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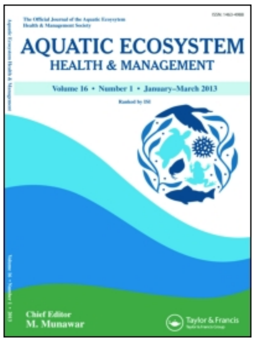

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Characteristics of vertical exchange process in the Pearl River estuary

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Being an estuary with the occasional appearance of hypoxia, the Pearl River estuary was selected to investigate its vertical exchange process by a validated 3-D numerical model. The concept of vertical exchange time was used to quantify the vertical exchange process and was calculated by adding a conservative tracer to the hydrodynamic model. The results revealed vertical exchange time has significant seasonal variation modulated by seasonally changed external forcing, and has similar structure with spatial variation in salinity. During the wet season, remarkably long vertical exchange times (>50 days) occurred at the lower estuary under 10 m depth, which was coincident with the frequently reported hypoxic zone. The entire Pearl River estuary was occupied by water mass with a vertical exchange time of <5 days during the dry season, which indicated the estuary's health condition during this period. Further analyses revealed the seasonal trend of vertical exchange time was closely related with salinity stratification and river runoff in which the lowest vertical exchange times can be estimated by linear regressions in certain stages. Tide modulated these exchange times in different time scales. Spring tide better mixed the water column and thus facilitated the vertical exchange process compared with neap tide. As a result, minimum vertical exchange time during spring tide was about 10 days shorter than that during neap tide. Flood-ebb tide also modulated vertical exchange time in the Pearl River estuary. Vertical exchange time varies with the tide and reached minimum and maximum values during valley and high tides, respectively.

Keywords: transport timescale, estuary circulation, stratification

Introduction

The vertical exchange process is important for bottom water renewal in estuaries and coastal waters, especially for bottom dissolved oxygen (DO) replenishment by carrying surface oxygen-saturated water parcels to the bottom layers. In the world-wide estuarine and coastal ecosystems, hypoxia often develops when the DO consumption rate of biochemical processes exceeds the oxygen supply for the sub-

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pycnocline water (Mallin et al., 2006; Lin et al., 2008; Scully et al., 2010). Studying the vertical exchange process can lead to better understanding of the impacts of physical processes on hypoxia.

However, it is difficult to quantify the vertical exchange process in coastal areas directly since the process is affected by many factors like stratification, vertical mixing, lateral advection, etc. It is necessary to seek a better way to characterize the vertical exchange process properly. Calculating the vertical transport timescale is a suitable method to quantify the magnitude of the vertical exchange process. The increase (decrease) of the vertical transport timescale directly results from the strengthened (weakened) vertical exchange. Adding artificial age tracers to a hydrodynamic model is an efficient way to calculate the vertical transport timescale. The concept of age has been widely used to calculate the transport timescales of water parcels (Thiele and Sarmiento, 1990; Delhez et al., 1999). Deleersnijder et al. (2001) introduced an Eulerian method to study the particle transport processes in the southern North Sea based on the age concept. Shen and Haas (2004) applied the age concept to the York River and found the age distribution was largely dependent on the river flow condition in this system. Shen and Lin (2006) and Xu et al. (2008) found stratification and wind have important impacts on age distributions in coastal areas. In this study, the age concept was used to calculate vertical exchange time (VET) of water particles in the Pearl River estuary (PRE). Transient tracers and isotopes are usually used in numerical models and natural waters to infer water age. In this way, the transport time represents the elapsed time since water was last in contact with the tracer source (Waugh et al., 2003; Delhez et al., 2004).

Although previous studies have paid much attention to the horizontal transport process in the PRE (Wong et al., 2003; Hu et al., 2011; Zhou et al., 2012; Zheng et al., 2014), the vertical exchange process and its dynamics have not been fully studied yet. In this study, we attempted to address two questions about the VET in one of the largest estuaries of China: (1) What was the spatial distribution of VET in the estuary? (2) How did physical factors control the VET distribution in the estuary, such as stratification, river runoff and tide? We applied a three-dimensional numerical model to reproduce the hydrodynamic circulation and calculate the VET to illustrate the characteristics of the vertical exchange process in the PRE based on realistic forcing.

Study area and methods

Study area

The PRE is a large estuary located in the northern South China Sea (SCS) with a complex river network (Figure 1a). The Pearl River discharges into the SCS through three sub-estuaries: Lingdingyang, Modaomen, and Huangmaohai. This study focuses on the major sub-estuary, the Lingdingyang estuary, which is commonly

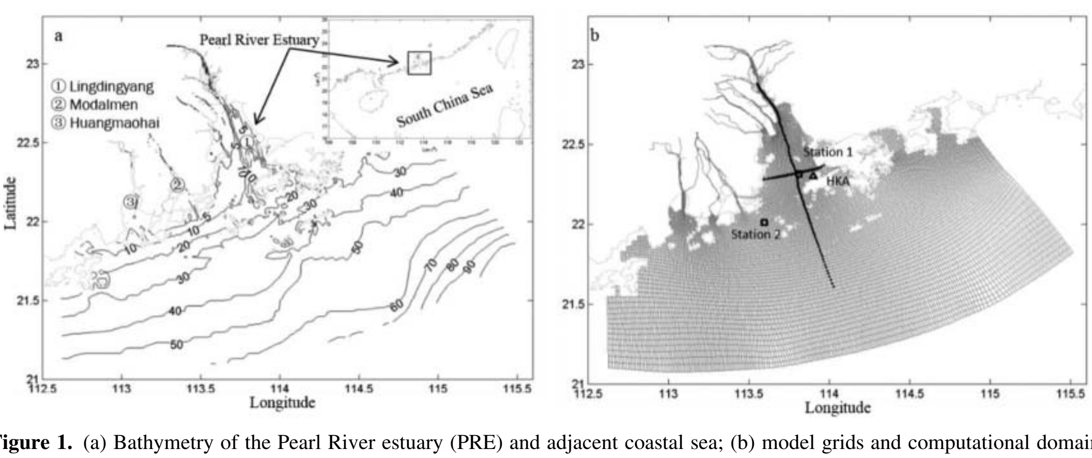

Figure 1. (a) Bathymetry of the Pearl River estuary (PRE) and adjacent coastal sea; (b) model grids and computational domain. The location of Hong Kong airport (HKA) is indicated by a triangle. The along-channel and across-channel transects used for later analyses are indicated by the bold lines. The along-channel transect is along the deep channel of the PRE. The selected Stations 1 and 2 are indicated by a square.

referred to as the PRE. The upstream river runoff is discharged into the PRE through eight inlets; i.e. Humen, Jiaomen, Hongqili, Hengmen, Modaomen, Jitimen, Hutiaomen and Yamen. The annual river discharge is approximately 10,524 m^3 s^{-1}, 80% of which is delivered during the wet season (April–September), with the rest delivered during dry season (October–March). The PRE is a microtidal estuary with about 1.0–2.0 m tidal ranges under impacts of four main tidal constituents: M2, S2, K1 and O1 (Dong et al., 2004). Tides propagate from offshore towards the estuary, and its ranges gradually increase and reach a maximum value near the river outlets (Mao et al., 2004). The circulation in the PRE and adjacent coastal water are under the influence of the East Asia monsoon, in which southwesterly and northeasterly winds prevail in summer and winter, respectively.

Hydrodynamic model description

The validated three-dimensional EFDC hydrodynamic model in the PRE (Zhou et al., 2012) was used in this study. The model grids were designed to cover the entire PRE, part of the complicated river network, and adjacent coastal waters (Figure 1b). There were 20 vertical sigma layers with high resolution near the surface and bottom layers, respectively. The horizontal resolution of the model grid ranged from 40 m inside the estuary to 1000 m in the shelf area. The open boundary was extended far from the PRE mouth to exclude the impact of the open boundary. The tidal harmonic constituents of the four major components (M2, S2, K1 and O1) extracted from Oregon State University Tidal Prediction Software (OTPS)[1] were used to drive the open boundaries. The temperature and salinity open boundary information was obtained from the World Ocean Database (2013).[2] Wind forcing was obtained from the Hong Kong airport (Figure 1b). River flow time series obtained from the upstream stations Shijiao, Gaoyao and Boluo were used to obtain the river discharge from the North River, West River and East River, respectively. River discharge from these three rivers was summed up to get the total freshwater runoff that discharged into the PRE. The ratio of freshwater runoff that discharged into each inlet was described according to the information released by the Pearl River Water Resource Conservancy[3]. By using the total freshwater runoff time series and ratio at each inlet the percentage of river discharge through each inlet can be calculated. More information about the river discharge can be found in Lu and Gan (2015) and Zhai et al. (2005).

Vertical transport timescale calculation

The vertical transport timescale (VET) is calculated as mean water age, which is governed by the following equations:

$$\frac{\partial C(t,x,y,z)}{\partial t} + \nabla (\vec{u}\, C(t,x,y,z) - K \nabla C(t,x,y,z)) = 0 \quad (1)$$

$$\frac{\partial \alpha(t,x,y,z)}{\partial t} + \nabla (\vec{u}\,(t,x,y,z) - K \nabla \alpha(t,x,y,z)) = C(t,x,y,z) \quad (2)$$

The mean water age can be calculated as follows:

$$a(t,x,y,z) = \frac{\alpha(t,x,y,z)}{C(t,x,y,z)} \quad (3)$$

Where $\nabla = i\frac{\partial}{\partial x} + j\frac{\partial}{\partial y} + k\frac{\partial}{\partial k}$, $C(t,x,y,z)$ is tracer concentration, $\alpha(t,x,y,z)$ is age concentration, $\vec{u}$ is the velocity field, and K is the diffusivity tensor. Conservative tracers were used to calculate the vertical transport timescales in the PRE based on Equations (1) and (2). For computing the VET, tracers were released throughout the entire surface of the computational domain. At the surface, the boundary conditions were specified as $C(t,x,y,z) = 1$ and $\alpha(t,x,y,z) = 0$. At the bottom, the boundary conditions were specified as $\partial C(t,x,y,z)/\partial z = 0$ and $\partial \alpha(t,x,y,z)/\partial z = 0$. VET represented the elapsed time since the water was last in contact with the water surface. The resulting water age at any location represented the transport time required for the water parcel to be transported from the water surface to that location, regardless

[1] See http://volkov.oce.orst.edu/tides/

[2] See http://www.nodc.noaa.gov/about/oceanclimate.html

[3] See http://www.pearlwater.gov.cn/zjls/t20071107_22029.htm

of its pathway. The VET concept has been applied to the Chesapeake Bay to investigate physical control on bottom hypoxia (Shen et al., 2013; Hong and Shen, 2013; Du and Shen, 2015).

Model experiment

The model was spun up for 120 days using climatologic data and forcing to obtain the initial condition. Then the model was run with real forcing from 1 January 2007 to 31 December 2008 to obtain the quasi-steady state. Finally we used this quasi-steady state as the initial condition to run the model with realistic forcing from 1 January 2007 to 31 December 2008 and saved the two-year model outputs for analyses.

Results

Temporal and spatial pattern of VET

The vertical profiles of VET, salinity, and longitudinal velocity along the west deep channel of the PRE (see Figure 1b for the location) during June–July and January–February are showed in Figure 2 to represent variables in the wet and dry seasons, respectively. The figure shows significant seasonal variation of VET in the PRE. VET reached its minimum value during the dry season, with weak stratification and estuarine circulation, while it reached its maximum value during the wet season with strong stratification and estuarine circulation in the PRE. Generally, VETs were less than 5 days in the whole estuary during the dry season, which indicated surface saturated DO can reach the bottom layer in a very short time, helping to keep the PRE in healthy condition (Luo et al., 2009). On the contrary, VET can reach more than 50 days in the lower PRE during the wet season, with times decreasing gradually toward the upstream areas. For instance, bottom VET reached 10–20 days, 20–50 days, and 50–60 days at the upper, middle and lower PRE, respectively. The long VET can result in hypoxia in the lower PRE, since the hydrodynamic field is unfavourable for the oxygen replenishment near the bottom layer (Yin et al., 2004; Luo et al., 2009).

For the purpose of illustrating the spatial variation of VET across the PRE, an across-channel transect (see Figure 1b for its location) was selected to show the results (Figure 3). VETs have similar structures with salinity values along the transect. VET and salinity increased from shoals toward the deep channel with the largest values appearing in the deep channel during both seasons. A similar phenomenon can be found in other estuaries (Shen and Lin, 2006; Xu et al., 2008). Vertical structure of VET was largely dependent on water depth and water column stability. Stronger two-layer estuarine circulation created a more buoyant surface and increased gravity at bottom, thus enhanced

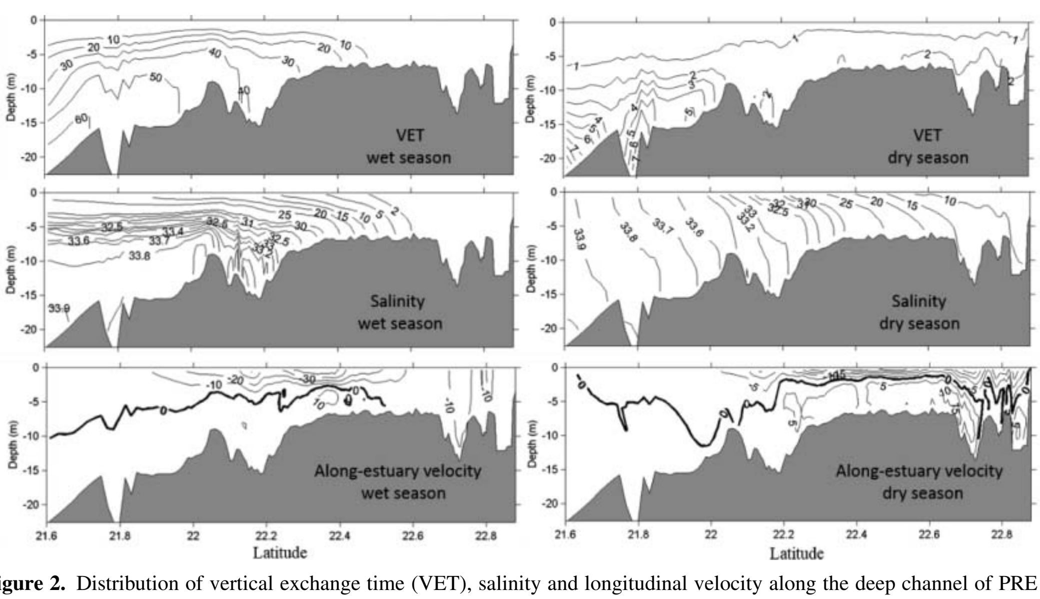

Figure 2. Distribution of vertical exchange time (VET), salinity and longitudinal velocity along the deep channel of PRE during the wet (left) and dry (right) seasons.

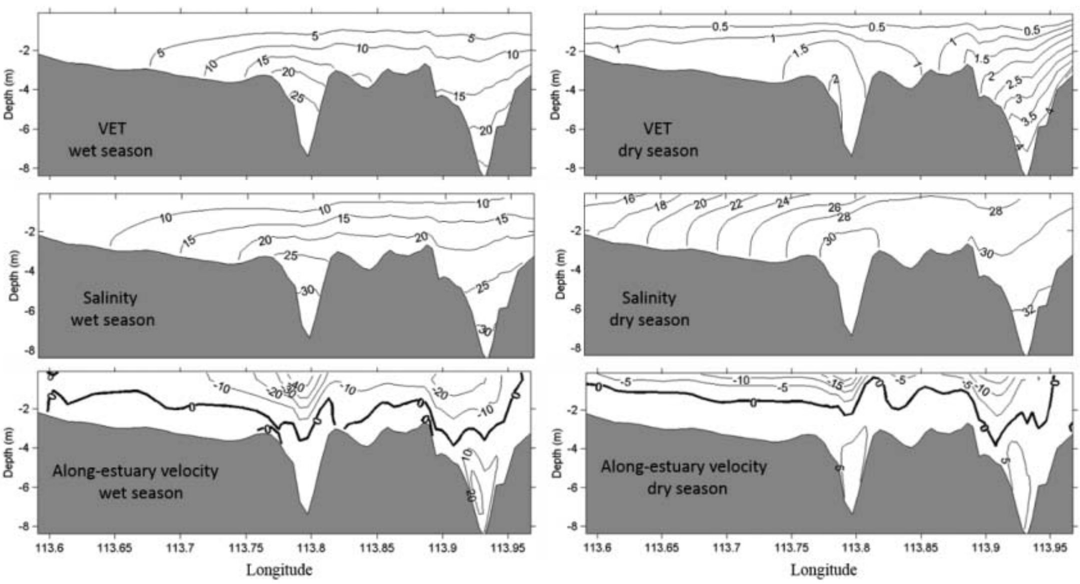

Figure 3. Distribution of vertical exchange time (VET), salinity and longitudinal velocity along the across-channel transect of PRE during the wet (left) and dry (right) seasons.

stratification and hindered vertical exchange. In addition, surface particles reached the bottom layer at the west shoal in about 5 days and 1 day for the wet and dry seasons, respectively. This is much faster than that at the east shoal, where the time was approximately 15 days and 4 days for the wet and dry seasons, respectively. Salinity profiles revealed that the west shoal has weak stratification and was the pathway for the diluted water mass being discharged into the SCS (Figure 3).

Variability of high VET water mass

Long VET in an ecosystem is usually accompanied by low possibility of DO replenishment by saturated surface water and results in a high risk of hypoxia (Rabouille et al., 2008). According to the research by Hong and Shen (2013), 23 days of VET is the threshold of hypoxia in the Chesapeake Bay and water mass with VET >23 was found to be hypoxic. A threshold of 25 days was selected in this study to estimate the percentage of the water mass that was subject to the condition of slow vertical exchange in the PRE. Here the 25 days did not mean the threshold of hypoxia in the PRE, it only represented the slowdown of vertical exchange when VET > 25 days. Lack of observed biological data prohibited us from verifying the reliability of this threshold value on forecasting the occurrence of hypoxia in the PRE. However, it was still meaningful to do the estimation.

The percentage of long VET (>25 days) water mass that appeared in the PRE was calculated to illustrate which area has the highest possibility of having weak ventilation. The across-channel and along-channel transects were selected to present the result. For comparison, the results in 2007 and 2008 were calculated separately. Thus, the results shown in Figure 4 represented the frequency of high VETs appearing in each year. It can be seen that long VETs mainly appeared under 2.0 m at the deep channel and its near shoal. No instances of increased VET occurred at the upper PRE, where the water was dominated by homogeneous river runoff. Over one-third of the year was under long VET condition below 10.0 m at the deep channel of the lower PRE. Although the river runoff in 2008 was much higher than in 2007 (Figure 6a), fewer instances of long VETs occurred during 2008, indicating complex dynamics for controlling VET in the PRE.

Discussion

Effect of water column stratification

Stratification has been regarded as a key factor to block vertical exchange of DO and lead

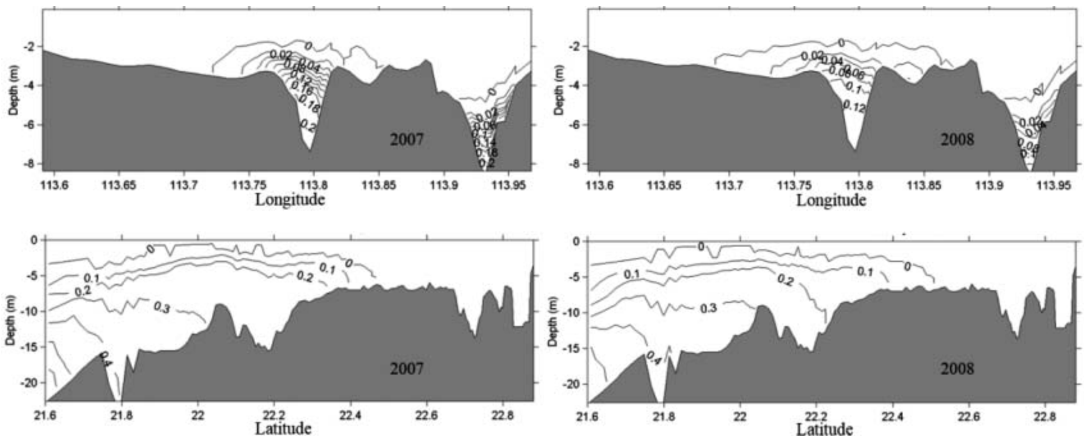

Figure 4. Contours of the percentage of VET >25 days in 2007 (left) and 2008 (right). Upper panels: across-channel transect; lower panels: along-deep transect.

to a bottom hypoxia condition in coastal and estuarine ecosystems (Stanley and Nixon, 1992; Mallin et al., 2006; Lin et al., 2008; Luo et al., 2009). Therefore, it was necessary to figure out the relation between stratification and bottom VET in an ecosystem. In the PRE, salinity difference between bottom and surface layers (S_b-S_a) can represent stratification of the water column (Wong et al., 2003) and it showed a positive correlation with bottom VET. To explore the relation between stratification and bottom VET, time series of the two variables at two stations, i.e. Station 1 at the lower PRE and Station 2 at the mouth, were compared during 2007 (Figure 1). Figures 5a and b show the scatter diagram and linear fit (y = p1*x + p2) between stratification and bottom VET at the two stations. It can been seen that the two variables have good linear relation in which correlation coefficients (CCs) both reached over 0.5 at the two stations, suggesting VET can be estimated by stratification directly. Using the linear fit, we predicted bottom VET at the two stations based on stratification during 2008 (Figures 5c and d). Overall, the correlation coefficients between estimated and modeled

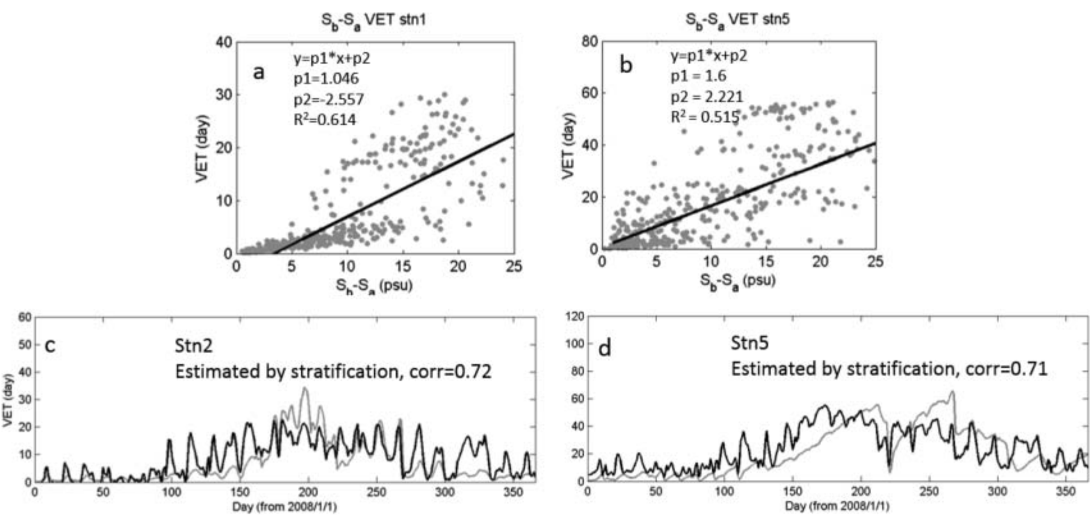

Figure 5. (a) Scatter diagram and linear fit between salinity stratification (S_b–S_a) and bottom VET at Station 1 in 2007; (b) same as (a) but for the results at Station 2; (c) modeled and estimated bottom VET at Station 1 in 2008 based on linear fit relation obtained in (a); (d) modeled and estimated bottom VET at Station 2 in 2008 based on linear fit relation obtained in (b). The P-value for the linear regression is set as 0.01.

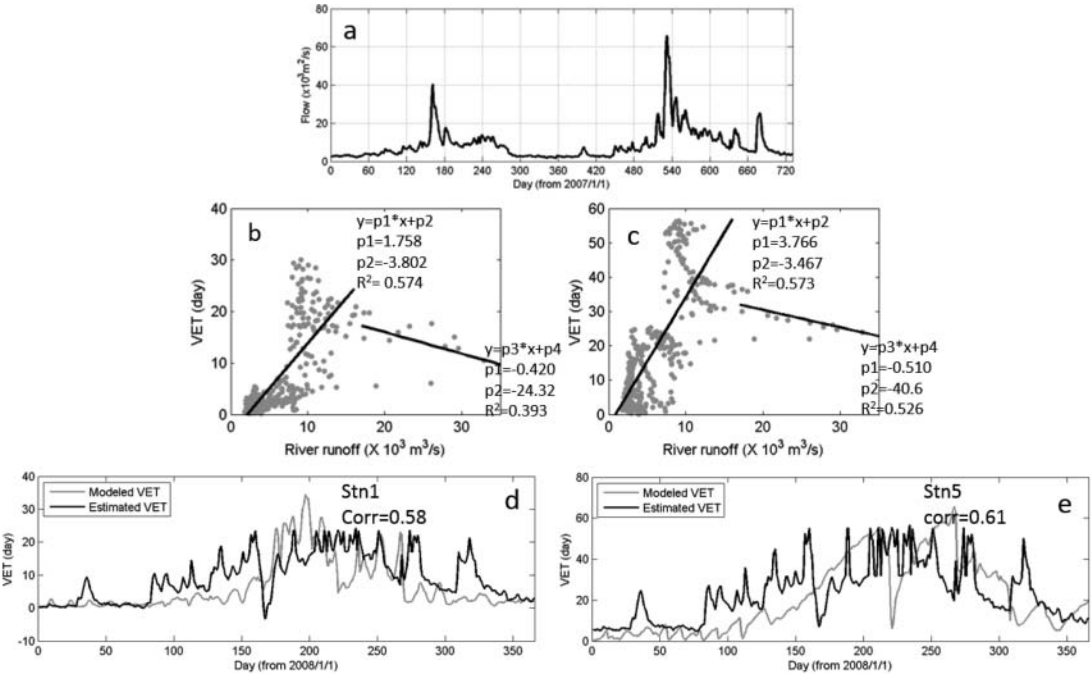

Figure 6. (a) Total river runoff; (b) scatter diagrams and linear fits between river runoff and bottom VET at Stations 1in 2007; (c) same as (b) but for the results at Station 2; (d) modeled (grey lines) and estimated bottom (black lines) VET at Station 1 in 2008 based on linear fit in (b); (e) modeled (grey lines) and estimated bottom VET (black lines) at Station 2 in 2008 based on linear fit relation obtained in (c). The P-value for the linear regression is set as 0.01.

VET both reached over 0.7 at the two stations and stratification estimated VET very well during dry and transition seasons. However, because stratification largely underestimated VET at high stratification conditions in which the difference reached 10–20 days during 2008, more factors need to be considered to evaluate VET in the PRE during the wet season.

Effect of river runoff

Shen and Lin (2006) released a tracer to simulate behavior of water particles in the James River estuary and found transport time was largely dependent on river runoff in which high river flow significantly accelerated the transport process in a horizontal direction. However, Hong and Shen (2013) found it played an inverse role on transport time in the vertical direction, where a longer VET was accompanied by higher runoff. In this study, model results also suggested river runoff can modulate VET in the PRE, as long VETs were seen in the wet season (Figures 2 and 3). To explore the potential direct relation between river runoff and VET, time series of bottom VET at the same two stations were selected to compare with river runoff (Figure 6). We used $16 \times 10^3 m^3/s$ as a cut-off point for river runoff and separately fitted the river runoff and VET in low and high river runoff conditions. The diagram scatter and linear fits during 2007 suggested VET could be directly estimated by river runoff during certain stages (Figures 6b and c). The CCs reached over 0.5 at the low river runoff condition. We also used this linear fit to predict VETs during 2008. Figures 6d and e show that VETs can be estimated well by the linear fits during the dry season (low river runoff conditions), especially at Station 1, while linear fits showed large discrepancies and time lag compared with model results during the wet seasons (high river runoff conditions). This indicates river runoff may not affect VET directly but through enhancing stratification and estuarine circulation in the PRE, both of which responded to river runoff with a few days to a few weeks delay from the river mouth to the lower PRE during the wet season. A sharp decrease of VET was noted around day 220 in 2008, which could have been due to strong winds at that time (Xu et al., 2008).

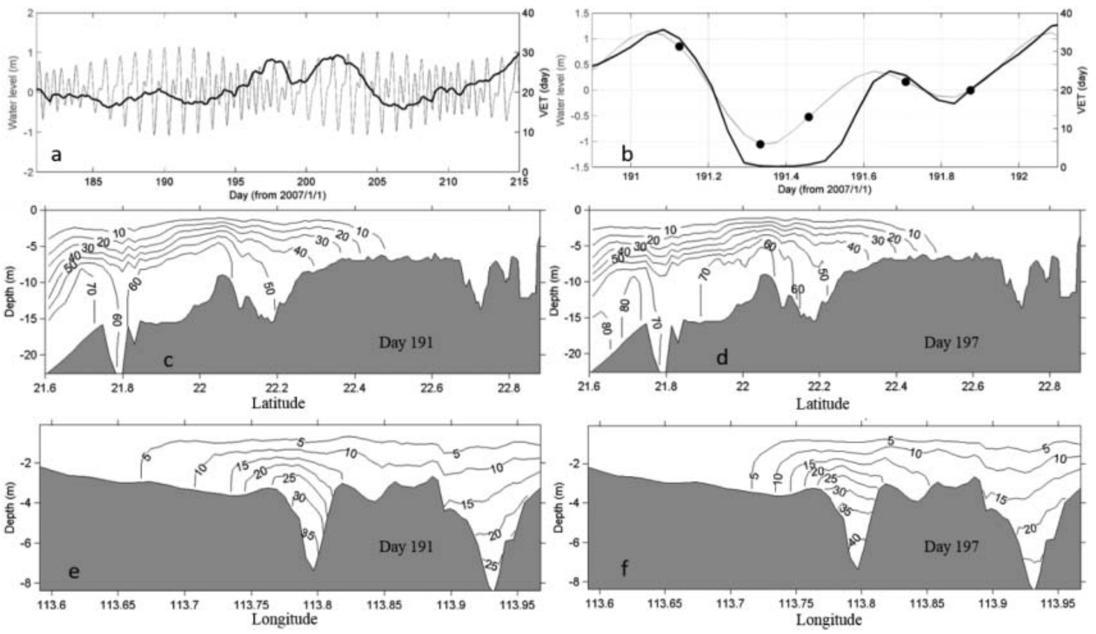

Figure 7. Instantaneous water level (grey line) superimposed by 25-h running smoothed bottom VET (black line) during spring-neap (a) and by instantaneous bottom VET (black line) during flood-ebb tides (b) at Station 1; VET along across-channel transect at spring (Day 191, c) and neap tides (Day 197, d); VET along deep channel at spring (Day 191, e) and neap tides (Day 197, f).

Tidal effect

Tide is regarded as the main actor to destroy stratification built by river runoff and mix water column, hence reduce the chance of the bottom hypoxia condition in an ecosystem mainly controlled by physical processes (Stanford et al., 1990; Borsuk et al., 2001; Lin et al., 2008; Chen et al., 2015). Zhang and Li (2010) stated that vertical DO fluxes were dominated by physical processes, including tidal forcing in the PRE. The PRE is a mixed-tidal estuary with fortnight variation of tides ranging from 1.0 m to 2.0 m, which modulates the VET in the same pattern. Figure 7a shows instantaneous water level and daily-mean bottom VET at Station 1 during a spring-neap tide cycle in 2007 when river runoff was largely steady. Bottom VET reached minimum (about 17 days) and maximum (about 30 days) values at spring and neap tides, respectively. Daily mean VET along the deep channel showed the same fortnight trend in which VET increased from 60 days at spring tide (day 191) to 70 days at neap tide (day 197) at the lower PRE under 10 m (Figures 7c and d). However, VET at the across-channel transection showed an inverse pattern at the west shoal (face to the estuary), where VET at spring tide apparently was larger than that at neap tide (Figures 7e and f). Zhang and Li, (2010) suggested advection flux may have dominated hypoxia during spring tide at this region, indicating it could bring old water from the deep channel to the shoal. Moreover, VET can be adjusted by the tide in a small time scale, i.e. flood-ebb tide cycle. Figure 7b shows that bottom VET shared the same trend with tidal elevation during the flood-ebb tidal cycle during spring tide, where long VETs (about 35 days) appeared with high tide at the middle PRE (Station 1). It attained total ventilation when tide levels reached valley value at this region, where it was dominated by river runoff. This total ventilation lasted for several hours, bringing saturated DO to the bottom layer and thus prohibiting the formation of hypoxia in this region (Yin et al., 2004).

Conclusions

In this study, we used VET to quantify the vertical exchange process in the PRE under the real forcing fields in 2007 and 2008 based on the validated EFDC hydrodynamic model. The remarkably long VET (>50 days) occurred in the wet season and mainly in the deep channel of the lower PRE, which corresponds to the zone with frequent hypoxia. On the contrary, the vertical exchange process took less than 5 days in the deep channel of PRE during the dry season, which corresponds to the good water quality seen in this area. Hence, VET can be a useful indicator for judging water quality condition in this ecosystem. Impacts of multiple potential factors on VET were discussed, including salinity stratification, river runoff, and tide. Weak stratification, small river runoff, spring tide and ebb tide all facilitate the vertical exchange process in the PRE. In addition, model results suggested other physical factors could affect VET in the PRE, such as wind, gravitational circulation, and advection processes. Further research is underway to reveal their impacts.

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