Wave-current Interaction in a River and Wave Dominant Estuary: A Seasonal Contrast

Liangwen Jia^{a,b,*}, Yi Wen^{a,b}, Shunqi Pan^c, James T. Liu^d, Jiawei He^{a,b}

^a Coastal Ocean Research Center, Sun Yat-Sen University, Guangzhou, 510275, China.

^b Guangdong Provincial Key Laboratory of Marine Resources and Coastal Engineering,
Guangzhou 510275, China

^c School of Engineering, Cardiff University, Cardiff, CF24 3AA, UK.

^d Department of Oceanography, National Sun Yat-Sen University, Kaohsiung, Taiwan 80424

ABSTRACT

The dynamic feature of the Modaomen Estuary (ME) in the Pearl River Delta in southern China has been the subject of extensive research. In previous studies, wave-current interaction (WCI) was often neglected due to its complexity. This study uses a coupled hydrodynamic module TELEMAC-2D and wave propagation module TOMAWAC in the TELEMAC-Mascaret modeling system to quantify the effects of WCI on the hydrodynamics in the ME. The coupled wave and current modeling system was well validated against the field measurements at selected locations. The model results show that WCI varies with the seasonal change in runoff in the ME. The effect of waves on the currents is insignificant during the wet season with a current change of no more than 0.07 m/s; but, in contrast, the currents have a noticeable effect on waves. However,

Corresponding author at Coastal Ocean Research Center, Sun Yat-Sen University, Guangzhou, 510275, China
Tel./fax: +86 20 84113644.
E-mail address: jjialwen@126.com(Liangwen,Jia).

during the dry season, the interactions of waves and currents on each other are found to be equally significant. When wave model and current model are coupled, the velocity could increase up to a maximum of 0.30 m/s and decrease up to a maximum of 0.17 m/s. WCI is greatly affected by the propagation directions of wave and current in both seasons. Generally, wave height decreases and current increases for a following wave and current; wave height increases and current decreases for an opposing wave and current. The effects of waves on currents change with the tide. Changes are larger during neap tide than during spring tide, and stronger during ebb tide than during flood tide.

Keywords: Modaomen Estuary; wave-current interaction; modeling; TELEMAC.

1. Introduction

With the combined actions from tides, waves and river discharges, the hydrodynamics in estuaries can be extremely complex. The interaction between currents and waves is often very strong and must be considered when examining the dynamics in estuaries. In the last several decades an increasing interest has been brought to wave-current interaction (WCI). The effects of the tide on wave propagation in shallow waters have been investigated by many researchers (Gonzalez, 1984; Huang et al., 1972; Longuet-Higgins and Stewart, 1960; Holthuijsen, 2007; Davidson et al., 2008). WCI has been investigated through both numerical modeling and laboratory experiments. The numerical applications demonstrated the significant influence of tidal flow on wave height variation in estuaries (e.g. Kang and Di Iorio, 2006; Guillou and Chapalain, 2012; Rusu et al., 2011; Wang et al., 2006). It is widely found that wave height modulates with

the tide, and an opposing tidal flow increases wave height whereas a following tidal flow decreases wave height in a coastal region. The effects of waves on currents have been studied based on laboratory experiments (Kemp and Simons, 1982, 1983; Klopman, 1994, 1997; Umeyama, 2005; Musumeci et al., 2006). These effects are greatly dependent on wave and current propagation directions. For the following wave cases, a reduction in current intensity is observed in the region below the wave trough; the contrary occurs for opposing waves and currents. Using a 2D WCI numerical model, Wang et al. (2012) examined the effect of waves on the depth-averaged velocity and found that flow velocity is increased for following waves and currents but decreased for opposing waves and currents. Zhang et al. (2014) found that when waves travel with a following current, the flow speed above the bottom boundary layer decreases toward the water surface when a wave trough arrives while the flow speed largely increases when the current is superimposed by a wave crest. Previous research on WCI more emphasized the action of currents on waves. A more in depth study on the effects of waves on currents is needed.

This study is conducted in the Modamen Estuary. The Modaomen Estuary (ME), located at the landward margin of the South China Sea shelf (Fig.1a), has evolved under a complex hydrodynamic environment. Prior to the 1980s, the outlet of the ME was situated at Guadingjiao. The area from the south of Guadingjiao to Hengqin Island and Sanzao Island was a semi-closed shallow sea, and the impact of waves on the estuarine morphology was weak due to the sheltering of these islands. However, the location of the outlet was rapidly extended due to a series of reclamation projects and siltation beginning in 1990. As a result, the outlet has now extended to Shilanzhou, approximately 10 km seaward from Guadingjiao, outside of Hengqin Island and Sanzao Island (Fig.1b). The estuary mouth and mouth bar are now subject to direct wave action

without the protection of the islands the previous estuary mouth had. Recent observations clearly indicate the importance of wave action on the hydrodynamics of the ME (Jia et al., 2009). The migration of the outlet has also resulted in the ME being re-classified from a typical river dominant estuary (Li, 1983) to a mixed river and wave-dominant estuary (Li et al., 1993). Although the effect of waves on the estuarine dynamics has been identified (Luo, 1983; Jia et al., 2009), no detailed research has been conducted on the impact of WCI on the estuarine dynamics in this area.

Observations in the last few decades have indicated an obvious seasonal variation in the hydrodynamics in the ME (Jia et al., 2009). During the flood season (April to September), the runoff is large and dominant while the wave is relatively weak, and vice versa during the dry season (October to March). It can be expected that WCI will vary with the different strengths of the runoff and waves. The seasonal variations of WCI will subsequently affect the sediment transport and morphological evolution.

WCI has been well studied in open coast environments (Mastenhrock et al., 1993; Holmedal et al., 2003; Rosales et al., 2008; Shi and Wang, 2008). But, in estuarine environments, the interaction between runoff, tides, and waves are far from being well understood. In particular, how waves affect tidal currents and vice versa in different runoff conditions have not been fully studied.

The main objective of the present study is to investigate the seasonal variation of WCI in the ME in different runoff conditions in an attempt to gain a better understanding of seasonal variation in the hydrodynamics of the ME. The second purpose of this paper is to test the numerical model by covering the wide estuarine environment in which WCI can occur in the ME. Because the

effects of waves on the depth-averaged currents are important, this study focuses on WCI in a depth-averaged current condition.

2. Study Area

The ME, located on the west wing of the Pearl River Delta (PRD) (Fig. 1a), is the main outlet of the Xijiang River from the upstream. The runoff is strong and the tides are relatively weak with the ratio of the multi-annual mean runoff to the flood tide discharge being 5.77. The multi-annual (1959-2010) mean runoff at the Makou Station (Fig. 1a), where the Xijiang River enters the PRD, is $7400 \text{ m}^3/\text{s}$. The monthly mean discharge varies from $11400 \text{ m}^3/\text{s}$ during the wet season (April to September) to $3420 \text{ m}^3/\text{s}$ during the dry season (October to March). The water discharge into the ME accounts for 37.86% of that measured at the Makou Station. The tides at ME are of irregular semi-diurnal/mixed type. The annual mean tidal ranges at the stations Sanzao and Denglongshan are 1.11 m and 0.86 m, respectively. Based on the Dawanshan wave station located southeast of the ME (Fig.1a), the dominant wave direction is southeasterly with an occurrence of 71%. The monthly mean wave height ranges from 1.01 m to 1.32 m with an average wave period of 5.15 s-5.70 s.

3. Methods

Numerical simulations are performed with the TELEMAC-Mascaret modeling system (www.opentelemac.org). For comprehensive modeling systems, such as ECOMSed (Hydroqual, 2002), Mike-21 (Warren and Bach, 1992), Delft3D (Lesser et al., 2004) and ROMS (Warner et al., 2008), a model system generally includes different flow modules (from 1D to 3D), and a wave model, which can be coupled for simulation of WCI. Those models mainly use finite difference

methods and are therefore constrained by the use of boundary fitted schemes (orthogonal curvilinear horizontal coordinate systems, sigma stretched vertical coordinates), which are more suitable for regular and simple geometry (Villaret et al., 2013). The TELEMAC-Mascaret system on the other hand is based on an unstructured grid and finite-element or finite volume numerical schemes (Hervouet, 2007) and is suitable for estuaries with irregular and complex geometry. The TELEMAC-Mascaret system is a package that includes modules for the modeling of free surface hydrodynamics, sediment transport, water quality, waves and groundwater flows. The system is developed by the Laboratoire National d'Hydraulique et Environnement (LNHE), a research department of the French Electricity Board (EDF R&D). TOMAWAC (TELEMAC-based Operational Model Addressing Wave Action Computation) is one of the sub-modules that models the changes in the power spectrum of wind-driven waves and wave agitation and is applicable for oceans, intracontinental seas, as well as in coastal zones. TELEMAC-2D, coupled with TOMAWAC, has been successfully applied to studies of WCI in various coastal systems (e.g. Briere et. al., 2007; Jones and Davies, 2008; Guillou and Chapalain, 2012). In a similar fashion, the present study uses the TELEMAC-2D module, internally coupled with TOMAWAC module, to study WCI in the ME.

This section first discusses relevant information about each model individually, then the model coupling, and finally the coupled modeling system application to the ME.

3.1. 2D Hydrodynamics

Hydrodynamics is computed with TELEMAC-2D module. The TELEMAC-2D flow module solves the shallow water equations (momentum and continuity), with several options for the horizontal diffusion terms (depth-averaged κ - ϵ , Elder model (1959) or constant eddy viscosity

models) and source terms (atmospheric pressure gradients, Coriolis force, etc.). The numerical discretization includes a choice of classical methods for the advection terms (characteristics, SUPG, distributive schemes). The basic features of these solution procedures can be found in Hervouet (2007).

The use of implicit schemes enables relaxation of the CFL limitation on time steps (typically, values of Courant numbers up to 10 or 50 are acceptable). Recently, ideas stemming from finite volume techniques have been coupled with these implicit schemes to ensure monotonicity of depth and mass conservation at machine accuracy. This method is applicable to the treatment of tidal flats, ensuring positive water depth and mass conservation without extra limitation of the time step (cf. Hervouet et al., 2011).

3.2. Wave propagation model

TOMAWAC is a third generation spectral wave propagation model that accounts for the effect of waves generated by wind, white-capping, nonlinear wave-wave interaction, refraction, shoaling and dissipation (cf. Benoit et al., 1996).

The model includes the relevant processes of refraction, shoaling and bottom friction-induced energy dissipation. A 2D reconstruction of the surface elevation is performed by linear superposition of the solutions obtained for monochromatic waves. Thus, the nonlinear wave-wave interactions, wave generation by wind and white-capping are not taken into account. These limitations appear not too restrictive for the current application as the modeled area is relatively small.

3.3. Internal Coupling of hydrodynamic module and wave module

3.3.1 Theoretical background of the WCI

a. Effects of currents on waves

The simplest and well-known feature of current effects on wave is the Doppler shifting on wave frequency, waves of the same apparent (absolute) period will have a longer intrinsic period in a following current and a shorter intrinsic period in an opposing current. The absolute frequency may be modulated by unsteady currents and intrinsic frequency may be modulated by propagation over spatial gradients of current (Wolf and Prandle, 1999). When current is both horizontally and vertically sheared, it can cause wave refraction, shoaling, breaking, focusing and defocusing, the effect of which is analogous to bathymetry (Dong and Kirby, 2012).

b. Effects of waves on currents

In the presence of surface gravity waves, the bottom friction coefficient for currents will be modified; the friction coefficient experienced by waves in a current regime will be larger than in no current environment (Wolf and Prandle, 1999). The wave-averaged effects on current can be interpreted either as radiation stress (Nicolle et al., 2009) or as vortex force (Uchiyama et al., 2010) depending on the treatment of wave advection terms.

3.3.2 Formulations considering the WCI

The general form of the continuity and momentum equations (Hervouet, 2007) in the TELEMAC-2D are given as:

$$\frac{\partial \eta}{\partial t} + \nabla(h\mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\nabla\mathbf{u} + \mathbf{f} \times \mathbf{u} = -g\nabla\eta + \nu\nabla^2\mathbf{u} + \mathbf{S}_p + \mathbf{S}_w + \mathbf{S}_b + \mathbf{S}_{rad} \quad (2)$$

where $\mathbf{u}=(u, v)$ is the depth-averaged horizontal velocity, η is the sea surface elevation, t is the time, h is the total water depth, $\mathbf{f}$ is the upward pointing unit vector scaled by the Coriolis

parameter, g is the gravity acceleration and ν is the eddy viscosity. The vectors S_p , S_w , S_b and S_{rad} correspond respectively to the atmospheric pressure at sea level, wind traction, bottom friction and the radiation stresses; $S_b = -(1/h\rho) \boldsymbol{\tau}_b$, ρ is the density of water, $\boldsymbol{\tau}_b$, the bottom stress, is formulated in the form of the Strickler's law.

Generally, as vertically integrated equations are employed to model tidal flows, the bottom frictional stress, $\boldsymbol{\tau}_b$, is represented by a quadratic relationship:

$$\boldsymbol{\tau}_b = \frac{1}{2} \rho C_d |\mathbf{u}| \mathbf{u} \quad (3)$$

where $\mathbf{u}$ is vertically averaged velocity, C_d is a dimensionless drag coefficient replaced sometimes by an alternative friction coefficient proposed by Chezy (Hervouet, 2007):

$$C_d = \frac{2g}{C^2} \quad (4)$$

here g is the gravity acceleration and C is the Chezy friction coefficient. The law of Strickler defines the value of the coefficient of Chezy:

$$C = KR_h^{1/6} \quad (5)$$

where $K \text{ (m}^{1/3} \text{ s}^{-1}\text{)}$ is the Strickler coefficient and R_h is the hydraulic radius, an approximation here is that $R_h = h$.

When TELEMAC-2D and TOMAWAC coupled, the wave-averaged effects on current are interpreted as radiation stress.

The 2D (depth-averaged) radiation stress tensor, S_{ij} (Longuet-Higgins and Stewart, 1964), is expressed as:

$$S_{ij} = \rho g \int_0^{2\pi} \int_0^{+\infty} \left[\frac{C_g}{C} \frac{k_i k_j}{k^2} + \left(\frac{C_g}{C} - \frac{1}{2} \right) \delta_{ij} \right] \times F(f, \theta) df d\theta \quad (6)$$

Where i and j point to the two horizontal coordinates x and y , δ_{ij} is the Kronecker symbol

(=1 if $i=j$ and 0 elsewhere), k is the wave number, C_g is the wave groups velocity, C is the wave phase speed, F is the wave spectrum, f is the wave frequency, θ is the wave direction. An additional forcing term, S_{rad} , thus should be added to Eq. 2:

$$S_{rad} = -\frac{1}{h\rho} \begin{pmatrix} \frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} \\ \frac{\partial S_{yx}}{\partial x} + \frac{\partial S_{yy}}{\partial y} \end{pmatrix} \quad (7)$$

where S_{xx} , S_{yy} , S_{xy} , S_{yx} are four components of the radiation stress tensor.

The radiation stress is calculated by TOMAWAC following Eq. 6, and the forcing term 7 is then added to the right-hand side of Eq. 2 solved by TELEMAC-2D.

The bottom friction coefficient for currents enhanced by the WCI is not included in TELEMAC2D-TOMAWAC coupling in present study.

3.3.3 Coupling method

The TELEMAC-2D model and a TOMAWAC model are directly coupled to represent wave-current interactions in both directions. TELEMAC transfers to TOMAWAC the updated values of current velocities and water depths while TOMAWAC solves the wave action density conservation equation, with reference to those current and water depth values, and returns to TELEMAC the updated values of the wave driving forces of FX and FY acting on the current (EDF R&D, 2011).

3.4. Computational Domain and Boundary Conditions

The model domain encompasses the Modaomen Estuary and upstream tidal river, including the Modaomen channel, the Hongwan channel, and the major tributaries of the Modaomen channel (Fig. 3). The open boundary is extended offshore to approximately 30 m isobath (Pearl

River Datum, the same below), and the upstream boundary stretches to the Zhuyin (ZY) tide-gauge station in the Modaomen channel where the major freshwater discharge is input to the system. There is one lateral boundary at the Maliuzhou (MLZ) tide-gauge station in the Hongwan channel. An unstructured grid was used for the model. There were 26,995 nodes and 52,202 grid cells in the computational domain, with grid size varying from 100 m to 1,000 m (Fig.3). The hydrodynamic model was driven by the hourly water elevations observed at stations ZY and MLZ, and the hourly water elevations obtained from the OSU tidal data inversion regional model developed for the China Seas (<http://volkov.oce.orst.edu/tides/YS.html>) at the nodes along the coastal open boundary.

Numerical simulations for a wet season were carried out from July 28-31, 2004. The model was validated with the measured water elevations (Pearl River Datum, the same below) at the Denglongshan (DLS), Dahengqin (DHQ) and Guadingjiao (DGJ) stations, and measured currents from 11:00, July 30, to 12:00, July 31, at DLS, DHQ and HW. The currents were measured with a current meter (DLS) and two Acoustic Doppler Current Profilers (DHQ and DGJ). The simulations for a dry season were carried out from October 18-30, 2005, validated with the water levels measured at stations DLS, and DHQ, and the currents measured from 17:00 on October 20, to 2:00 on October 22 (spring tide), and from 11:00, October 27, to 17:00, October 28 (neap tide), at DLS, DHQ, West channel and East channel. The currents were measured with current meters. The depth-averaged velocities obtained from the measured currents were compared against the computed velocities.

The incident wave conditions specified along the open boundary of the computational domain were obtained from the Dawanshan wave station. For the wet season, the incident waves

with a significant wave height of 1.62 m, and a wave period of 5.34 s from SE (104°) were used. For the dry season, the incident waves with a significant wave height of 1.75 m, and a wave period of 5.6 s from NE (62°) were specified. During the simulation period in the wet season, the wind was gentle with the speed being less than 3m/s; thus, the wind was neglected in the model. For the dry season, wind with a mean velocity of 5m/s from the east (90°), obtained from the measurement data at Station East channel, was considered as an input for the model for the whole domain.

3.5. Validation of the TELEMAC-2D Model

The depth-averaged models are usually sensitive to the bottom friction. The Strickler formula is applied to calculate the bottom friction in the TELEMAC-2D model and the Strickler coefficient K affects the model results most strongly. The best agreement between the numerical results and the observations was obtained with a Strickler coefficient K of $70 \text{ m}^{1/3}/\text{s}$ in wet season and $55 \text{ m}^{1/3}/\text{s}$ in dry season. The turbulent viscosity is constant for the domain and the velocity diffusivity is specified as $0.1 \text{ m}^2/\text{s}$. In addition, horizontal salinity gradients are not taken into account, because the measurements showed that the flow is partially mixed during most time of the tidal cycle, the effects of the density driven currents on the depth-averaged flow are negligible.

The computed water elevations were compared against those measured at the DLS, GDJ and DHQ stations (locations see Fig. 2) in wet season (Fig. 4a, b and c) and at the DLS and DHQ stations in dry season (Fig. 5a and b). The amplitudes of the modeled water level are in close agreement with the observations at all stations, and the root-mean-square errors (RMSEs) between the model predictions and the observations are less than 0.10 m, as shown in Fig. 4 and Fig. 5. The comparison between the computed and observed depth-averaged velocities and directions at the

observation stations DLS, DHQ and HW (locations see Fig. 2) in wet season is shown in Fig. 6a, b and c, and the comparison at stations DLS, DHQ, West channel and East channel (locations see Fig. 2) in dry season is shown in Fig.7a-d. It can be seen that the model reproduces the observations satisfactorily. The averaged RMSEs for all the stations are less than 0.13 m/s, except at station DHQ during the spring tide of the dry season (see Fig.6 and Fig. 7).

3.6. Validation of the coupled model

After the TELEMAC-2D model was validated, the TELEMAC-2D module and TOMAWAC module were coupled for simulating the combined wave, tide and runoff conditions. The time step for TELEMAC-2D is set to 30s and that for TOMAWAC is set to 3s, the coupling period for the two modules is set to 30s. The computational time required to solve the TOMAWAC module and the TELEMAC-2D module takes about three quarters and one-quarter of the total time, respectively.

The water level is unchanged at all stations with and without coupling wave and current. The current inside the outlet is little affected by WCI because wave heights are very small due to sheltering by the islands and large bottom friction. During the dry season in 2005, the observation stations in West Channel and East Channel, located outside of the outlet, were used for validation of the coupled model. The results show that the currents are slightly improved during spring tide and neap tide when wave and current are coupled (Table 1).

There is no observed wave data in the model domain during the simulation period. The results of the wave model were compared against the other wave model results in the Pearl River Estuary (Wang *et al.*, 2006). The modeled results in the same sites of the two models are very consistent, indicating that the wave results simulated using the coupled model are reasonable.

4. Results

The changes in current in the presence of wave and changes in the wave in the presence of current were analyzed, respectively, for the simulations with and without coupling wave and current.

4.1. Wet Season

The runoff at station ZY is from the Xijiang River and runoff conditions in the upstream boundary can be explained by the measured data at station Makou, the dominant discharge station in the Xijiang River. The daily mean river discharges at Station Makou during the measurement period on July 30 and 31 were 14000 and 12400 m³/s, respectively, which is slightly higher than the mean discharge during the wet season. The runoff at the upstream boundary represents a wet season condition.

As shown in Fig. 2, Stations 1 to 13, along the section from the river channel to the open sea, are selected to compare the current variation. The currents at the stations inside the Jiaobeisha channel (Fig.8a) and outside of the mouth bar (Fig. 8c and Fig.8d) have no significant change when wave and current are coupled. A relatively large change in the current can be observed inside the mouth bar when wave and current are coupled, but no more than 0.07 m/s at Station 5 (Fig.8b). On average, the current is reduced by 0.04 m/s at peak ebb (Fig. 9a).

The wave heights show periodic fluctuation with the tides, as shown in Fig.10. The wave height has a phase lag of about a quarter of the tidal period outside the mouth bar (station 7 and 10). The wave height decreases during flood tide and increases during ebb tide. Upon reaching the mouth bar (Station 5), the phase between wave height and tide is reduced. Landward of the mouth bar (Station 3), the wave height varies consistently with the tide level.

Wave heights reduce upon propagation. At peak flood, wave heights vary from 1.45 m outside of the mouth bar (Station 10) to 0.36 m in the mouth bar (Station 6), and to only 0.02 m inside the channel (Station DHQ). At peak ebb, wave heights vary from 1.49 m outside of the mouth bar (Station 10) to 0.63 m in the mouth bar (Station 6), and to only 0.02 m inside the channel (Station DHQ).

4.2. Dry Season

The daily mean river discharges during the measurement period in dry season at Station Makou were below 5000 m³/s, much smaller than the 7300 m³/s of the multi-annual mean runoff. The runoff of the upstream boundary can represent dry season conditions.

The current is significantly altered during the dry season using the coupled model. The velocity is changed slightly during spring tide, and greatly during the spring-neap transition period and neap tide. At Stations 5 and 7, the velocity decreases when the tide is ebbing and increases when the tide is flooding. At Station 10, the velocity decreases in both ebb and flood tides during the spring tide and the spring-neap transition period, and increases during neap tide. The velocity experiences little changes at Station 3, located inside the Jiaobeisha channel, since the wave energy is substantially dissipated when it arrives in the channel (Fig. 11).

During spring tide, the velocity increases at peak ebb in the area 22 km (Station 1) to the open boundary, with a maximum increase of 0.10 m/s when wave module and current module are coupled. Upon propagation, the velocity decreases slightly in the area 11 km to 22 km (stations 7 to 11) as wave propagates upstream, with an averaged value of 0.04m/s. At peak flood, the velocity increases greatly in the area 19 km to 27 km (stations 10 to 13), with a maximum increase of 0.14m/s, but changes slightly in other areas with the coupling of wave module and

current module (Fig. 12).

During neap tide, the velocity in the area from 0 to 14 km (station 1 to station 8) decreases slightly at peak ebb with the coupling of wave module and current module. The velocity increases with the deepening of the water depth in the area 14 km to the open boundary, having a maximum increase of 0.30 m/s. At peak flood, the velocity in the area 0 to 10 km increases by 0.02 m/s on average, but it decreases significantly 10km away to the open boundary, with the largest decrease at 0.17 m/s (Fig. 12).

As indicated above, the waves have a noticeable effect on the hydrodynamics in the ME during the dry season. Spatially, the effect decreases gradually as the wave parameters diminish landward. Temporally, the effect during neap tide is greater than that during spring tide.

The wave height fluctuates with the tidal stage, similar to that during the wet season (Fig.13). The wave height has a phase lag of about a quarter of the tidal period outside the mouth bar (station 7 and 10). The phase between wave height and tide is reduced in the mouth bar (station 5). Inside the Jiaobeisha channel, the wave height varies consistently out of phase with the tide variation.

Upon propagation, the wave heights at peak flood decrease from 1.46m at station 10 (outside the mouth bar) to 0.27 m at station 6 (in the mouth bar), and to only 0.27 m at station DHQ. At peak ebb, wave heights decrease from 1.54 m at station 10 to 0.70 m at station 6, and to only 0.01 m at station DHQ.

5. Discussion

TELEMAC-2D simulation of the depth-averaged currents was evaluated with the use of a

current only model and with the use of a wave-current coupled model. The numerical simulations reproduce well the currents in conditions of high runoff and low runoff, respectively. A satisfactory numerical approach of the tidal hydrodynamic conditions was integrated into the wave propagation module. TOMAWAC reproduced reasonable wave propagation. The model results of internal coupling between TELEMAC-2D model and TOMAWAC model are reliable.

The analysis of the results using the coupled wave and current model suggests that WCI in the ME changes with runoff, tide and wave. This section mainly discusses the effects of these forcings on WCI.

5.1. Effect of Runoff

The runoff is strong but wave and tide are relatively weak during the wet season in the ME. The model results show that WCI has little effect on the hydrodynamics during the wet season in the ME. The main reason is that velocity is dominated by the barotropic force, which is little affected by wave radiation stress and more determined by runoff than by tidal fluctuation during the wet season.

It is clearly seen from table 2 that the residual current mainly results from the runoff and is very close to the ebb tidal current. The current induced bottom shear stresses (BSS) are significant under strong runoff, whereas wave induced BSS are minor. The wave and current combined BSS are determined by runoff, which changes the velocity a little when wave and current are coupled.

The runoff is weak and the wave and tide are relatively strong during the dry season in the ME. The tidal current and wave become the major forcings in the ME. Both the current and the wave induced BSS are important, so the velocity is changed significantly when wave and current

are coupled.

With the seasonal variations in runoff and wave in the ME, it is obvious that the wave brings a minor effect on the current in wet season. Both the effects of wave on the current and current on the wave are important in dry season.

5.2. Effect of Tides

The results indicate the significant effect of tidal current on wave height in both wet season and dry season in the ME. Wave height generally decreases when it is flood tide and increases when it is ebb tide. These findings are consistent with the results of WCI modeling in the Pearl River Estuary (Wang *et al.*, 2006) and with the observations in the Columbia River entrance (Gonzalez, 1984). The opposing currents (ebbing) increase the radiation stress, which makes the wave height higher, and following currents (flooding) decrease the radiation stress, which reduces wave height (Gonzalez, 1984). Upon propagation, phases between wave height and tide are reduced. We believe that this spatial change is determined by the combined effect of the radiation stress and the bottom friction. The bottom friction is decreased while flooding, which increases wave heights, and increased while ebbing, which decreases wave heights. The bottom friction grows when water depth becomes shallow from the shelf to the estuary: 15 m-17 m at Station 10, 4.5 m-6.5 m at Station 7, and only 2 m to 4 m at Station 5. Therefore, in the deep water outside the mouth bar, the effect of the bottom friction is small, and the wave height varies with the change in the radiation stress. This results in an increase in wave height during an ebbing current and a decrease of wave height during a flooding current. Upon reaching the shoaling region of the Mouth bar, the effect of the bottom friction is increased. Wave height varies with the change in both radiation stress and bottom friction, which results in the reduction of the phase between wave

height and tide. When waves break at the mouth bar, the wave energy transformations are periodic with the tidal flow, which result in the consistency of wave height and tide.

5.3. Effect of the Wave

The model results show the significant effects of waves on the tidal current in dry season. The complexity of current change is displayed using the coupled model; but it is obvious that the effects of wave on the current are greatly affected by the propagation direction between waves and currents. The wave direction is northeast near the open boundary, shifts to the east, then gradually to the southeast in front of the mouth bar because of refraction. During the ebb tide, the current direction is south by west and follows the wave direction (northeast) near the open boundary; the BSS are increased and the currents are thus increased. Upon propagation, the current opposes the wave, the BSS are decreased and the current is thus decreased. During the flood tide, the current direction is west by north and also follows the wave direction near the open boundary; in the peak flood of spring tide, the velocity is increased, but in the peak flood of neap tide, the velocity is decreased, which may be related to bottom friction. Upon propagation, the current direction turns from westnorth to northwest, following the wave and the current is increased (Fig.14). Generally, the flow velocity is increased for following waves and currents and decreased for opposing waves and currents.

The model results also show that the effects of wave on the current change with the tide. Changes are bigger during neap tide than during spring tide. The main reason is that tidal current velocity is greatly decreased while wave height is mildly increased from spring tide to neap tide, which makes the effects of the wave stand out during neap tide.

It should be noted that the WCI effects could be over (or under) estimated, since the bottom

friction for currents enhanced by the WCI is not included in the TELEMAC-2D and TOMAWAC coupled model. The flow module is run in a depth averaged mode and the horizontal salinity gradients are not taken into account, which may cause inaccuracy for the current computation, especially in a short period when the flow is well stratified.

6. Conclusions

The internally coupled TELEMAC-2D and TOMAWAC modeling system has been applied to the ME to study the impact of WCI on the hydrodynamics in the estuary. The model was first validated against measured data with satisfactory agreement, and was followed by simulations of WCI for both wet and dry seasons, driven by different offshore wave conditions from the measured data.

WCI varies with the runoff in the ME. Waves have a minor effect on the current under strong runoff in wet season, with a change in current of no more than 0.07 m/s, while the effects of wave on current and current on wave are significant under small runoff in dry season.

Currents exert a significant effect on waves in both wet season and dry season. Generally, within a tidal period, the ebbing flow generally increases wave height and the flooding flow decreases wave height. Upon propagation, wave height has a phase lag of about a quarter of the tidal period outside the mouth bar; the phase lag is reduced in the mouth bar; wave height varies consistently with the tide level inside the mouth bar.

Waves bring a noticeable effect on tidal currents in the dry season. Generally, flow velocity increases for following waves and currents and decreases for opposing waves and currents. The effects of waves on the currents change with the tide: larger during neap tide than during spring tide, stronger during ebb tide than during flood tide. With the coupling of wave model and current

model, velocity could increase up to a maximum of 0.30m/s at the peak ebb of neap tide, while velocity could decrease up to a maximum of 0.17 m/s at the peak flood of neap tide.

The present study discovers the basic characteristics of WCI in the ME and forms a good foundation for further research. The similar results have also been found in the Altamaha River (Kang and Di Iorio, 2006) and the Tagus estuary (Rusu et al., 2011). Our main findings can provide reference for the different estuaries in the world. However, the mechanisms under the effects of WCI are very complex and cannot be well solved by the present study. 3D model simulations with different incident waves are required to further examine the effects of WCI on vertical current profile, which will help to explore the mechanisms of WCI in the ME.

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Figure Captions

Figure 1. (a) Location of Study area in relation to the Pearl River Delta, and (b) Close-up of Study area

Figure 2. TOMAWAC and TELEMAC-2D computational domains, the locations of measurement stations on July 2004 and October 2005 and the stations 1-13 for analysis

Figure 3. The computational mesh and boundaries

Figure 4. Measured and computed times series of the free-surface elevation on July 2004 at stations DLS(a), DHQ(b) and GDJ(c) (Hours from 2004/7/28 0:00)

Figure 5. Measured and computed times series of the free-surface elevation on October 2005 at stations DLS(a) and DHQ(b) (Hours from 2005/10/19 0:00)

Figure 6. Measured and computed time series of the amplitudes and directions (clockwise from the north) of the depth averaged currents on July 2004 at stations DLS(a), DHQ(b) and HW(c) (Hours from 2004/7/28 0:00)

Figure 7. Measured and computed time series of the amplitudes and directions (clockwise from the north) of the depth averaged currents in the spring tide and the neap tide on October 2005 at stations DLS(a), DHQ(b) ,West channel(c) and East channel(d) (Hours from 2005/10/19 0:00)

Figure 8. Comparison of the amplitudes and directions of the depth-averaged currents with current only and wave-current coupled on July 2004 at stations 3(a), 5(b), 7(c) and 10(d) (Hours from 2004/7/28 0:00)

Figure 9. Comparison of amplitudes of the depth-averaged currents with current only and wave-current coupled along the longitudinal axis at peak ebb (a) and peak flood (b) on July

2004

Figure 10. Computed time series of the significant wave height and the water depth on July 2004 at stations 3(a), 5(b), 7(c) and 10(d) (Hours from 2004/7/29 1:00)

Figure 11. Comparison of amplitudes of the depth-averaged currents with current only and wave-current coupled on October 2005 at stations 3(a), 5(b), 7(c) and 10(d) (Hours from 2005/10/18 0:00)

Figure 12. Comparison of amplitudes of the depth-averaged currents with current only and wave-current coupled along the longitudinal axis at peak ebb (a) and peak flood (b) in spring tide, peak ebb (c) and peak flood (d) in neap tide on October 2005

Figure 13. Computed time series of the significant wave height and the water depth on October 2005 at stations 3(a), 5(b), 7(c) and 10(d) (Hours from 2005/10/19 1:00)

Figure 14. Amplitudes and directions of the depth-averaged currents and the significant wave heights and directions after coupled, current (a) and wave (b) at peak ebb in spring tide, current (c) and wave (d) at peak flood in spring tide; current (e) and wave (f) at peak ebb in neap tide, current (g) and wave (h) at peak flood in neap tide on October 2005

606	Table Captions
607	Table 1. RMSEs between observed and predicted velocities by current-wave coupled model
608	at the stations West channel and East channel for a period representing the dry season (Hours
609	from 2005/10/19 0:00)
610	Table 2. Flood tide velocities, ebb tide velocities and residual current velocities measured
611	during the wet season (July 30 11:00 to July 31 12:00, 2004)
612	
613	

Figure

a

b

Fig. 1.

Fig. 2.

Fig. 3.

Fig.3.a

Fig.3.b

a

b

c

Fig. 4.

a

b

Fig. 5.

a

b

c

Fig. 6.

DLS(Spring Tide)

DLS(Spring Tide)

DLS(Neap Tide)

DLS(Neap Tide)

DHQ(Spring Tide)

DHQ(Spring Tide)

DHQ(Neap Tide)

DHQ(Neap Tide)

West Channel(Spring Tide)

West Channel(Spring Tide)

West Channel(Neap Tide)

West Channel(Neap Tide)

East Channel(Spring Tide)

East Channel(Spring Tide)

East Channel(Neap Tide)

East Channel(Neap Tide)

a

b

d

Fig. 8.

a

b

Fig. 9.

a

b

c

d

Fig. 10.

a

b

c

d

Fig. 11.

Fig. 12.

a

b

c

d

Fig. 13.

a

b

c

d

e

f

g

h

Fig. 14.

Table 1. RMSEs between observed and predicted velocities by current-wave coupled model at the stations West channel and East channel for a period representing the dry season (Hours from 2005/10/19 0:00)

<i>station</i>	<i>West channel</i>		<i>East channel</i>	
tide	spring	neap	spring	neap
velocity (m/s)	0.110	0.080	0.111	0.122

Table 2. Flood tide velocities, ebb tide velocities and residual current velocities measured during the wet season (July 30 11:00 to July 31 12:00, 2004)

<i>Velocity(m/s)</i>							
Stations	layer	flood tide	direction	ebb tide	direction	residual current	direction
DLS	surface	0.13	277.58	0.82	147.58	0.75	148.2
	middle	0.10	305.89	0.72	133.75	0.66	133.85
	bottom	0.10	313.64	0.60	132.58	0.54	132.56
HW	surface	0.05	326.62	0.60	137.66	0.52	137.57
	middle	0.04	303.49	0.48	122.12	0.44	122.11
	bottom	0.02	335.71	0.44	121.95	0.37	121.7
DHQ	surface	0.37	327.05	0.88	156.01	0.68	156.78
	middle	0.31	330.3	0.76	151.07	0.59	151.13
	bottom	0.24	328.64	0.64	152.96	0.50	153.29