The circulation and salt stratification over the south branch of the Yangtze estuary

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Abstract. The hydrodynamics of China’s Yangtze Estuary is very complicated, due to highly irregular bathymetry, large freshwater discharge from the Yangtze River, strong tidal currents, large salinity gradients and strong interaction between the river and sea waters. Oceanographic measurements were made over the lower part of the Yangtze Estuary (the South Branch of the Yangtze Estuary) to examine the circulation structure and intra-tidal variability of salinity. The least-squares fit to main harmonics was made to explore the sub-tidal circulation. The observed ADCP currents were decomposed into the along-channel and cross-channel velocity to examine the spatial and temporal variability of circulation in the region. The observed study in the 2005 wet season and the 2009 dry season in different channels showed that the tidal straining effect is a major forcing mechanism on salinity stratification and sub-tidal circulation of the Yangtze Estuary. The tidal straining induced circulation was found to be equally important as the classical gravitational circulation in the Yangtze Estuary. This played an important role in maintaining semi-diurnal periodic salinity stratification in the region.

1. Introduction
The Yangtze Estuary is the largest estuary in China which is located on the east coast of China at the mouth of Yangtze River. Geyer and MacCready [1] described it as a time-dependent salt wedge estuary. There are large fresh water buoyancy flow and strong mixing processes. The tidal boundary layer can reach the surface in the water column. Giddings et al [2] found the strong forced salt wedge estuaries (such as the Yangtze Estuary) exhibited more intra-tidal variability than that of well and partially mixed estuaries. The Yangtze Estuary can exhibit more variability in currents, stratification, and horizontal density gradients on a tidal time scale than other coastal-plain estuaries such as the Columbia River estuary [3] and the Hudson River estuary [4]. Hence, it is of great interest to find out the variability of mixing and stratification over the flood-ebb tidal cycle in the Yangtze Estuary. Understanding the circulation and salt stratification process in the Yangtze Estuary is very important for the ecosystem in the estuary.

The significant efforts were made in the past to examine the classical gravitational circulation in many coastal-plain estuaries [5-9], the gravitational circulation was thought to result from a balance between the barotropic pressure gradient, the baroclinic pressure gradient and the shear stress by tidal...
mixing. The shear stress here was assumed to be tidally averaged, based on a constant eddy viscosity acting on the shear. However, the shear in the tidal current tends to induce a periodic variation due to flood-ebb asymmetry, it was found that the observation of the circulation in most estuaries has significant tidal asymmetry in turbulent mixing and salinity stratification [3]. It was also found that salinity stratification affected vertical eddy viscosity and longitudinal salinity gradient, which were two of the primary factors determining the strength of the along-channel mean currents. The salinity stratification of water column in most estuaries is unsteady with space and time changes during the tidal cycle due to the shear-viscosity covariance. During the flood tide, the vertical mixing was enhanced while the stratification was reduced, resulted in reduced vertical shear stress. During the ebb tide, the restratification reduced vertical mixing and then enhanced vertical shear stress [10]. The longitudinal salinity gradient was an important factor to shape the estuarine circulation and stratification. It was assumed to be independent of time and space change in previous studies.

The interaction between the along-channel salinity gradient and the vertical shear in the along-channel velocity at tidal time scales was firstly referred to as tidal straining [11]. The tidal straining force tends to develop stratification during ebb tides and reduce stratification during flooding [12,13]. The sub-tidal circulation was created under the presence of variable stratification found by Stacey et al [14]. The straining circulation was contribution of tidal mixing asymmetry to estuarine circulation. The asymmetry was presented as enhancement of vertical mixing during flood and suppression of vertical mixing during ebb. So the tidal straining effect was defined as the covariance between eddy viscosity and vertical shear of longitudinal currents in a more general sense. Burchard and Hetland [15] examined turbulence model and found that tidal straining was an important generation mechanism for sub-tidal circulation in switched mixing-stratified estuaries in recent study. They showed that the contribution of tidal straining amounts to typically two-thirds of the estuarine circulation at the maximum, compared to a one-third contribution from gravitational circulation. So the role of tidal straining process has been highlighted in many estuarine circulation studies, including the circulation process in the Yangtze Estuary.

Most studies on the estuarine circulation in the Yangtze Estuary focused on the basic processes of water and sediment changes and salt intrusion [16,17]. However, the role of salinity stratification in the estuary has not been extensively studied, and more attention needs to be given to issues such as the nature of estuarine flows and the important role of vertical exchange of materials by turbulent mixing. Different from previous studies, a main objective of this study on estuarine circulation and stratification in the Yangtze Estuary is to addressing the role of periodical salinity stratifications and of vertical exchanges. The study of periodical stratification process driving by tidal straining circulation has never been studied in the Yangtze Estuary. The periodical salinity stratification variability reflects the interaction between vertical mixing strength and horizontal gradient force during tidal processes. To study the vertical unsteady stratification and mixing mechanism of the Yangtze Estuary is very important. Numerical circulation models have been used increasingly to study the stratification processes as well as temporal and spatial variations of estuarine circulation. However, there is no perfect numerical circulation model that is able to resolve all physical processes in the estuary. Therefore, more observational studies are needed to better understand estuarine circulation and stratification variability in different estuaries. Furthermore, oceanographic observations are needed to assess model accuracy, which is a key step for model development and application. To investigate stratification process over the south branch of the Yangtze Estuary, the observational study was made using ADCP and salinity measurements.

The observational study about shallow stratified estuary by Van Maren and Hoekstra [18] showed that the intra-tidal stratifying and de-stratifying mechanisms depended strongly on the seasonally varying discharge. It was also found that the Yangtze Estuary has highly variable river discharge during dry and flood season of the year, which was a dominant force causing a strong stratification outside of the mouth. To examine the tidal straining effect on the intra-tidal variability of salinity stratification, the measurements at these two typical seasons (flood season in 2005 and dry season in 2009) were selected to quantitatively estimate the potential energy needed for stratification generated
by circulation, tidal straining and stirring. Basing on the observations in 2005 and 2009, the paper intends to examine the tidal and sub-tidal circulation pattern, salinity stratification and mechanism responsible for periodic stratification in the South Branch of the Yangtze Estuary. In particular, we use observations from the South Branch to study the spatial and temporal patterns of circulation and stratification as well as tidal variability of salinity stratification mechanism.

The structure of the paper is as follows. Section 2 addresses the field measurements in the Yangtze Estuary and methods of analysis. Section 3 presents sub-tidal and tidal circulations in the South Branch estuary based on the observations. Section 4 discusses the salt stratification and tidal straining effects in the South Branch. A conclusion is included in section 5 to summarize the results and findings in present study.

2. Materials and methods

2.1. Study area

![Bathymetric map of Yangtze Estuary in China and locations of measurements during field program in August 2005.](image)

**Figure 1.** Bathymetric map of Yangtze Estuary in China and locations of measurements during field program in August 2005. Measurements were made along five transects, marked by AA’ (Biandan Sandbank), BB’ (Hengsha waterway), CC’ (North Channel and South Channel), DD’ (North Passage), and EE’ (South Passage). Islands of Changxing, Hengsha, Jiuduan Sandbank and Chongming are marked by #1, #2, #3 and #4, respectively. Triangles mark tidal stations and bold solid circles show vertical measurement stations. Two solid lines in the North Passage are converging jetties of the deep water channel. The 10-m and 5-m contour lines are water depths below mean sea level.

The Yangtze Estuary is the largest estuary in China. The estuary has three-order branches and four outlets to the East China Sea (figure 1). Downstream from Xuliujing, the estuary branches into the North Branch and the South Branch, forming Chongming Island between the two branches. The South Branch separates into the North Channel and the South Channel, forming Changxing and Hengsha Islands between the two channels. The South Channel further bifurcates into the North Passage and the South Passage, forming Jiuduan Shoal. There are large variability in currents, stratification, and
horizontal density gradients on a tidal time scale within the estuary. The general circulation and hydrography in the Yangtze Estuary are influenced by tides, atmospheric forcing and freshwater discharge from the Yangtze River. Because of long-term effects of the Coriolis force and other factors, the estuary has evolved into a branching estuary. The asymmetric tides then induce the hydrodynamic behavior of these branches. The main discharge flows into the South Branch, and the flow diversion ratio of the northern branch has decreased continually in recent years. The present study is focused on the tidal and sub-tidal circulation patterns, salinity stratification, and related periodic processes in the South branch of the Yangtze estuary.

In this study, the South Branch and the adjacent waters including the North Channel, the South Channel, the North Passage and the South Passage are referred to as the South Branch for simplicity. The Hengsha waterway is a junction of the waterway of the North Channel and the North Passage. There are three sub-areas in the deep waterway of the North Passage: the upper channel on the entrance of the North Passage near the Hengsha Island (CB1, CS0, and CS1 marked in figure 1); the middle channel (CB2, CS2, and CSW) which is the curved section of the passage; and the lower channel (CS3, CS4, and CS5) which is connected to the open mouth of the estuary.

The Yangtze River has an annual mean monthly discharge of about 29,300 m$^3$/s, with a maximum monthly discharge of about 49,500 m$^3$/s in July and a minimum discharge of about 10,500 m$^3$/s in January. The Yangtze Estuary is a meso-tidal estuary with a typical tidal range of about 2.66 m at Zhongjun (figure 1) near the mouth. The tidal range decreases upstream from the mouth to the upper part of the Yangtze Estuary. The annual average suspended sediment concentration in the open mouth of the estuary is about 0.5 kg/m$^3$.

Oceanographic measurements used in this study are time-series measurements of sea level, currents, temperature and salinity taken at several transects and stations in the Yangtze Estuary by the Hydrology Bureau of Yangtze River Water Conservancy Commission in flood year 2005 and dry year 2009. The measurements were carried out at two specific areas: one in the upper part of the South Branch and the other in the lower part of the South Branch with three outlets (i.e., the North Channel, North Passage and South Passage) during a wet season with spring tides in 2005. The tidal level of the study area is highly variable spatially, with the water depth of less than 10 m below the mean sea level at the river mouth and the upper river (see in figure 1). The tidal range at the open mouth of the Yangtze Estuary (31.1° N, 122.28° E, Niupijiao Station marked in figure 1) was about 3.88 m and the maximum river discharge at the Datong Station was about 40,000 m$^3$/s when the measurements were taken in 2005.

2.2. Field surveys and water sample analyses

The observations used in this study also include the ocean currents measured at five transects (AA', BB', CC', DD', and EE', marked by dashed lines in figure 1) using ship-board ADCP (Acoustic Doppler Current Profiler, RD-DR0300 and RD-DR0600) with Ashtech BR2G/DGPS-1 (with HyPack for windows software) beacons for positioning and navigation. The accuracy of the GPS position is 0.75m and can be synchronous with ADCPs. The ADCPs were mounted onboard vessels, which transacted at speeds less than 3.0 m.s$^{-1}$. These down-looking ADCPs with frequencies of 300 KHz and 600 KHz were deployed at 1 m below the sea surface with a 1 m vertical sampling step. The ADCP ping rate is about 1 to 2 pings per second at each transects. Additional measurement transects were performed until a good precision of velocity data was reached. The deepest bin of the ADCP measurements was about 10% of the local water depth above the seabed. The GPS data were logged concurrently with the ADCP data to ensure accurate positioning of the instruments. The shipboard ADCP measurements were extrapolated to the side-lobe area and the water surface and the bottom at each location by interpolation model, which had been calibrated by a large amount of data from propeller-type current meter measurements that are not presented here. In this study, only ADCP measurements acquired along each transect with a horizontal sampling step of 100-300 m at 6 depths between surface and local bottom depth h (0, 0.2 h, 0.4 h, 0.6 h, 0.8 h, h) were used. The observed currents were linearly interpolated in the vertical direction. The ADCP measurements were conducted
hourly during two 28 h cycles (include two M_2 periods of tidal cycle). During the flood season in 2005, the first period was from 5:00 August 19, 2005 to 8:00 August 20 over the open mouth and the South Passage area. The second period was from 7:00 August 21, 2005 to 11:00 August 22 over the upper-estuary area and the North Channel respectively. During the dry season in 2009, the observed period in the North Passage was from 7:00 April 27, 2009 to 13:00 April 28 and in the South Passage was from 18:00 April 25, 2009 to 23:00 April 26.

During these periods, water samples (about 1 L each time) and single-point velocity measurements were made using the propeller-type current meters at the mouth of the estuary in the North Channel (BG1, BG2, and BG3 marked in figure 1), the North Passage (CS1, CS2 and CSW) and the South Passage (NC1, NC2, NC4, NC5, and NC3) in this paper. There were also water samples taken near transect AA’ and transect CC’, which are located around the fork of the North and South Channel, but the observed salinity is very low in these areas during the two periods. The water samples were filtered for the salinity analysis and then dried and weighted to calculate suspended sediment concentrations. The sampling frequency of the water samples was about one hour and these samples were collected at surface, bottom and 0.2 h, 0.4 h, 0.6 h, 0.8 h at same time with velocity measurements. The salinity data were obtained by applying titration method to water samples and then measuring the chloride concentration.

2.3. Analysis method for sub-tidal circulation

The South Branch of the Yangtze Estuary is an irregular semi-diurnal tide type with significant tidal distortion in the estuary. The main tidal constituents in the Yangtze Estuary are the semidiurnal tidal constituents (M_2, S_2, N_2, K_2), the diurnal tidal constituents (K_1, O_1, P_1, Q_1) and quarter-diurnal shallow water tidal constituents (M_4, MS_4, M_6). These three tidal constituents (M_2, M_4 and K_1) accounted for about 98% of the total tidal variance during the observation periods.

The observed currents and salinity at these transects and vertical profiles over the South Branch during the tidal cycle were used to explore the sub-tidal and tidal circulations and salinity distributions along-and cross-the channels. In order to extract the tidal and residual flow from the current observations, the observed horizontal currents were separated into the tidal flow and sub-tidal flow using the least-squares fit method. The observed flow u’ in terms of the sum of harmonics and the sub-tidal velocity u_o:

\[ u' = u_0 + \sum_{j=1}^{M} A_j \sin(\omega_j t + \phi_j) \]  

(1)

The squared errors(\( \varepsilon^2 \)) between the observed current u’ and the harmonic components is written as:

\[ \varepsilon^2 = \sum_{i=1}^{N} [u - u]^2 \]  

(2)

By defining \( a_i = A_i \cos \phi_i \) and \( b_i = A_i \sin \phi_i \) and by minimizing the about square error with respect to \( u_0, a_i \) and \( b_i \), we have:
The above equation system can be written as

\[
\begin{pmatrix}
\sum_{i=1}^{N} u_i \\
\sum_{i=1}^{N} u_i \sin(\omega t) \\
\sum_{i=1}^{N} u_i \cos(\omega t)
\end{pmatrix}
= 
\begin{pmatrix}
N \\
\sum_{i=1}^{N} \sin(\omega t) \\
\sum_{i=1}^{N} \cos(\omega t)
\end{pmatrix}
\begin{pmatrix}
\sum_{i=1}^{N} \sin(\omega t) \\
\sum_{i=1}^{N} \sin^2(\omega t) \\
\sum_{i=1}^{N} \sin(\omega t) \cos(\omega t) \\
\sum_{i=1}^{N} \cos(\omega t) \\
\sum_{i=1}^{N} \sin(\omega t) \cos(\omega t) \\
\sum_{i=1}^{N} \cos^2(\omega t)
\end{pmatrix}
\begin{pmatrix}
\frac{u_0}{a_i} \\
a_i \\
b_i
\end{pmatrix}
\tag{3}
\]

The above equation system can be written as

\[
B = AX
\]
\[
X = A^{-1}B
\]  
\tag{4}

Based on equation (3), \(u_0\), \(a_i\) and \(b_i\) can be calculated. The amplitude and phase of each tidal constituent can then be calculated from \(a_i\) and \(b_i\). Three principal tidal constituents used in this study are the \(M_2\), \(M_4\) and \(K_1\) harmonic components in the above three tidal constituents. The performance was quantified by goodness and root mean square (rms) errors, defined by:

\[
\text{goodness} = \frac{\sum \left[ <U_{\text{obs}}>-U_{\text{pred}} \right]^2}{\sum \left[ <U_{\text{obs}}>-U_{\text{obs}} \right]^2}.
\]  
\tag{5}

\[
\text{rms} = \left[ \frac{1}{N} \sum (U_{\text{obs}} - U_{\text{pred}})^2 \right]^{\frac{1}{2}}.
\]  
\tag{6}

Where \(U_{\text{pred}}\) is sub-tidal current that resulted from the harmonic analysis and \(U_{\text{obs}}\) is current from observation. In equation (5) the brackets represent the tidally averaged current values. In equation (6) \(N\) is the number of measurements in the time series. Goodness value higher than 95% is considered representative of an excellent agreement between tidal fit results and observations. The rms values is compared with the local tidal currents and if the errors range between 5% and 10%, it can be considered a very good agreement.

The tidal harmonic fit calibration is performed at the transect EE’ in the South Passage. Figure 2 presents the principle axis component (along-channel direction) of the depth-averaged tidal currents estimated from the current observations using the above harmonic analysis. The goodness of the tidal current fit by \(M_2\), \(M_4\) and \(K_1\) components is 0.97 and the rms value was about 2%. The amplitude of depth-mean tidal flow at this location is about 1.33, 0.25 and 0.17 m.s\(^{-1}\) for the \(M_2\), \(M_4\) and \(K_1\) respectively, indicating that the \(M_2\) tidal current is the predominant constituent in the study region. The \(M_4\) tidal current is sufficient to indicate that the shallow water tidal constituents are an important component in the Yangtze Estuary.
Figure 2. Time series of along-channel components of observed (solid lines with diamond symbols) and tidal (dashed lines) depth-mean currents in South Passage. Tidal components (amp1, amp2 and amp3 are currents of M\textsubscript{2}, M\textsubscript{4}, and K\textsubscript{1} components respectively) were estimated from the observed currents using tidal harmonic analysis. The residual (mean) is the difference between observed and tidal currents. The agreement between tidal fit results and observations were performed by goodness values and rms (root mean square) errors. The tidal currents shown are those using (a) M\textsubscript{2} only, (b) a combination of M\textsubscript{2} and M\textsubscript{4}, and (c) a combination of M\textsubscript{2}, M\textsubscript{4} and K\textsubscript{1} components.

2.4. Along- and cross-channel current decomposition

The observed along- and cross-channel currents at transects were rotated according to the coordinate system and decomposed by the principle component analysis (PCA) to further study the lateral circulation and vertical distributions during the semidiurnal tidal cycle. The measurements made by the ADCPs were rotated to get the along-channel and cross-channel components of the observed currents. These along-channel and cross-channel components are obtained using the principle component analysis [19]. The principle component analysis is a statistical method to get the major axis of observed vectors and axis rotation angles by the least squared error theory and the maximum variance theory. The current rotated angle between the major axis and the original axis was calculated from the equations:
\[ \theta = \arctan \left( \frac{\text{cov}}{\sqrt{D + E}} \right) - \left( \frac{(Y - \bar{Y})^2 - (Y - \bar{Y})^2}{2} \right) \]

\[ D = \left( (X - \bar{X})^2 - (X - \bar{X})^2 + (Y - \bar{Y})^2 - (Y - \bar{Y})^2 \right)^2 \]

\[ E = \sqrt{D - 4 \left[ (X - \bar{X})^2 - (X - \bar{X})^2 \right] \times \left[ (Y - \bar{Y})^2 - (Y - \bar{Y})^2 \right] - \text{cov}^* \text{cov}} \]

Where the covariance is defined as \( \text{cov} = (X - \bar{X}) \times (Y - \bar{Y}) - (X - \bar{X}) \times (Y - \bar{Y}) \), the over-bar represents time mean value of variances. The observed velocity is \( *U = u + i*v \), after calculating the rotate angle of the velocity, the observed velocity can be represented by plural \( 0_iU e^{\theta} \), where the major component is the real part of \( U \) and the minor component is the imaginary part of \( U \), the new components obtained from PCA method can describe the along-channel currents and cross-channel currents at the measurement transects.

The coordinate system used in this study is defined such that the \( x \) axis was in the along-channel direction and positive seaward; the \( y \) axis was in the cross-channel direction and positive to the right hand of the landward direction; and the \( z \) axis was positive upward (figure 1). After decomposition, the along-channel direction in the longitudinal axes of the channels of the South Branch was aligned clockwise about 20 degrees to the east direction in the upper part of the estuary, 12 degrees in the North Channel and the South Channel and about 35 degrees in the South Passage and the North Passage. The same tidal harmonic analysis was also used to estimate the along-channel and cross-channel components of the tidal and sub-tidal currents at each transect.

2.5. Derived evolution of salt stratification

The horizontal salinity gradient is the key driving force for the estuarine circulation, which in turn is the key dynamical variable that maintains salinity stratification in estuaries. Assuming the horizontal salinity gradient is constant for tidal circulation on time scales less than a few days and the horizontal divergence of turbulence salt flux is small, and taking into account the balance of along-channel salt advection and vertical salt diffusion, the one dimensional conservation equation for salt in the estuary can be expressed as

\[ \frac{\partial S}{\partial t} = -u \frac{\partial S}{\partial x} + \frac{\partial}{\partial z} \langle S' w' \rangle \]

Where \( \langle S' w' \rangle \approx K_z \frac{\partial S}{\partial z} \), \( K_z \) is the eddy diffusivity of salt, the evolution of vertical salinity stratification can be obtained by differentiating equation (8) with respect to \( z \):

\[ \frac{\partial}{\partial t} \frac{\partial S}{\partial z} \text{ evolution of stratification} = - \left[ \frac{\partial u}{\partial z} \frac{\partial S}{\partial x} \right] \text{ straining} - \left[ u \frac{\partial}{\partial x} \frac{\partial S}{\partial z} \right] \text{ advection} + \frac{\partial^2}{\partial z^2} K_z \frac{\partial S}{\partial z} \text{ mixing} \]

3. Results

3.1. Observed tidal currents
Figure 3. Vertical distributions of along-channel (a–c) and cross-channel (d–f) components (units: m.s\(^{-1}\)) of the observed tidal currents at transect BB' (1-Hengsha Waterway), transect CC' (2-North Channel) and transect EE' (3-South Passage) from the second flood to ebb tidal period. Shaded areas represent the bottom along this transect. Vectors toward the right represent positive velocities and toward the left negative velocities. Positive velocity values in panels a–c indicate landward flow, and northward flow in panels d–f.

The current observations made by ADCPs also provided information on the temporal and spatial distributions of along-channel and cross-channel circulation during a tidal cycle. Observed along-channel tidal currents at transect BB' (figure 3-1) indicate that water in Hengsha Waterway flowed northwestward (up to 0.7 m.s\(^{-1}\)) from the North Passage to the North Channel during flood tide, and southeastward from the North Channel to the North Passage with larger speed during the ebb. At
transect CC', the observed along-channel tidal currents (figure 3-2) were essentially rectilinear (up to 1.8 m.s$^{-1}$), and the flow directions reversed abruptly by almost exactly 180 degrees between the ebb and flood tidal periods. At both transects, the observed along-channel currents were vertically uniform in the top 5 m but as the water became deeper, its speed decreased (figures 3-1 and 3-2). Figure 3-1 also demonstrates that at the maximum flood tide (defined as the time of maximum current during flood tide), the observed cross-channel tidal currents at transect BB' had a two-layer structure in the vertical, with relatively strong westward tidal currents in the top 3 m and eastward sub-surface currents (up to 0.1 m.s$^{-1}$). At the maximum ebb tide (defined as the time of maximum current during ebb tide), the observed cross-channel tidal currents at transect BB' had very complex spatial distributions. By comparison, the observed cross-channel tidal currents at transect CC' (figure 3-2) were weaker, with more organized spatial structures at the maximum flood and ebb tides than at transect BB' (figure 3-1). During the flood-to-ebb period, cross-channel flows at the two transects were weaker than the along-channel flow.

The observed tidal flow at transect EE' in the South Passage had large semidiurnal tidal currents with deep channel-shoal asymmetry (figure 3-3). At the maximum flood (figure 3-3a), the observed along-channel currents at EE' were strong (up to 2.5 m.s$^{-1}$) and landward (northwestward) in the top 5 m, but as the water became deeper, the speed of the current decreased and the vertical shear was strong. At the maximum ebb (figure 3-3c), the observed along-channel tidal currents at EE' reversed their directions towards the sea (southeastward), with intense tidal currents (up to 2.5 m.s$^{-1}$) in the top 5 m and a decreased currents with depth below 5 m. The observed along-channel currents weakened during the slack period, with significant variations in the horizontal and vertical directions. In comparison to the along-channel currents, the observed cross-channel currents at EE' were weaker. Relatively strong cross-channel flows occurred during the second half of the flood tide, with large tidal flow throughout the water column directing northward at transect EE'. Yan et al [17] found in an observation that the Coriolis force was an important factor in generating cross-channel circulation in the Yangtze Estuary. As a result, the water level of the northern bank is higher than that of the southern bank in the South Branch. As suggested by other studies [20], the cross-channel circulations are probably caused by the flood-ebb asymmetry.

3.2. Observed sub-tidal circulations

The observations made by shipboard ADCPs in two semidiurnal tidal cycles at the five transects were used to obtain sub-tidal currents. Figure 4 presents vertical profiles of the sub-tidal flow estimated from the observed currents. The estimation was made using tidal harmonic analysis at transects AA' and BB'. The observed along-channel sub-tidal currents (u) were seaward and southeastward at both transects, indicating the major impacts of river discharge from the Yangtze River on the sub-tidal circulation in the South Branch of the Yangtze Estuary during the observation period. At transect AA', the observed cross-channel currents reached 0.1 m.s$^{-1}$, and the observed along-channel seaward currents reached 0.5 m.s$^{-1}$. At transect BB', the observed along-channel sub-tidal currents ran from the North Channel to South Channel with an average speed of about 0.5 m.s$^{-1}$. This was mainly due to bifurcation of the seaward estuarine circulation, affected by Hengsha Island and the ebb-dominated flows in the North Channel. By comparison, in the lower part of the South Branch, the observed sub-tidal currents had inflow and outflow at the same transect.

It was noted that the cross-channel current was weak at transects AA' whereas the along-channel velocity was strong (speeds exceeding 0.5 m.s$^{-1}$) on the sub-tidal scale. This indicates that the sub-tidal currents in the South Branch were nearly longitudinal outflows. Observed sub-tidal circulations in the cross-channel direction at transect BB' (figure 4) featured westward flow (up to 0.2 m.s$^{-1}$) in the upper layer and eastward flow (up to 0.15 m.s$^{-1}$) in the bottom layer. Sub-tidal circulations in the cross-channel direction observed at transects DD' and EE' were not significant.
Figure 4. Vertical distributions of along-channel (a, c) and cross-channel (b, d) components of the observed sub-tidal currents at transects AA’ (a, b) and BB’(c, d). Shaded areas represent the bottom along the two transects. Vectors in upper panels directed to the right represent seaward flow (panel a) and southeastward flow (panel c).

Figure 5. Distribution of along-channel residual flows at transect CC’(a-b), DD’(c) and EE’ (d). The velocity field has a contour interval of 0.04 m.s$^{-1}$. Positive values show outflow directed seaward and negative values indicate landward inflow. Thick gray contour depicts zero velocity. Shaded areas represent the bottom along this transect.

Figures 5(a) and 5(b) present the vertical distribution of the observed along-channel sub-tidal flow
at transect CC’. Transect CC’ had a current distribution similar to that of transect AA’. The observed along-channel sub-tidal currents (u) were seaward at both transects, with the observed along-channel seaward currents reached 0.5 m.s$^{-1}$. Figure 5(c) showed the along-channel sub-tidal flow at transect DD’ in the North Passage, which features seaward flow on the north side of the passage and landward flow on the south side. The main seaward flow on the north side occurred mainly in the deep channel, where local water depths were greater than 10 m. The observed along-channel flow featured pronounced lateral and vertical shear with stronger currents (0.1 to 0.7 m.s$^{-1}$) in the upper water column over the middle passage, and weaker currents (0.1 to 0.2 m.s$^{-1}$) over the adjacent shoal and bottom area. The along-channel sub-tidal flow at transect EE’ (figure 5(d)) in the South Passage had the same pattern as DD’ at the open mouth.

3.3. Observed along-channel salinity stratification

![Figure 6](image)

**Figure 6.** Vertical distributions of the observed salinity along longitudinal axis of the downstream part of the North Channel (transect BG, left panels) and South Passage (transect NC, right panels), for flood (a, d) and ebb tide (b, e) on August 19, 2005. Panels (c) and (f) present sub-tidal salinity distributions along the transects. The contour interval is 2 psu/km. Shaded areas represent the channel bottom along the two transects. Thicker gray lines represent salinity 0.5 psu.

Based on the observed salinity distributions shown in figure 6, the tidal excursion of approximately 15 km during the tidal cycle suggests that advection was an important factor on salinity stratification. The along-channel salinity gradient was estimated to be about 3–7 psu/m in the lower part of the North Channel, which is stronger than the horizontal gradient (about $5 \times 10^{-4}$ psu/m) in Chesapeake Bay [20]. This strong horizontal salinity gradient observed in the lower part of the Yangtze Estuary is mainly due to the interaction between a large amount of freshwater discharged from the Yangtze River and the high salinity water from the East China Sea. As a result, baroclinic dynamics has a strong impact on sub-tidal circulation in the lower part of the estuary. Although in general the salinity density gradient determines the shape of shallow estuarine circulation, the ratio of circulation to tidal straining is more critical for periodic unsteady salinity stratification. Both factors play an important role in salt balance and transport. The main processes controlling stratification during the tidal cycles include circulation, tidal stirring and tidal straining. Tidal straining is the differential displacement of a horizontal density gradient by the vertical current shear. This causes stratification to increase during the ebb and to decrease during the flood, even in the absence of mixing [11]. The effect of a baroclinic circulation pattern is always to increase stratification whereas tidal stirring decreases stratification.
Figure 6 presents the observed salinity along longitudinal axes of the lower parts of the North Channel (transect BG) and South Channel (transect NC). Salinity isolines advanced landward with the flood tide and retreated with the ebb tide, with net displacement of about 15 km during a tidal cycle. This indicates that salinity distributions were significantly affected by tidal currents in the lower part of the South Branch. The tidally averaged salinity contour line 0.5 psu was in the area adjacent to Hengsha Island (near station BG1 at transect BG, and near station NC1 at transect NC). There was significant difference in vertical profiles of tidally averaged salinity between transects BG and NC (figures 6(c) and 6(f)).

Comparison between salinity distributions from stations BG1 to BG3 at transect BG in the North Channel and those from NC1 to NC3 at transect NC in the South Passage (figure 6) indicates stronger vertical mixing in the South Passage than in the North Channel during the flood-to-ebb period. The cause is that the salinity distribution and salt intrusion in the region were mainly affected by estuarine morphology, tides, river runoff, bottom friction and wind forcing [21,22].

4. Discussion

4.1. Relationship between tidal circulation and salt stratification

We found that there were obvious intra-tidal variability in currents and stratification on a tidal time scale. The estuarine circulation could be driven by tidal nonlinearities in shear stress [13]. What kind of circulation driven mechanism within this estuary is not unclear currently. The observed two-layer flow structure on these transects was consistent with a study on sub-tidal circulations in weakly stratified shallow estuaries by Jay and Smith [3]. They found that the barotropic effects and steady horizontal density gradient drove sub-tidal circulation in partially mixed estuaries. Stacey et al [14] and Burchard and Hetland [15] pointed out that there was variability of stratification in partially mixed estuary and that tidal straining could also cause sub-tidal circulation when the stratification is asymmetrical during tidal period. The observed flood-ebb tidal current asymmetry with enhanced shear and stratification during ebb tides and strong mixing and weaker stratification during flood tides leads to a significant asymmetry in turbulent mixing. The asymmetric tidal mixing caused salinity distribution to vary over the flood-ebb tidal cycle. In Yangtze Estuary, the observations agree with the finding of Li and Zhong [20] that circulations are probably caused by the flood-ebb asymmetry.

Figure 7 presents vertical profiles of observed salinity during the tidal cycle at station BG2 in the North Channel and station NC2 in the South Channel. The vertical salinity stratification had significant semi-diurnal tidal variability in the Yangtze Estuary during the observation period. The stratification enhanced during the ebb period and de-stratified with intense mixing during the flood period. This phenomenon was observed in Liverpool Bay by Simpson et al [11], who described the switching between the stratified and mixed states over a semidiurnal tidal cycle as the strain-induced periodic stratification (SIPS). The mechanism of SIPS, which is caused by the intra-tidal variation of tidal straining effects on the vertical stratification, is defined as the ratio of horizontal salinity gradient to vertical shear stress during the tidal cycle. Previous studies suggested that the vertical stratification was unstable and changed rapidly during the increased freshwater flow into the sea [11,12]. The horizontal tidal straining term in equation (9) is the effect of vertical shear stress acting on horizontal salinity gradients, which caused vertical salinity asymmetry during the tidal cycle. The semi-diurnal tidal variability of vertical stratification began at the maximum flood with intense vertical mixing and reached maximum stratification during ebb flow, with the bottom-to-top salinity difference about 10 psu at station BG2, and about 8 psu at station NC2. The intense vertical stratification lasted for about 2 to 3 hours. At the maximum ebb, the top-bottom salinity difference was near zero throughout the water column. This asymmetry in the vertical salinity profiles in the lower part of the South Branch of the Yangtze Estuary (at stations BG2 and NC2) appeared to be related to the tidal straining effect. According to equation (9), the along channel tidal straining at stations BG2 and NC2 were calculated, the results in figure 7 showed that the horizontal salt gradient were generally stable (about 0.3 psu/km), the vertical velocity stress changed abruptly between flood and ebb tide, with positive value.
Figure 7. The left panel shows the vertical profiles of the observed salinity and velocity at station BG2 (upper panel) in the North Channel and at station NC2 (lower panel) in the South Passage during the tidal period. The right panel shows the time series of the salt gradient (a, d), velocity shear (b, e) and along-channel straining term (c, f) during a tidal cycle, while the shaded areas denotes the outline hours 21–28 (corresponding to panels a–c) and 16–25 (corresponding to panels d–f), respectively.

during flood tide and negative during ebb tide. The positive stress leads to positive tidal straining effects and the increase in tidal mixing, while negative stress leads to negative tidal straining effects and the generation of vertical stratification in the water column. Typical tidal straining (strain-induced periodic stratification, SIPS) tends to develop stratification during ebb tides and well mixing during flood tides. The highest stratification occurred during the transition from flood to ebb tide. However, the observed tidal variations in vertical salinity stratification in the Hudson Estuary by Scully and Geyer [13] were not consistent with the traditional patterns due to the along-channel tidal straining effects. This indicates that other processes such as the advection transport may modify salinity stratification. The vertical salinity profiles at BG2 and NC2 at various times shown in figure 7 also revealed that the maximum stratification developed during ebb tides of the second tide cycle (hour 24) and lasted for about 2 hours (hours 24 and 25) at BG2 (North Channel), and that there was de-stratification during the next hour by intense vertical mixing. The periodic stratification lasted longer in the South Passage than in the North Channel. The maximum stratification developed during ebb tides of the second tide cycle (hour 20) at NC2 (South Passage) lasted for about 3 hours (hours 20 to 22), lasted longer than at BG2 (North Channel). The maximum bottom-to-top salinity difference in
these two channels showed that the stratification at NC2 in the South Passage was weaker than at BG2 in the North Channel. This is most likely caused by the different stratification stabilities, varying salinity gradients, and mixing intensity in these two channels. During the period from flood to ebb tide (panels a–f in figure 7 with shaded areas), the salt gradient was larger and more stable in the North Channel than in the South Passage. The velocity shear and along straining increased in the North Channel while decreased in the South Passage during this period. However, the horizontal advection and salinity gradient were driven by strong river discharge and river-ocean interaction and generated a steady estuarine circulations and stratification in the Yangtze Estuary. Tidal straining was a major generation mechanism for the sub-tidal circulation and periodic stratification during the tidal cycle. Figure 7 showed that the straining term scale is about $2 \times 10^{-7} \text{ psu} \cdot \text{s}^{-1} \cdot \text{m}^{-1}$ at stations (BG2 and NC2) in the South Branch, with extensive straining effect during flood tides and decreasing straining effect during ebb tides. The importance of along-channel tidal straining on stratification is most likely to be important in Yangtze Estuary, which has strong river discharge, large horizontal salinity gradient and flood-ebb asymmetry during the observation period. The combined influence of the estuarine circulation and stratification determine the salt flux and the fresh water outflow within the estuary while their intensity varied with the strength of the river discharge. Because of the complex bathymetry and forcing characteristics, the Yangtze Estuary has strongly stratified aquatic environments, and tends to have vigorous water and salt exchange, due to the estuarine circulation.

4.2. Role of circulation, tidal straining and mixing on stratification

There were close relationships between the flood-ebb asymmetry of shear stress and stratification within this estuary. How the circulation, tidal straining and mixing playing on periodic stratification during the tidal cycle needs for deeply discussion. The estuarine stratification evolution was driven by tidal straining, horizontal advection, horizontal salinity gradient and turbulent mixing. The horizontal salinity gradient and advection were important in the estuarine circulation. With the assumption that the contribution to stratification by tidal straining and the estuarine circulation are independent, the potential energy respect to time in equation (10) was used to describe the growth and decay of stratification [11]:

$$\frac{\partial \phi}{\partial t} = \left( \frac{\partial \phi}{\partial t} \right)_{\text{Cir}} + \left( \frac{\partial \phi}{\partial t} \right)_{\text{Strain}} + \left( \frac{\partial \phi}{\partial t} \right)_{\text{Stri}} = 0.0031 \frac{g^2 h^4}{N \rho} \left( \frac{\partial \rho}{\partial x} \right)^2 + 0.031g h \bar{u} \frac{\partial \rho}{\partial x} - \varepsilon k \nu \frac{[\bar{u}]}{h} \tag{10}$$

Where the local contributions to stratification induced by the estuarine circulation, the tidal straining with the interaction of the tidal shear with the horizontal salinity gradient and bottom tidal stirring, $[\bar{u}]$ is averaged tidal current amplitude, $\bar{u}$ is depth averaged current, the bottom drag coefficient $k = 1.2 \sim 1.5 \times 10^{-3}$ and eddy viscosity value $N.z = 0.001 \sim 0.08$ in the Yangtze Estuary, take $\varepsilon = 0.004$ determined from the distribution of thermal stratification in shelf seas [23]. It was found in equation (10) that the density gradient was an important fact to salinity stratification, which determined the different contribution of circulation and tidal straining to stratification during the tidal cycle. The density gradients during the tidal period were calculated according to salinity and sediment measurements along the North Channel, North Passage and the South Passage, respectively. The time series of density gradients along the South Branch were shown in table 1.
Table 1. Time series of density gradient along the South Branch of the Yangtze Estuary.

| Station | BG2 (2005) | NC2 (2005) | CS2 (2009) | NC2 (2009) |
|---------|------------|------------|------------|------------|
|         | $10^{-3}$ g m$^{-3}$ | $10^{-3}$ g m$^{-3}$ | $10^{-3}$ g m$^{-3}$ | $10^{-3}$ g m$^{-3}$ |
| time(hour) |          |            |            |            |
| 1       | 0.383     | 0.248      | 0.036      | 0.184      |
| 2       | 0.351     | 0.196      | 0.033      | 0.135      |
| 3       | 0.487     | 0.222      | 0.107      | 0.143      |
| 4       | 0.440     | 0.326      | 0.143      | 0.020      |
| 5       | 0.461     | 0.378      | 0.261      | 0.042      |
| 6       | 0.522     | 0.390      | 0.320      | 0.118      |
| 7       | 0.480     | 0.367      | 0.368      | 0.134      |
| 8       | 0.492     | 0.349      | 0.396      | 0.128      |
| 9       | 0.490     | 0.345      | 0.354      | 0.044      |
| 10      | 0.320     | 0.343      | 0.319      | 0.048      |
| 11      | 0.227     | 0.300      | 0.242      | 0.348      |
| 12      | 0.185     | 0.219      | 0.181      | 0.276      |
| 13      | 0.276     | 0.154      | 0.152      | 0.227      |
| 14      | 0.306     | 0.127      | 0.114      | 0.177      |
| 15      | 0.346     | 0.144      | 0.107      | 0.113      |
| 16      | 0.308     | 0.333      | 0.149      | 0.080      |
| 17      | 0.434     | 0.397      | 0.348      | 0.021      |
| 18      | 0.537     | 0.415      | 0.397      | 0.060      |
| 19      | 0.490     | 0.388      | 0.406      | 0.124      |
| 20      | 0.526     | 0.365      | 0.388      | 0.224      |
| 21      | 0.496     | 0.353      | 0.374      | 0.293      |
| 22      | 0.418     | 0.375      | 0.350      | 0.215      |
| 23      | 0.374     | 0.337      | 0.298      | 0.225      |
| 24      | 0.363     | 0.313      | 0.171      | 0.189      |
| 25      | 0.389     | 0.295      | 0.264      | 0.147      |
| 26      | 0.447     | 0.225      | 0.216      | 0.110      |
| 27      | 0.389     | 0.230      | 0.164      | 0.112      |
| 28      | 0.502     | 0.235      | 0.150      | 0.088      |

Figure 8 shows the time series of observations about the vertical salinity, velocity at station BG2 in the North Channel, CS2 in the North Passage and at station NC2 in the South Passage during the tidal period. There were periodic stratifications during the semi-diurnal tidal cycle, switched by well-mixing and strong vertical stratification. From the results calculated by equation (10) in figure 8 (1-a to 1-f, 2-a to 2-f), the tidal straining played a role as important as the estuarine circulation in salt stratification during flood season in 2005. The potential energy induced by circulation was about $1.5 \times 10^{-3}$ J m$^{-3}$ at station BG2 in the North Channel and about $0.9 \times 10^{-3}$ J m$^{-3}$ at station NC2 in the South Passage during the flood time, which developed the stratification. However, the potential energy induced by the tidal straining was negative, which decayed the stratification. During the ebb, the potential energy induced by bottom stirring was much larger than the circulation, which developed the mixing. The tidal straining, however, was positive to reduce the salt stratification. Figure 8 (3-a to 3-f, 4-a to 4-f) showed that tidal stratification during the dry season observed in April 2009 at stations (CS2 and NC2) in the South Branch had spatial patterns similar to the stratification in flood season observed in 2005. Yet the stratification was weaker and persisted longer in 2009, with less discharge than in 2005.
Figure 8. Time series of the observed depth averaged velocity (1-a, 2-a, 3-a, 4-a) and bottom to top salinity difference (1-b, 2-b, 3-b, 4-b) at stations (BG2 and NC2 in upper panel) during the flood season tidal period in August, 2005 and at stations (CS2 and NC2 in lower panel) during the dry season tidal period in April, 2009, respectively. Time series of potential energy induced by circulation (1-c, 2-c, 3-c, 4-c), tidal stirring from bottom friction (1-d, 2-d, 3-d, 4-d), along-channel tidal straining (1-e, 2-e, 3-e, 4-e) and the total energy (1-f, 2-f, 3-f, 4-f) during a tidal cycle at stations BG2, CS2 (left panel) and NC2 (right panel), respectively.

The results of the observational study in the South Branches of the Yangtze Estuary in 2005 showed that tidal straining was strong, sometimes twice stronger than circulation in flood season and spring tides. In contrast, it was found that the salinity stratification induced by tidal straining and circulation was much weaker in dry season. During the dry season and flood tide in 2009, the potential energy induced by circulation was about $0.5 \times 10^{-3} \text{ J m}^{-3}$ at station CS2 in the North Passage and about
0.2×10\(^3\) J m\(^{-3}\) at station NC2 in the South Passage, with ΔS about 5 psu during the maximum stratification. Besides, the measurements in these three outlets (i.e. the North Channel, North Passage and South Passage in figure 8) showed that the North Channel was more stratified than the North Passage. The mixing of the South Passage was stronger than other outlets.

In this study, the current and salinity measurements were used to quantify tidal and sub-tidal circulations, salinity distributions, and associated temporal and spatial variability in the South Branch of the Yangtze Estuary. In the upstream portion of the South Branch, the observed along-channel tidal flow was about 1–2 m s\(^{-1}\) without much cross-channel circulation. By comparison, in the downstream portion of the branch, the observed along-channel tidal flow was about 1.5–2.5 m s\(^{-1}\) with some weak cross-channel flow, particularly during the slack tide.

Analysis of the measurements in the Yangtze Estuary demonstrated that vertical profiles of the observed tidal currents and salinity were significantly asymmetric between the flood and ebb tides. Due to the asymmetric tidal current, there was a significant stratification in the vertical distribution of salinity in the South Branch. The vertical stratification was stronger in the North Channel than in the South Channel, and the upstream salt intrusion lasted longer in the South Passage than in the North Channel.

Bottom-to-top salinity differences (ΔS) were used to examine variations of vertical salinity stratification during a tidal cycle. It was found that the maximum stratification at station BG2 in the North Channel occurred about 2 h after the maximum flood period, with ΔS about 30 psu during the maximum stratification. The bottom-to-top salinity difference at station NC2 in the South Passage during the second tidal cycle showed strong stratification, with maximum ΔS about 10 psu, smaller than at BG2. The analysis of salinity stratification at the open mouth of the South Branch indicate that more studies are needed to gain a clearer understanding of time-dependent salinity stratification and sub-tidal circulation in this region. From the observed periodic stratification analyzed in areas where the vertical salinity changed from strong-mixing to steady stratification during the semi-diurnal tidal cycle, it is clear that the tidal straining effect is a major forcing mechanism, which is of the same importance as the interaction of vertical shear stress and horizontal salinity gradient. In addition to the tidal straining effect, the salinity stratification may also decrease or increase in shallow water estuaries due to the tidal advection effects, which equals to the advection transport of a depth-varying longitudinal density gradient. As the longitudinal density profile is always assumed to be constant in most studies about partially mixed estuaries, the different contribution of tidal straining and tidal advection to the salinity stratification is not assessed here. These two processes would be clear if provided with a longer time series. The semi-tidal excursion of along-channel salinity suggests that the advective transport of horizontal salinity gradient may play an important role in estuarine stratification.

5. Summary

This study revealed very strong temporal and special variations in stratification in the South Branch of the Yangtze Estuary, indicating the important role of tidal straining in a strongly forced salt wedge estuarine flow. From observed study in the 2005 wet season and the 2009 dry season in different channels, we confirm that the tidal straining effect is a major forcing mechanism on salinity stratification and sub-tidal circulation of the Yangtze Estuary. It was found that tidal straining play an important role in periodic stratification of the Yangtze Estuary. From the description of growth and decay of stratification by potential energy [11] in different outlets of this estuary, tidal straining was found to have a strong influence on the tidal variations of longitudinal circulation during the flood to ebb tidal cycle. The tidal straining induced circulation was equally important as the classical gravitational circulation in the Yangtze Estuary. This is consistent with observational study of Giddings et al [2] of the role of the tidal straining in the salt wedge estuaries. The results can basically reflect the stratification characteristics of the surface to bottom salinity over the flood-ebb tidal cycle of the periodic stratified areas in the South Branch of Yangtze Estuary. The conclusion is that the Yangtze River estuary is driven by the process of runoff and tidal currents, and the salinity diffusion
forms a diluted water flow at the mouth of the Yangtze Estuary, the salinity stratification alternates with vertical mixing periodically during the flood and ebb tidal cycle.

The lateral tidal variability showed weakly variations relatively in the Yangtze Estuary, indicated that the secondary circulation may not important as the longitudinal circulation during the tidal cycle. The vertical salinity profiles within the South Branch changed from strong-mixing to steady stratification during the semidiurnal tidal cycle. The semi-tidal excursion of salinity in the North Channel and South Channel indicated that the advection transport may also change the stratification. This advection-induced stratification mechanism was not deeply discussed in present study because the observed data length is limited to figure out this problem.

A notable finding is the different strength of stratification and mixing between the flood and dry season in these branches. The tidal straining was strong, sometimes twice stronger circulation in flood season and spring tides than in dry season. In contrast, it was found that the salinity stratification induced by tidal straining and circulation was much weaker in dry season.

Acknowledgments
The authors appreciate Bureau of Hydrology, Changjiang Water Resources Commission for the support of data. The authors wish to thank scientists at the Horn Point Lab of the University of Maryland and Jinyu Sheng at Canada Dalhousie University for constructive suggestions. This research work is financially supported by The National Key R&D Program of China (Item Nos. 2016YFC0400901).

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