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STUDY ON WATER AGE IN AN ESTUARY USING THREE-DIMENSIONAL MODELS

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ABSTRACT

The age of water (AW) concept is applied in the Pearl River Estuary to investigate the water exchange process in three-dimensional space and its seasonal variation. A three-dimensional AW model is built based on the advanced hydrodynamic model MIKE3, and the model has been verified against a field survey dataset in the Pearl River Estuary. Using this model, the spatio-temporal distributions of water age are numerically determined in response to hydrodynamic factors. The predictions indicate that the mean AW values inside the Pearl River Estuary during the wet season and the dry season are approximately 10 days and 25 days, respectively. In general, lower AW values are observed at the surface, with higher values occurring near the bed, while in the wet season, a more obvious AW stratification can be observed. A comparison between the barotropic and baroclinic predictions indicates that the density-induced circulation causes a significant decrease in the exchange timescales.

INTRODUCTION

Many estuarine systems in the world are facing environmental problems, especially those estuaries located near regions of rapid economic development. Previously published studies indicate that both the amount of pollutant input and the water exchange rate contribute to the estuarine water quality conditions (Sheldon and Alber, 2002; Simons et al., 2006, Sun et al., 2013a, b). The water exchange process in an estuary is usually complex due to the interactions of dynamical processes in multiple spatio-temporal dimensions.

In this paper, the concept of age of water (AW) has been applied to estimate the timescale quantifying the transport mechanism for dissolved substances in the Pearl River Estuary (PRE). Figure 1 shows a map of the study area, in which the PRE is bounded by a bold black line. The PRE is situated along the northern shelf of the South China Sea, which is a typical estuary experiencing tidal fluctuation and significant seasonally varying freshwater discharge (Dong et al., 2004). The average discharge is 2×10^4 m^3/s in the wet season and 4×10^3 m^3/s in the dry season (Yin et al. 2008). As a link between the limnetic environment through eight tributaries and the marine environment, this estuary's upstream-downstream physical state varies primarily in response to the interaction of discharge and tidal mixing. The density gradient drives a baroclinic forcing and creates a vertical circulation, leading to apparent three-dimensional dynamical characteristics in (Wong et al., 2003). Furthermore, the estuary's delta region has experienced rapid socio-economic changes in the past three decades that has increased the nutrient input. The wastewater discharge has caused severe environmental problems, such as persistent hypoxia and nutrient-related algal blooms (Dai et al., 2008, Sun et al., 2013b). The hydrodynamic processes of the PRE have been studied using mathematical models and field observations, including salinity and temperature distributions, circulation and tidal phenomena (Wong et al., 2003; Harrison et al., 2008).

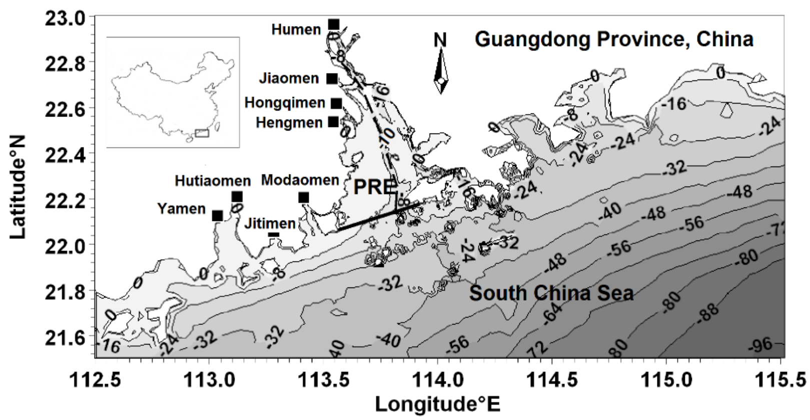


Figure 1. Topography of the Pearl River Estuary and the adjacent coastal area
Squares: entrances of eight major tributaries;

METHODS

The age of water (AW), which is time- and location-dependent, has been identified as a fundamental water exchange timescale and is widely used in analysing the spatial variations of water exchange (Delhez et al., 2004a; de Brauwere et al., 2011). Deleersnijder et al. (2001) introduced the constituent-oriented age and residence time theory, which is a general theory by Eulerian formalism, providing a series of equations for predicting the spatial and temporal AW distributions of every water constituent or group of constituents (Deleersnijder et al., 2001).

In the current study, a three dimensional hydrodynamic model, i.e. MIKE3, has been enhanced with an 3D AW module. The enhanced model was used to predict the water age distribution the PRE. To investigate the influence of the hydrodynamic conditions on the AW distributions, two scenario analyses were carried out. Case 1 was conducted under the natural hydrodynamic condition for a baroclinic mode. Case 2 was conducted under the same conditions as case 1, except for the barotropic mode. By comparing with the results of case 1, the influence of density-induced circulation on the AW can be obtained. This study focused on the age of the freshwater, and the tracer was released with the discharge from eight tributaries in all cases.

MODEL CALIBRATION AND VALIDATION

Field survey data obtained from 28 sampling stations during the period from 2006 to 2007 were used to validate the model. The model predictions were compared with the measured data, with selected results being presented herewith. Figure 2 shows the comparisons of the predicted and measured water surface elevations at three sampling stations in July and October 2006. The data from 8th to 10th Jul, 2006 represent the spring tide in the wet season. The predicted water elevation generally agreed well with the measured data.

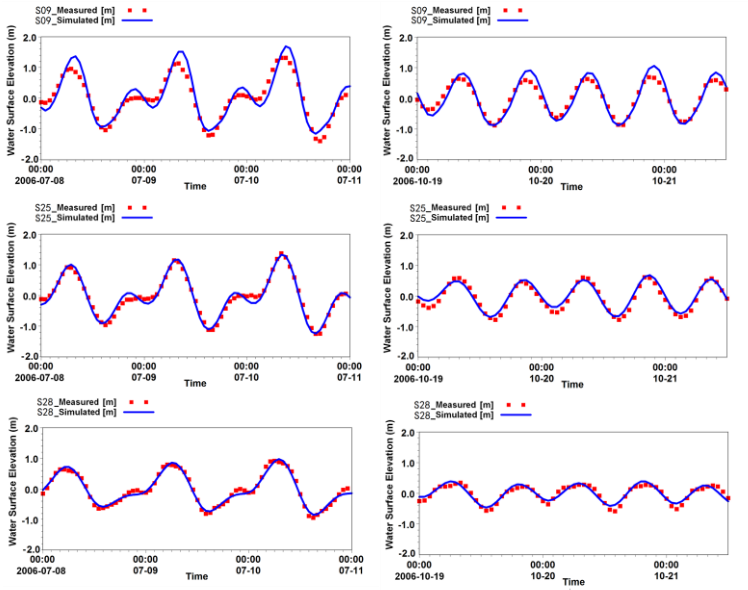
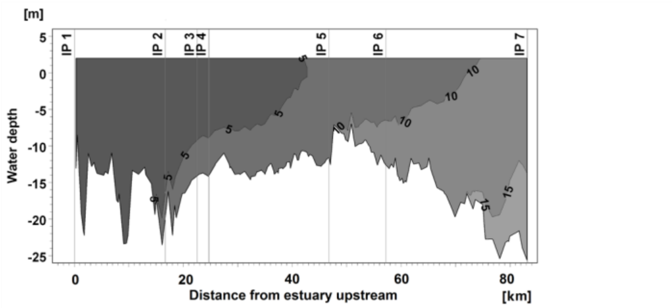


Figure 2. Comparisons between measured and predicted water elevations at three stations in July and October 2006.

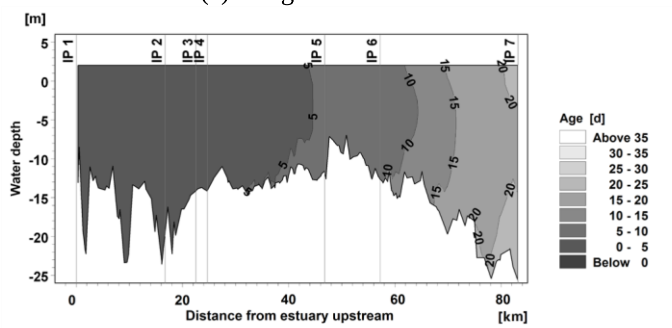
RESULTS AND DISCUSSIONS

In the PRE, the combined effects of the river discharge and tides resulted a two-layer stratified structure during the wet season, while the estuary was partially mixed in the dry season. The density gradients induced the circulation, with outflow freshwater in the upper layers and inflow sea water in the lower layers. The influence of density-induced circulation is more important in a micro-tidal estuary than in a macro-tidal estuary (Shen and Lin, 2006). As the PRE is a micro-tidal estuary, the results showed that the density-induced circulation played a significant role in regulating the transport process in the PRE. By running the model for both the baroclinic mode (case 1) and barotropic mode (case 2), the contribution of density-induced circulation to the water exchange processes in the PRE was investigated in the current study.

Figure 3 shows the predicted AW distributions in the wet season for the baroclinic and barotropic modes, respectively. Compared with the AW of the baroclinic mode, the surface AW of barotropic increased from less than 10 days to between 10 and 20 days in the lower estuary. The near bed AW value decreased from 5 to 10 days to less than 5 days in the upper estuary while the value increased from approximately 15 days to 25 days near the estuary mouth. Compared with the vertical AW profile in the wet season for the baroclinic mode shown in Figure 3(a), the AW distribution vertical profile was more uniform without density-induced circulation Figure 3(b). For the first 40 km upstream, the AW was less than 5 days all along the water depth. The surface-bed AW difference was nearly zero along the longitudinal cross-section. The results indicated that the density-induced circulation caused a decrease in the exchange timescales by more than 50%. With the impacts of density-induced circulation, the AW values in July and January were 9.38 days and 50.74 days lower, i.e., decreases by 51.07% and 68.64%, repsectively .



(a) using baroclinic modes



(b) using baroclinic modes

Figure 7. Age distributions in the wet season using the baroclinic and barotropic modes

CONCLUSIONS

The main objective of this study was to better understand the distributions of the age of water in the PRE and the effect of density-induced currents. A three-dimensional AW model was developed based on the hydrodynamic model MIKE3 and the model was verified against field measurements. The characteristics of the AW distributions inside the PRE, as well as the relationship between the AW values and its hydrodynamic conditions, were investigated.

The results indicate that the baroclinic effect plays an important role in the distribution of the AW. B y neglecting the baroclinic pressure gradient due to the density gradient, the AW stratification becomes weaker, which shows the importance of density-induced circulation in the vertical circulation system. The mean AW can increase significantly without the baroclinic pressure gradient.

Acknowledgments

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