THE IMPACT OF RADIATION STRESS IN A COUPLED WAVE-TIDE-SURGE MODEL

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1. INTRODUCTION

Because wind generates waves as well as storm surges, their generation is closely related. Moreover, the strong nonlinear interactions that exist between tides and storm surges in shallow water, result in important interactions between waves and tide-surge motions. In this study, the coupling of waves and tide-surge motions is implemented by several mechanisms wherein waves and the mean flow, or the water level associated with the tide and surge, are allowed to interact with each component of the total motion affecting the other motions. These mechanisms mainly include the wave-dependent surface wind stress, the bottom stress, and the radiation stress. In the past ten years, several studies (Mastenbroek et al., 1993; Zhang et al., 1996; Jin et al., 1998; Yin et al., 2001) considered wave and tide-surge interaction mechanisms. However, because of large spatial resolutions used in these studies, the effects of radiation stress were ignored or poorly simulated. In this study, high-spatial resolution and a coupled wave-tide-surge interaction numerical model, are used to study the effects of radiation stress on wave heights and sea level.

The focus of this study is wave-tide-surge interactions in the coastal region, specifically the Huanghe Delta area of China. High quality models are implemented for waves, tides and surges on a fine-resolution grid. The coupling mechanism considered is wave radiation stress. For moderately high wind and current conditions, the coupled model simulations are shown to result in an enhancement in wave heights and sea level of as much as 67 cm and 50 cm, in observed conditions that were 3.05 *m* and 2.7 *m*, respectively.

2. COUPLED WAVE-TIDE-SURGE MODEL

The coupled wave-tide-surge interaction numerical model is composed of an advanced shallow water wave model and a two-dimensional tide-surge model. The two-way interactions between waves and tide-surge motions are studied on the basis of radiation stress mechanism.

2.1 *Wave Model*

The third generation shallow water wave model YWE-WAM was used in the study. This model is based on the wave action balance equation, with most of the source functions taken directly from the standard WAM model of Komen et al. (1994). An explicit representation of the energy dissipation caused by depth-limited breaking in shallow water is taken into account. The basic equations are:

$$\frac{\partial N}{\partial t} + \nabla[(\vec{C}_g + \vec{u})N] + \frac{\partial}{\partial \sigma}[C_\sigma N] + \frac{\partial}{\partial \theta}(c_\theta N) = \frac{S}{\sigma} \tag{1}$$

$$N = N(\sigma, \theta, \vec{x}, t) = \frac{F(\sigma, \theta, \vec{x}, t)}{\sigma} \tag{2}$$

$$C_g = \frac{1}{2}\left(1 + \frac{2kd}{\sinh 2kd}\right)\frac{\sigma}{k} \quad ; \quad C_\theta = -\frac{1}{k}\left(\frac{\partial \sigma}{\partial d}\frac{\partial d}{\partial m} - \vec{k} \cdot \frac{\partial \vec{u}}{\partial m}\right) \tag{3}$$

$$C_\sigma = \frac{\partial\sigma}{\partial d}\left(\frac{\partial d}{\partial t} + \vec{u}\cdot\nabla d\right) - C_g \vec{k}\cdot\frac{\partial\vec{u}}{\partial s.} \tag{4}$$

where $F(\sigma,\theta)$ is the spectral density, d, $\vec{k}$, $\vec{u}$ are water depth, wave number vector, velocity vector, s is the space coordinate in the propagation direction, θ, the two-dimensional space gradient is ∇, and m is the spatial coordinate perpendicular to the propagation direction, s. The formulations for propagation speed C_g, C_σ and C_θ give a detailed consideration of the effect of varying depth and currents on wave propagation. Source functions are given by: $S = S_{in} + S_{nl} + S_{dis} + S_{bot} + S_{dbs}$, including wind input, nonlinear interactions, white-capping dissipation, bottom friction and depth-limited breaking dissipation. A detailed description of the model is given by Yin et al. (1996).

2.2 *Tide-Surge Model*

A two-dimensional numerical tide-surge model with ADI (Alternative Direction Implicit) difference scheme and radiation stress is used. The mass equation is:

$$\frac{\partial\zeta}{\partial t} + \frac{\partial(Du)}{\partial x} + \frac{\partial(Dv)}{\partial y} = 0 \tag{5}$$

the momentum equations are

$$\begin{aligned}\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv &= -g\frac{\partial\zeta}{\partial x} - \frac{1}{\rho_w}\frac{\partial p_a}{\partial x} \\ &+ \frac{1}{\rho_w D}\left(\tau_x - \tau_{bx} - \frac{\partial s_{xx}}{\partial x} - \frac{\partial s_{xy}}{\partial y}\right) + A\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)\end{aligned} \tag{6}$$

$$\begin{aligned}\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu &= -g\frac{\partial\zeta}{\partial y} - \frac{1}{\rho_w}\frac{\partial p_a}{\partial y} \\ &+ \frac{1}{\rho_w D}\left(\tau_y - \tau_{by} - \frac{\partial s_{yx}}{\partial x} - \frac{\partial s_{yy}}{\partial y}\right) + A\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right)\end{aligned} \tag{7}$$

where u and v are the components of the depth-averaged velocity in the eastward and northward directions, respectively; t is the time, f is the Coriolis parameter; A is the horizontal eddy viscosity; g is gravitational acceleration; ρ_w is the density of sea water; D is the total depth ($= d + \zeta$); mean water depth + surface elevation); s_{xx}, s_{xy}, s_{yx} and s_{yy} are components of the radiation stress tensor; p_a is the atmospheric pressure $\vec{\tau}_s = (\tau_x, \tau_y)$ is the surface wind stress; and $\vec{\tau}_b = (\tau_{bx}, \tau_{by})$ is the bottom stress.

Surface wind stress is generally assumed to take the form

$$\vec{\tau}_s = \rho_a C_d |\vec{w}_{10}| \vec{w}_{10} \tag{8}$$

where ρ_a is the air density; C_d, is the surface aerodynamic drag coefficient and $\vec{w}_{10}$ denotes wind velocity vector at $10m$ reference height. A wave-age dependent C_d formulation would assume the functional dependence of the HEXOS relation of Smith et al. (1992). However, in this study, we take a conventional approach, following Hsu (1986), and we assume that C_d takes the form,

$$C_d = \lambda \left\{ \frac{0.4}{14.56 - 2\ln|\vec{w}_{10}|} \right\}^2 \tag{9}$$

where λ is an adjustable coefficient depending on differing weather conditions (~1.1 for typhoons, ~1.0 for extra-tropical systems). Bottom stress is assumed to be,

$$\vec{\tau}_b = \rho_w \gamma |\vec{u}| \vec{u} \ , \ \gamma = \frac{ng}{c_z^2} \tag{10}$$

where c_z is the Chezy-Manning coefficient and $\vec{u}$ is the current velocity vector. The radiation stress components are given by

$$s_{xx} = \rho g \int_o^\infty \int_o^{2\pi} [(n - \frac{1}{2}) + n\cos^2\theta] F(\sigma,\theta) d\sigma \ d\theta \tag{11}$$

$$s_{xy} = s_{yx} = \rho g \int_o^\infty \int_o^{2\pi} (n \sin\theta \cos\theta) F(\sigma,\theta) d\sigma \ d\theta \tag{12}$$

$$s_{yy} = \rho g \int_o^\infty \int_o^{2\pi} ((n - \frac{1}{2}) + n\sin^2\theta) F(\sigma,\theta) d\sigma \ d\theta \tag{13}$$

where $n = \frac{1}{2}\left(1 + \frac{2kd}{\sinh 2kd}\right)$. Given $F(\sigma,\theta)$ by a wave model, radiation stress can therefore be obtained.

2.3 *Initial and Boundary Conditions*

Initial conditions are that currents and surface elevation are zero,

$$\zeta = u = v = 0 \tag{14}$$

Lateral boundary conditions are assumed zero for flow normal to the solid boundary and along the open boundary,

$$\zeta = \frac{P_b - P_o}{\rho g} + \sum f_i H_i \cos[\omega_i t + (v+u)_i - g_i] \tag{15}$$

where P_o and P_b are the values for atmospheric pressure outside a storm and at the open boundary, respectively; ρ is the density of sea water, g is gravitational acceleration; ω_i is the radian frequency; harmonic constants H_i and g_i are the amplitudes and phase angles of each tidal constituent; f_i is the nodal factor of each tidal constituent; t is the time; $(v+u)_i$ is the initial phase and u_i is the nodal correction angle. The ten constituents are, in the standard notation, K_1, O_1, P_1, Q_1, M_2, S_2, N_2, K_2, S_a, S_{sa}.

2.4 *The Coupling Procedure*

Implementation of the coupling between wave and tide-surge models followed the procedure:

a) Prior to the coupling, the two models are initialized separately. Thus, the wave model is warmed up for 12hr, and the tide-surge model, for 4 days. The initialization is performed in a manner that allows the synchronized coupling of the two models to be achieved.
b) The wave model is run (coarse-grid time steps: 15 minutes, fine-grid: 5 minutes) using the computed change of water depth (mean water depth plus tide-surge elevation) and inhomogeneous and unsteady currents from the two-dimensional tide-surge model to obtain related wave parameters and wave spectrum.
c) The radiation stress is calculated using the wave spectrum and passed back to the tide-surge model.
d) The two-dimensional tide-surge model is run (15 minute time-steps) using the calculated radiation stress, surface wind stress and bottom stress. This gives newly computed elevations and currents, which are passed back to the wave model to repeat the sequence of the computations.

During the simulation process, computed results of interest, for example, the significant wave heights, the mean wave periods, the directional wave spectrum, water surface elevations and current velocities, with and without the inclusion of waves and tide-surge interactions can be output by the wave model and tide-surge model, as described.

3. NUMERICAL STUDY OF THE HUANGHE DELTA COASTAL AREA

Huanghe Delta coastal area is located in the southwest region of the Bohai Sea. This area has great strategic importance because it is the most important oil production area of the Shengli Oilfield. The fine-resolution grid area, as shown in Figure 1, is the Huanghe Delta coastal area, which is the focus of this study. This area can be characterized as having relatively big waves and strong set-up due to shallow water depths (generally less than 12 m). Therefore there is a challenge both for offshore design criteria as well as for prediction, particularly in severe storms, involving extreme wind and waves conditions. Accurate forecasts of waves and sea level are quite important for the safety of offshore personnel and property. The focus of this study is to consider the effect of radiation stress on wave heights and sea level, in the context of a wave-tide-surge interaction model. A secondary objective is to offer a feasible analysis for the operational adoption of a coupled wave-tide-surge model to forecast waves and the sea level in a coastal region such as the Huanghe Delta area.

3.1 *Case Descriptions*

Two storm cases occurred on 22-25 April 1998 and 1-2 April 1999, where measured wave data were collected from the buoy site, 38°13′N, 118°19′E, shown in Figure 1. The wind fields were prepared by the Ocean University of Qingdao. Nested coarse- and fine-resolution grids for the wave model are 16′×16′ and 2′×2′, respectively. The tide-surge model implemented on the 2′×2′ grid for the entire Bohai Sea. The effects of radiation stress on wave heights and sea level in the Huanghe Delta coastal area (specifically, 118°24′—119°24′E, 37°48′—38°14′N) can be analyzed by comparing results from uncoupled and coupled model simulations.

3.2 *Impact of radiation stress on wave heights and sea level*

To investigate the influence of radiation stress in wave-tide-surge interactions, the coupled wave-tide-surge model only includes the radiation stress mechanism. Figures 2-5 show comparisons of simulated and measured wave heights and sea level for the two cases, at the buoy. From Figures 2-3, the wave heights simulated by coupled wave-tide-surge model show overall improvement, particularly for the second storm case (1-2 April 1999), compared to those simulated by the uncoupled wave model at maximum wave heights values. Moreover, Figures 4-5 show that the sea level simulated by coupled wave-tide-surge model is improved compared to those simulated by the uncoupled tide-surge model. The improvement is more clearly evident at the maximum set-up values, and in very good agreement with the measured data. Table 1 shows that radiation stress can increase the wave heights by as much as 67 cm, and sea level, by as much as 50 cm. Overall, the comparisons from the two cases show that the coupled wave-tide-surge model gives better results than the uncoupled model.

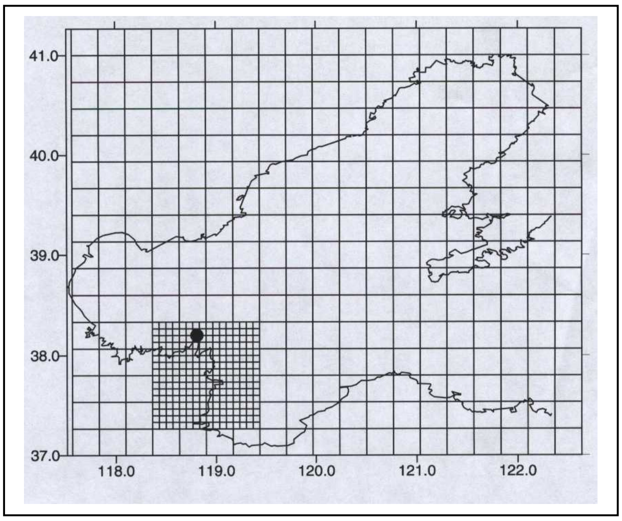

Figure 1. The Bohai and Huanghe Delta coastal area, with buoy location •. The fine-mesh grid in Figure 1 is shown as 4′ to avoid blackening the figure. The actual resolution is 2′ in the computations.

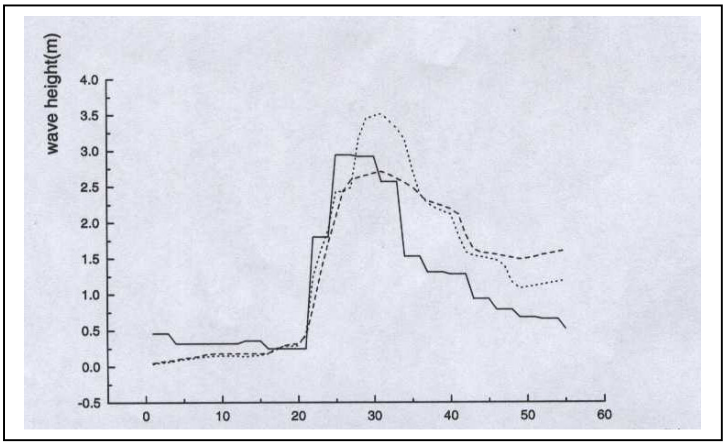

Figure 2. Comparisons of simulated and measured wave heights for the 20UTC 22 April 1998- 02UTC 25 April 1998 storm. Measured data —, uncoupled wave model ---, coupled wave-tide-surge model, …. .

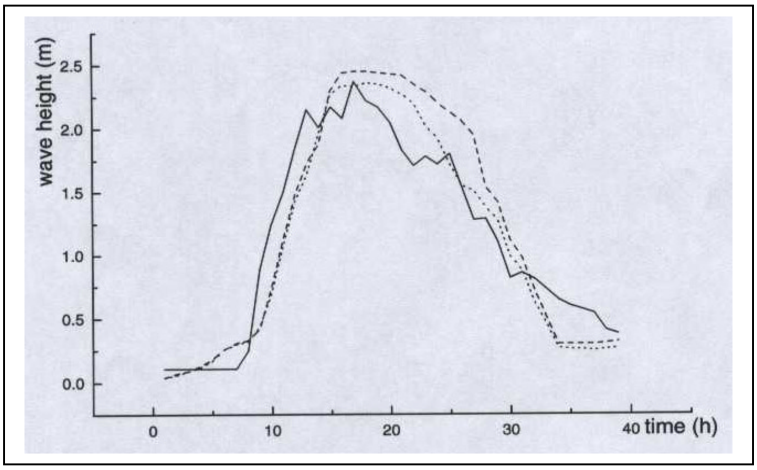

Figure 3. As in Figure 2, for the 00UTC 01 April 1999- 14UTC 02 April 1999 storm.

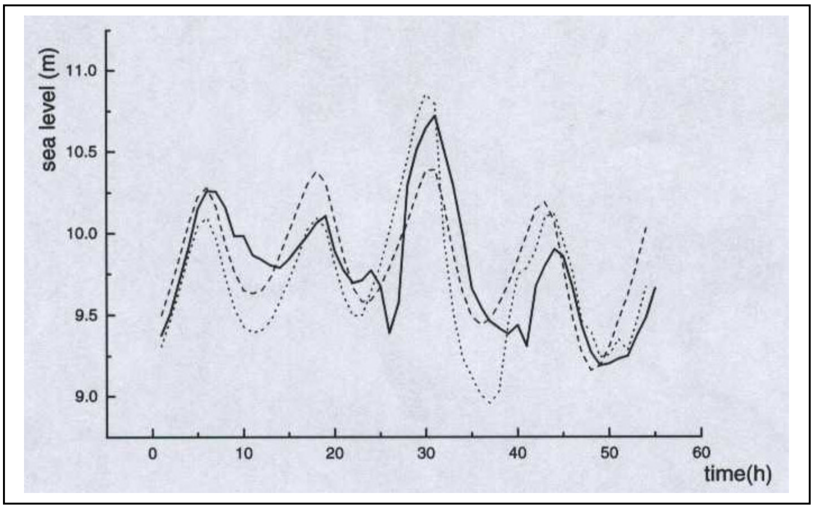

Figure 4. Comparisons of simulated and measured sea level for the 20UTC 22 April 1998- 02UTC 25 April 1998 storm. Measured data —, uncoupled tide-surge model ---, coupled wave-tide-surge model, …. .

Table 1. Comparisons of simulated and measured maximum wave heights and sea level (*m*). The actual sea level is, *as indicated,* observed or computed - 8.0m for the 1st storm, *as indicated*, observed or computed - 3.0m for the 2nd storm, respectively for these two storms. For 1998, 8.0m is the distance from the buoy level to the datum surface, for 1999, 3.0m is this distance.

Cases	Sea Level			Wave Height		
	Observed	Uncoupled model	Coupled model	Observed	Uncoupled model	Coupled model
22-25 April98	10.7	10.3	10.8	3.05	2.65	3.32
01-02 April99	4.75	4.5	4.7	2.37	2.45	2.35

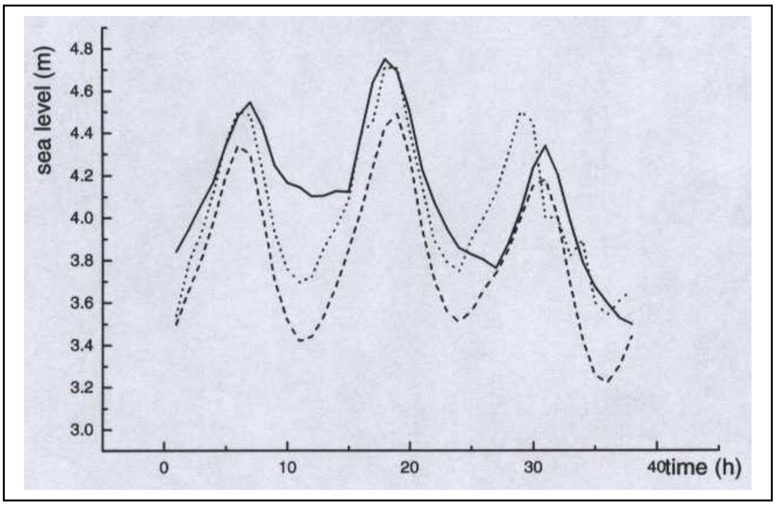

Figure 5. As in Figure 4, for the 00UTC 01 April 1999- 14UTC 02 April 1999 storm.

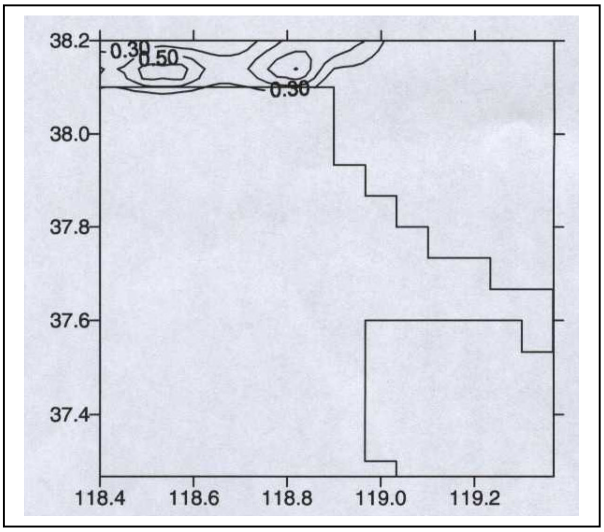

Figure 6. The difference distributions of wave heights simulated by the coupled wave-tide-surge model minus the uncoupled model for the storm peak (02 UTC, 24 April 1998). Units are *m.*

Figures 6-9 show the difference distributions for wave heights and sea level as simulated by the uncoupled wave model, the uncoupled tide-surge model and coupled wave-tide-surge model. This is for two storm cases in the Huanghe Delta coastal area, specifically for the period of maximum wave height and set-up. Figures 6-7 show that the effects of radiation stress result in over 50 cm wave height increase. Figures 8-9 show that this mechanisms can result in over 20 cm sea level increase. This is very important for design criteria and ocean engineering of offshore structures. Moreover, the storm cases considered in this study are relatively moderate. Strong waves, extra-tropical storms or typhoon-force storms causing big waves and strong set-up in the Huanghe Delta coastal area would give more dramatic results. In these circumstances, it is expected that the effects of radiation stress would be much larger.

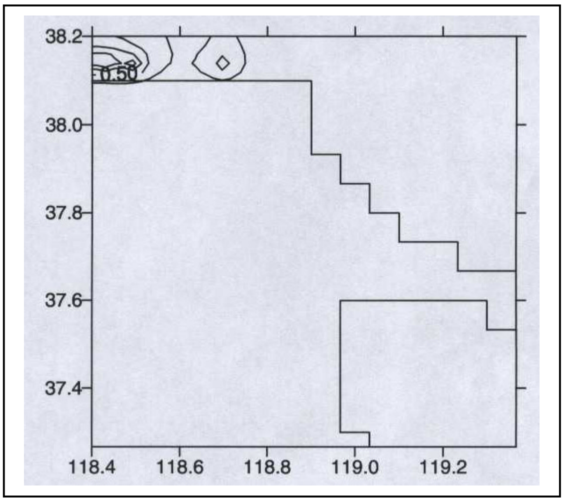

Figure 7. As in Figure 6 for the storm peak (17UTC, 01 April 1999).

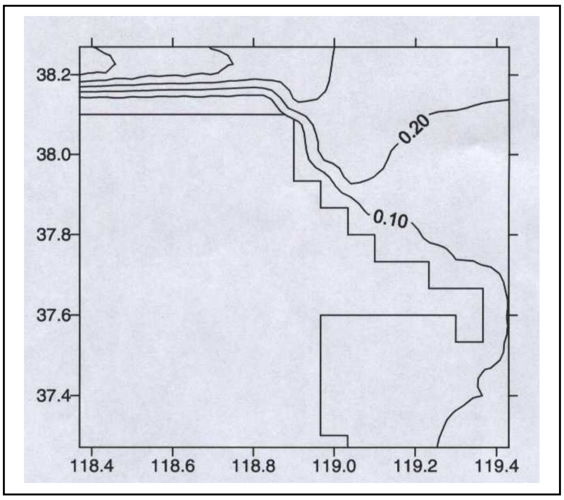

Figure 8. The difference distributions of sea level simulated by coupled wave-tide-surge minus the uncoupled model for the storm peak (02 UTC, 24 April 1998). Units are *m*.

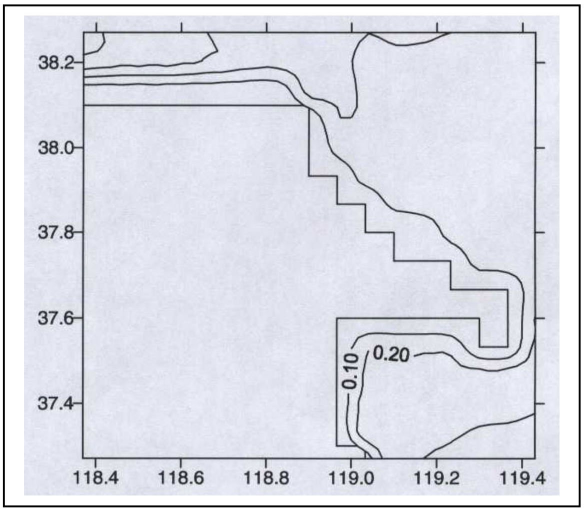

Figure 9. As in Figure 8 for the storm peak (17 UTC, 01 April 1999).

4. CONCLUDING REMARKS

The focus of this study is a coastal high-resolution (2′×2′) coupled wave-tide-surge interaction model, including the radiation stress mechanism. Comparisons and analysis of simulated and measured wave heights and sea level considered two moderate storm cases for the Huanghe Delta coastal area. We show that the effects of radiation stress on wave heights and sea level can reach 67 cm and 50 cm maximally, respectively. Moreover, there are areas where wave increases are over 50cm and set-up influences are over 20cm. Overall, we show that the wave heights and sea levels simulated by the coupled wave-tide-surge model agree better with the measured values than uncoupled model results, particularly for peak storm conditions. Therefore, we suggest that for offshore design and prediction applications, the coupled wave-tide-surge model should be implemented and wave radiation stress should be included, particular for high waves and strong set-up associated with typhoon or extra-tropical conditions as characterized in the Huanghe Delta coastal area.

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