-ebb-small-flood and the big-ebb-big-flood are examined for summer. The strongest ebb current is found at the low-low tidal phase with the maximum seaward transport. The flood current occupies the entire section at the high-high tidal phase with largest landward transport. In winter, the circulation of the two scenarios with different tidal patterns of small-ebb-small-flood and small-ebb-big-flood are investigated. Strongest flood current occurs in stations C2-C3 according to the tidal phase during the big-flood tidal phase. Low salinity/cold temperature river waters are inversely correlated with the magnitude of the flood current. Combined with
flood and ebb current during both winter and summer, it can be concluded that the flood current starts from the bottom at the eastern side of estuary while the ebb currents exists at the western side. The stratification is the strongest during ebb tide in the lower part of the estuary where the river water encounters sea water and tidal straining effect occurs.

The net transports across the boundary of the estuary-shelf are estimated. In the above two tidal patterns, the volume, salt and heat transports are all directed seaward during small flood period in both summer and winter, while they are both landward in the big-flood tidal phase in the two seasons. The averaged net volume transport is twice larger than that in summer while the difference between salt and heat flux is reduced in winter. Mainly seaward transports occur during ebb tide and mainly landward during flood tide.

Using a three dimensional numerical model, we have studied the subtidal, intra-tidal circulation characters in the PRE in summer and winter. The model results provide a qualitatively similar circulation and transport as those observed in the filed measurements. We have conducted process-oriented modeling study to examine the characteristics of the transports of volume, salt and heat fluxes. The analyses reveal that the heat transport is mainly dominated by magnitude of the volume transport due to small temperature gradient in PRE and shelf area. However, salt flux presents a different pattern for both the velocity and salinity oscillations have a great contribution to the salt flux. In summer, landward subtidal transports across the cross-estuary boundary occur at the bottom layer in the western part of the PRE and in the east channel. The outflow, however, concentrates on the surface in the west channel. In winter, landward transports occur mainly along west channel, and the seaward currents peaks at the west side of the PRE. Seaward volume and heat transports in winter are much smaller than those in summer due to smaller magnitude of river discharge, while salt transport shows a larger value in winter with overall higher salinity in PRE.

Tidal prism varies considerably in PRE, which affects significantly the ratio of river flow to tidal volume and the exchanges between estuary and shelf, especially in winter. Transports during ebb or flood tide are many times more than sub-tidal transports, although the net transports are determined by the sub-tidal transports. These volume, heat and salt fluxes also exhibit spring-neap variations. Our results confirm Geyer and Cannon's [43] hypothesis that increased mixing during spring tides results in reduced exchange flow between the estuary and
the adjacent shelf. It appears that the variations of mixing are more important than advective nonlinearity in PRE, leading to a tendency for stronger exchange flows during neaps than springs.

We also decomposed the tidally averaged salt and heat flux into subtidal cross-sectionally averaged transport, shear dispersion and tidal oscillatory flux. The results indicate that salt loss in the estuary is mainly due to river runoff. The exchange flow and tidal pumping provide salt flux into estuary. Salt balance is maintained by these three processes. Barotropic subtidal heat flux dominates the storage of the heat flux in summer and winter.

This study also examined how transports vary with different forcing in different seasons. Change in river discharge takes directly effect on the net volume and heat transports. Tidal forcing also leads to great changes in transports due to mixing effect by tides. It is found that tides have the largest effect on salt transports in summer and winter. The volume, heat and salt transports have least sensitivity to the change of wind magnitude, and the wind effect has opposite effect on these fluxes in the two seasons. Both field measurements and modeling result show that the landward sub-surface currents over the shelf was strengthened during upwelling wind relaxation. The dynamic analysis indicates that the strengthening is caused by the shoreward pressure gradient force built up during the upwelling.

This study provided an investigation of sub-tidal and intra-tidal circulation, hydrographic features and corresponding volume, salt and heat transports in the PRE and adjacent shelf based on the field measurements and the process-oriented numerical modeling. It enhanced our understanding of the exchange and transport between PRE and the adjacent shelf and the underlying process and mechanism.
REFERENCE


[24] W. Gong, J. P. Y. Maa, B. Hong, and J. Shen, "Salt transport during a dry season in the


