

Numerical Study of Wave Tide Surge Coupling Processes^{*}

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Risk assessment of storm surge and wave hazards in the Huanghe Delta coastal area of the Bohai Sea requires accurate prediction of storm surge and wave hazards. So this study is aimed at establishing a coastal high-resolution ($2' \times 2'$) two-way coupled wave-tide-surge model including three main physical mechanisms. The model was used for comparisons and analysis of simulated and measured wave heights and sea level in two moderate storm cases in the Huanghe Delta coastal area. We show that the effects of different physical mechanisms on wave heights are mainly determined by wave-current interaction by radiation stress in the wave energy equation. Wave age dependent surface wind stress and radiation stress mechanisms in the coupling wave-tide-surge interaction have positive impact on sea level, and wave-current interaction bottom stress mechanism show negative impact on sea level. The comprehensive effects of three main physical mechanisms show positive net impact on sea level and increase it by as much as 25 cm. We show that the wave heights and sea levels simulated by the coupled wave-tide-surge model agree better with the measured values compared to uncoupled model results, particularly for peak storm conditions.

1. INTRODUCTION

As wind generates waves and storm surges, their generation is closely related. The strong non-linear interactions between tides and storm surges in shallow water result in important interactions between waves and tide surge motions. This study showed that the coupling of waves and tide surge motions is driven by several mechanisms where in waves and the mean flow, or the water level associated with the tide and surge, interact with each component of the total motion affecting the other motions. These mechanisms mainly include the wave-state dependent surface wind stress, the wave-current interaction bottom stress, and the radiation stress. In the past ten years, several studies (Mastenbroek *et al.*, 1993; Davies *et al.*, 1994; Zhang

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etal., 1996 Jin *et al.* 1998 Yin *et al.*, 2001) considered wave and tide-surge interaction mechanisms. However, because of the large spatial resolutions used in these studies, the effects of radiation stress were ignored or poorly simulated and only some individual coupling mechanisms were studied or some studies considered only one-way coupling. Lin *et al.* (2003) made a preliminary study on the impact of radiation stress using two-way coupling model. In this work, high spatial resolution and a two-way coupled wave-surge interaction numerical model are used to study the net effects of several physical mechanisms driving wave heights and sea level.

This study is focused on wave-tide-surge interactions in the coastal region, specifically the Huanghe Delta area of the Bohai Sea. High quality models are implemented on waves, tides and surges on a fine resolution grid. The coupling mechanisms considered are wave-radiation stress, wave-current interaction, bottom stress and wave-state dependent surface wind stress. For moderately high wind and current conditions, coupled model simulation results are compared with synchronic in situ measurements of waves, currents and elevation, and finally the net impacts are studied to give quantitative estimates and appraisal of the wave-surge coupling interaction. This is extremely important for risks assessment of storm surge and wave hazards in the Huanghe Delta coastal area, marine environmental forecasts, ocean engineering design etc. In the Bohai Sea.

II . 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. Two-way interactions between waves and tide-surge motions are studied on the basis of wave-state dependent surface stress, wave-current interaction, bottom stress and radiation stress mechanisms.

(1) Wave Model

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

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

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

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

$$C_\sigma = \frac{\partial}{\partial \sigma} \left(\frac{\partial \sigma}{\partial t} + \vec{u} \cdot \nabla \right) - C_g \vec{k} \cdot \frac{\partial \vec{\theta}}{\partial \sigma} \quad (4)$$

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

(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

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

the momentum equations are

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} - fu = -g \frac{\partial \zeta}{\partial x} - \frac{1}{\rho_w} \frac{\partial p_a}{\partial x} + \frac{1}{\rho_w D} \left\{ \tau_x - \tau_{bx} - \frac{\partial s_{xx}}{\partial x} - \frac{\partial s_{yx}}{\partial y} \right\} + A \left\{ \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right\} \quad (6)$$

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

where u and v are 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:

$$\vec{\tau}_s = \rho_a C_d \left| \vec{w}_{10} \right| \vec{w}_{10} \quad (8)$$

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. In this study, a conventional approach C_d following Hsu (1986), is assumed to take the form:

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

where λ is an adjustable coefficient depending on different weather conditions (~ 1.1 for typhoons, ~ 1.0 for extra-tropical systems). For considering wave dependent state surface wind stress, a wave age dependent C_d formulation would assume the functional dependence of the HEXOS relation of Smith (1992), but here we take a more convenient expression following Donelan *et al.* (1993):

$$C_d = 3.7 \times 10^{-5} \frac{w_{10}^2}{g} \left(\frac{C_p}{w_{10}} \right)^{-0.9} \quad (10)$$

C_d can be obtained by

$$C_d = \left[\frac{\kappa}{\ln 10 - \ln z_0} \right]^2 \quad (11)$$

where c_p is phase velocity of spectral peak and κ is Kaman constant ($=0.40$).

When we do not consider wave current interactions, bottom stress is assumed to be

$$\vec{\tau}_b = \rho_w \gamma |\vec{u}| \vec{u}, \quad \gamma = \frac{ng}{c_s^2} \quad (12)$$

where c_s is the Chezy-Manning coefficient and $\vec{u}$ is the current velocity vector

According to the wave-current interaction model of Grant and Madsen (1979), in the form published by Signell *et al* (1990), a collinear flow implies that the total bed shear stress is given by

$$\tau_t = \tau_c + \tau_w \quad (13)$$

where τ_c is an instantaneous current shear stress and τ_w is the maximum wave bed stress as given by

$$\tau_w = \frac{1}{2} \rho f_w |U_0|^2 \quad (14)$$

where U_0 is the maximum near bed wave orbital velocity, and f_w is the wave friction factor. The near bed wave orbital velocity is given by

$$U_0 = \frac{a_w \sigma}{\sinh kh} \quad (15)$$

where a_w is the wave amplitude, σ is wave frequency, and k is the wave number determined from the linear dispersion relation

$$\sigma^2 = (gk) \tanh(kh). \quad (16)$$

The wave friction factor f_w can be readily computed from the semi empirical expression of Jonsson and Carlsen (1976), based on laboratory observations. This implies

$$\frac{1}{4 \sqrt{f_w}} + \lg \left(\frac{1}{4 \sqrt{f_w}} \right) = -0.08 + \lg \left(\frac{A_b}{k_b} \right) \quad (17)$$

where $k_b = 30z_0$ and z_0 is the *bottom* roughness length and $A_b = U_0 / \sigma$.

If we assume that the current does not influence the wave field, the wave friction velocity is given by

$$U_{*w} = \left(\frac{\tau_w}{\rho} \right)^{1/2}. \quad (18)$$

At initial time $t=0$, an initial current friction factor f_c , excluding wind wave turbulence, is determined from

$$f_c = 2 \left[\frac{0.4}{\ln(30z_r / k_{bc})} \right]^2 \quad (19)$$

with k_{bc} taken as the Nikuradse roughness $k_{bc} = k_b = 30z_0$, with z_r taken as 100 cm above the bed. Once f_c is determined, U_{*c} can be readily computed from

$$U_{*c} = \left(\frac{\tau_c}{\rho} \right)^{1/2} \quad (20)$$

where $\tau_c = \sqrt{F_B^2 + G_B^2}$ and F_B and G_B are given as

$$F_B = \frac{1}{2} f_c \rho u (u^2 + v^2)^{1/2} \quad (21)$$

$$G_B = \frac{1}{2} f_c \rho v (u^2 + v^2)^{1/2}. \quad (22)$$

The combined friction velocity U_{*cv} for waves and currents is given by

$$U_{*cv} = \left(U_{*c}^2 + U_{*g}^2 \right)^{1/2}. \quad (23)$$

The apparent bottom roughness k_{bc} felt by the current due to the presence of waves is given by

$$k_{bc} = k_b \left[C_1 \frac{U_{*cv} A_b}{U_w k_b} \right]^\beta \quad (24)$$

with $C_1 = 24.0$ from Grant and Madsen (1979), and

$$\beta = 1 - \frac{U_{*c}}{U_{*cv}}. \quad (25)$$

The value for k_{bc} is then used at the next time step to determine f_c and hence the bed stress due to the wave field and the time evolving viscosity field may be estimated as

$$\vec{\tau}_c = \frac{1}{2} \rho f_c |\vec{u}|^2 \vec{u} \quad (26)$$

The radiation stress components are given by

$$s_{xx} = \rho g \int_0^\infty \int_0^{2\pi} \left[\left(n - \frac{1}{2} \right) + n \cos^2 \theta \right] F(\sigma, \theta) d\sigma d\theta \quad (27)$$

$$s_{xy} = s_{yx} = \rho g \int_0^\infty \int_0^{2\pi} (n \sin \theta \cos \theta) F(\sigma, \theta) d\sigma d\theta \quad (28)$$

$$s_{yy} = \rho g \int_0^\infty \int_0^{2\pi} \left[\left(n - \frac{1}{2} \right) + n \sin^2 \theta \right] F(\sigma, \theta) d\sigma d\theta \quad (29)$$

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

(3) Initial and Boundary Conditions

Initial conditions are that currents and surface elevation are zero

$$\zeta = u = v = 0 \quad (30)$$

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

$$\zeta = \frac{P_b - P_o}{\rho g} + \sum f_i H_i \cos [\omega_i t + (\nu + u)_i - g_i] \quad (31)$$

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 seawater, 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 con-

stituent 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 in standard notation are K_1 , O_1 , P_1 , Q_1 , M_2 , S_2 , N_2 , K_2 , S_a , S_x .

(4) The Coupling Procedure

Implementation of the coupling between wave and tide surge models followed the procedure below.

- Prior to the coupling the two models are initialized separately. Thus the wave model is warmed up for 12 h and the tide-surge model for 4 days. Initialization is performed in a manner permitting the synchronized coupling of the two models.
- The wave model is run (in 3 minute time steps) for 5 time steps 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 such as wave spectrum.
- The wave age dependent surface wind stress, radiation stress and wave current bottom stress are calculated using the wave spectrum and passed back to the tide surge model.
- 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, 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.

III. NUMERICAL STUDY OF WAVE-TIDE-SURGE COUPLING INTERACTION IN THE HUANGHE DELTA COASTAL AREA

The Huanghe Delta coastal area located in the southwest region of the Bohai Sea has great strategic importance because it is the most important oil production area of the Shengli Oilfield. The fine resolution grid area shown in Fig. 1 is the Huanghe Delta coastal area which is the focus of this study. This area is characterized by relatively big waves and strong setup due to its shallow water depth (generally less than 12 m) and long fetch, and presents a challenging problem for offshore design for prediction, particularly in severe storms with extreme wind and waves conditions. Accurate forecasts of waves and sea level are very important for the safety of offshore personnel and property and for risks assessment. This study is aimed at determining the comprehensive effects of different coupling interaction physical mechanisms on wave heights and sea level in the context of a wave-surge coupling interaction model and gives a quantitative estimate and comprehensive appraisal of coupling interaction. A secondary objective is to offer a feasible analysis for the operational adoption of a coupled wave-surge model to forecast

waves and storm surges hazards and lay the foundation of risks assessment of storm surge and wave hazards in a coastal region such as the Huanghe Delta area

(1) Case Descriptions

A storm cases occurred on 22 ~ 25 April 1998 and one on 1-2 April 1999 where synchronized in situ measured wave current and elevation data were collected from a buoy at $38^{\circ}13'N$, $118^{\circ}19'E$ (shown in Fig. 1). The observed wind fields were prepared by Ocean University of China. The wave model and tide surge model were implemented on the $2' \times 2'$ grid covering the entire Bohai Sea. The comprehensive effects of different physical mechanisms on wave heights and sea level in the Huanghe Delta coastal area (specifically, $118^{\circ}24' \sim 119^{\circ}24'E$, $37^{\circ}48' \sim 38^{\circ}14'N$) can be analyzed by comparing results from uncoupled and coupled model simulations synchronized in situ measurements of wave current and elevation data.

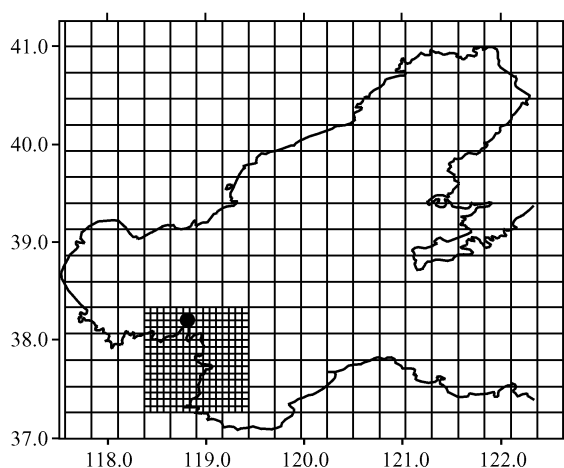


Fig. 1 The Bohai and Huanghe Delta coastal area with buoy location

The fine mesh grid in Fig. 1 is shown as $4'$ to avoid blackening the figure. The actual resolution is $2'$ in the computations for the entire Bohai Sea

(2) Impact of radiation stress on wave heights and sea level

The coupled wave tide surge model used to investigate the influence of radiation stress in wave tide surge interactions only includes a radiation stress mechanism. Fig. 2 ~ 5 compares simulated and measured wave heights and sea level for the two cases at the buoy. From Fig. 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, Fig. 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 setup values and in very good agreement with the measured data. Radiation stress can increase the wave heights by as much as 67 cm, and sea level by as much as 50 cm. This indicates the impact of radiation stress is positive.

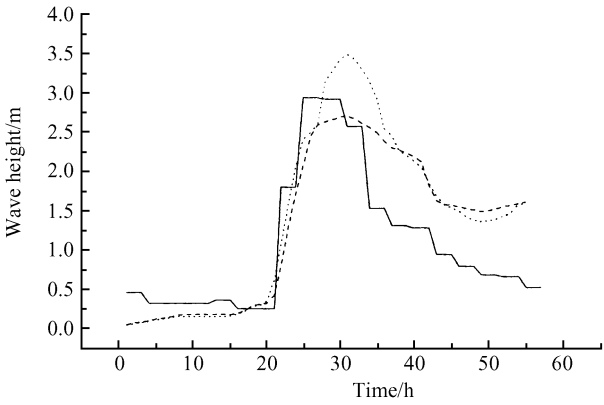


Fig. 2 Comparisons of simulated and measured wave heights for the 20UTC 22 April 1998-02UTC 25 April 1998 storms

Measured data—; uncoupled wave model---; coupled wave-tide surge model(radiation stress mechanism)....

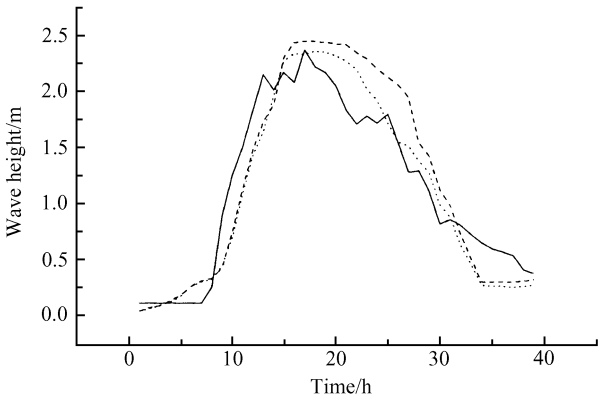


Fig. 3 As in Fig. 2 for the 00UTC 01 April 1999-14UTC 02 April 1999 storms

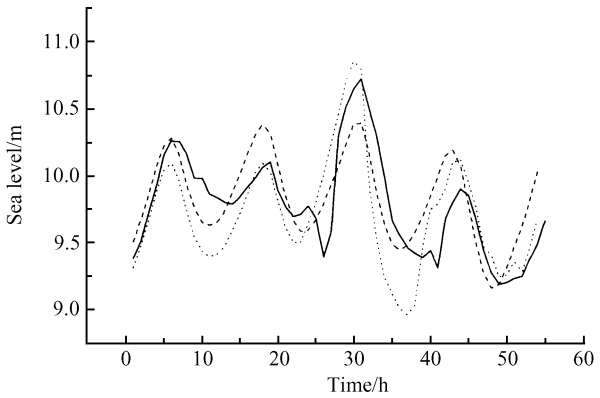


Fig. 4 Comparisons of simulated and measured sea level for the 20UTC 22 April 1998-02UTC 25 April 1998 storms

Measured data—; uncoupled tide surge model---; coupled wave-tide surge model(radiation stress mechanism)....

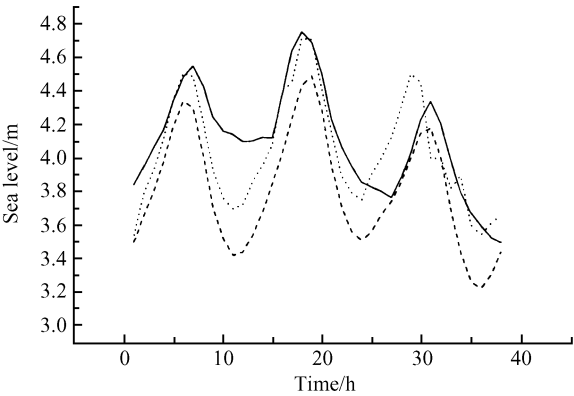


Fig. 5 As in Fig. 4 for the 00UTC 01 April 1999 - 14UTC 02 April 1999 storm

(3) Impact of wave-current interaction bottom stress on wave heights and sea level

To investigate the influence of wave-current interaction bottom stress in wave-tide-surge interactions, the coupled wave-tide-surge model used ouag includes the wave-current interaction bottom stress mechanism. Fig. 6 ~ 7 show comparisons of simulated and measured sea level for the two cases at the buoy. It follows that wave height estimates (Figures not shown) are almost the same as those in Fig. 2 ~ 3. Fig. 6 ~ 7 show that estimated sea level obtained from the coupled wave-current model are smaller than the results obtained from the uncoupled tide-surge model. These effects can be understood in terms of the wave-bottom effects. The effects of waves on the current bottom boundary layer is significant and in fact the bottom stress is increased due to the wave-current interaction. Therefore, the coupled wave-current model is an important consideration because of the physical factors that it represents. Moreover, our results imply that the coupled wave-current model should be the basis for simulating the current velocity and sea level in the nearshore region. The results also showed that the impact of wave-current interaction bottom stress is negative.

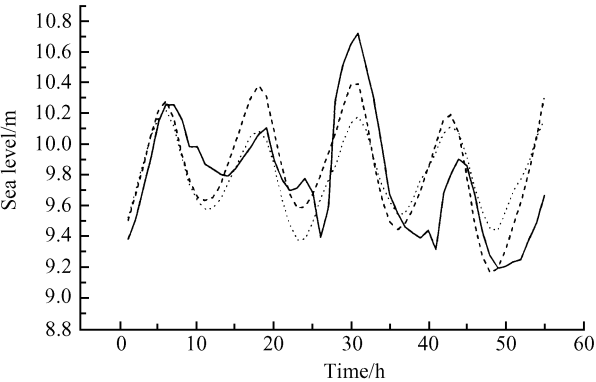


Fig. 6 Comparisons of simulated and measured sea level for the 20UTC 22 April 1998 - 02UTC 25 April 1998 storm

Measured data—; uncoupled tide surge model—; coupled wave tide surge model (wave-current interaction bottom stress mechanism)....

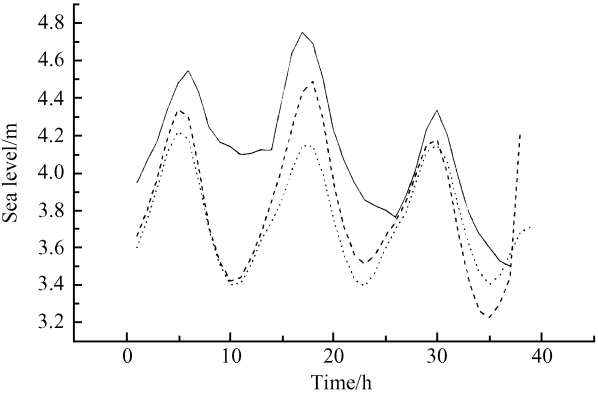


Fig. 7 As in Fig. 6 for the 00UTC 01 April 1999-14UTC 02 April 1999 storms

(4) Impact of wave age dependent surface wind stress on wave heights and sea level

To investigate the influence of wave age dependent surface wind stress in wave tide surge interactions the coupled wave tide surge model includes the wave age dependent mechanism. Fig. 8~9 show comparisons of simulated and measured sea level for the two cases at the buoy. Again almost same wave height estimates (Figures not shown) as the Fig. 2~3 were obtained. Moreover Fig. 8~9 show that the sea level simulated by coupled model is improved compared to sea level simulated by the uncoupled tide surge model. The improvement is more clearly evident at the maximum setup values and in very good agreement with the measured data. These effects can be understood because young wind waves are usually steeper than old wind waves and therefore extract more momentum from the air flow. As a result airflow over young wind sea is rougher than over old wind sea and wave age dependent surface wind stress driving tide surge motion is generally increased compared to traditional surface wind stress. Wave age dependent surface wind stress can increase the sea level by as much as 25 cm, which indicates the impact of wave state dependent surface wind stress is positive.

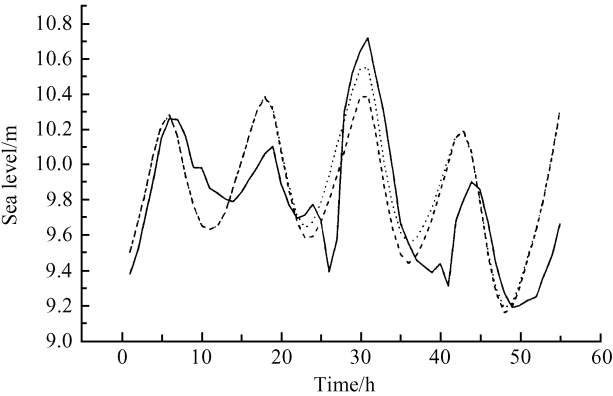


Fig. 8 Comparisons of simulated and measured sea level for the 20UTC 22 April 1998-02UTC 25 April 1998 storms

Measured data—; uncoupled tide surge model- - -; coupled wave tide surge

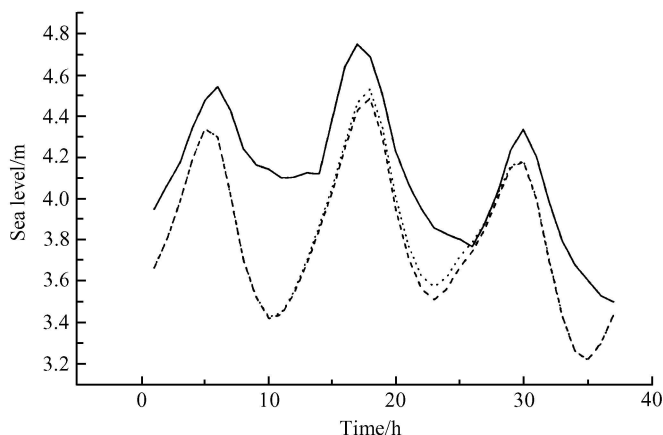


Fig.9 As in Fig.8 for the 00UTC 01 April 1999-14UTC 02 April 1999 storms

(5) Net impact of all physical mechanisms on wave heights and sea level

To investigate the net influence of all physical mechanisms in wave-tide surge interactions the coupled wave-tide surge model includes all physical mechanisms considered. Fig. 10~13 show comparisons of simulated and measured wave heights and sea level for the two cases at the buoy. Fig. 10~11 show that 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. Again the wave height estimates were almost the same as those in Fig. 2~3 with only radiation stress mechanism included which indicates that the wave height estimates from different physical mechanisms in the coupling modelling change little. This is because the impacts of different physical mechanisms on wave heights are mainly determined by wave-current interaction with radiation stress in the wave energy equation. However because the impacts of different physical mechanisms on currents are not too large the feedback of this impact on wave height estimates is very small. That is why the wave height estimates from different physical mechanisms look almost unchanged. Moreover, Fig. 12~13 show that the sea level simulated by coupled wave-tide surge model is improved compared to that simulated by the uncoupled tide-surge model. The improvement is visible particularly at the maximum setup values and in better agreement with the measured data. Overall the comparisons from the two cases show that the coupled wave-tide surge model gives better results than the uncoupled model. The net impact of three main physical mechanisms on sea level is around 20 cm. That means the positive impact from wave-age dependent surface wind stress and radiation stress dominates over the negative impact from wave-current interaction bottom stress. This is very important for design criteria and ocean engineering of offshore structures and for marine environment forecasts. Moreover the storms considered in this study were relatively moderate. Strong waves, extra-tropical storms or typhoon force storms causing big waves and strong setup in the Huanghe Delta coastal area would give more dramatic results. In these circumstances it is expected that the positive net impacts of three main physical mechanisms would be much larger.

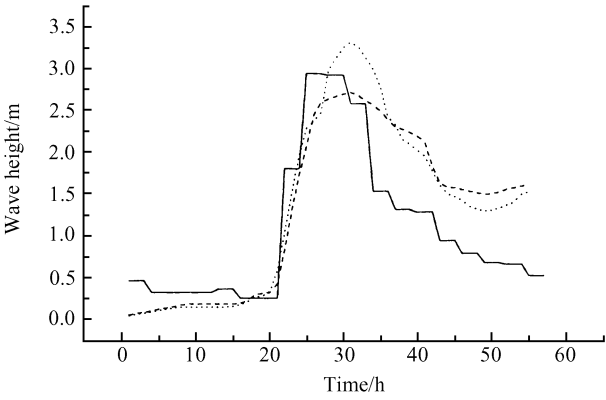


Fig 10 Comparisons of simulated and measured wave heights for the 20UTC 22 April 1998 02UTC 25 April 1998 storms

Measured data—; uncoupled wave model---; coupled wave tide surge model(comprehensive mechanism)....

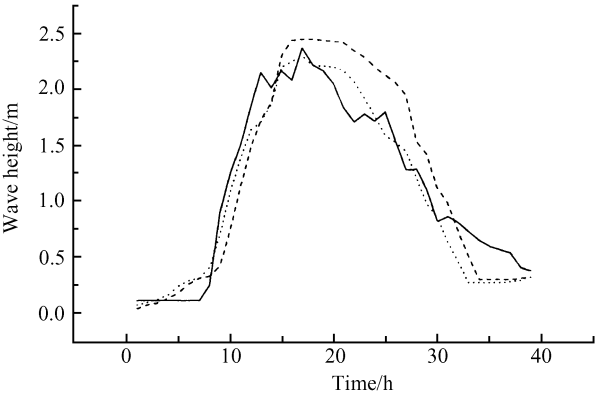


Fig. 11 As in Fig. 10 for the 00UTC 01 April 1999 14UTC 02 April 1999 storms

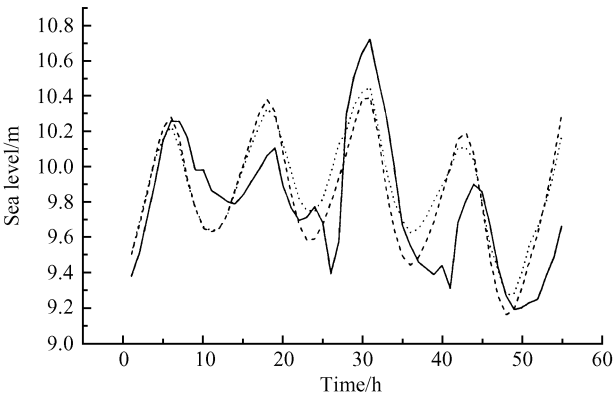


Fig 12 Comparisons of simulated and measured sea level for the 20UTC22 April 1998 02UTC 25 April 1998 storms

Measured data—; uncoupled tide surge model---; coupled wave tide surge model(comprehensive mechanism)....

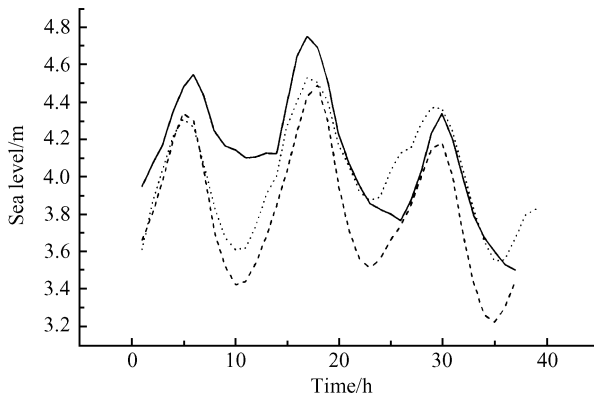


Fig. 13 As in Fig. 12 for the 00UTC 01 April 1999-14UTC 02 April 1999 storms

IV. CONCLUDING REMARKS

The focus of this study is a coastal high-resolution ($2' \times 2'$) two-way coupled wave-tide surge interaction model to study the net effects of several physical mechanisms on wave heights and sea level. Comparisons and analysis of simulated and measured wave heights and sea level considered two moderate storm cases for the Huanghe Delta coastal area and gave a quantitative estimate and appraisal for the wave-tide surge coupling interaction. We show that the effects of different physical mechanisms on wave heights are mainly determined by wave-current interaction with radiation stress in the wave energy equation. Wave-age dependent surface wind stress and radiation stress mechanisms in the coupling wave-tide surge interaction show positive impact on sea level, and wave-current interaction bottom stress mechanism shows negative impact on sea level. The comprehensive effects of the three main physical mechanisms show positive net impact on sea level and increase it by as much as 25 cm. Overall, we show that the wave heights and sea level 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 accurate risks assessment of storm surge and wave hazards and prediction applications and for offshore design, the coupled wave-tide surge model should be implemented and three main physical mechanisms should be included, particularly for high waves and strong set up associated with typhoon or extra-tropical conditions existing in the Huanghe Delta coastal area of the Bohai Sea.

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海浪和潮汐风暴潮耦合过程的数值研究

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摘要

海浪和风暴潮是重要的海洋灾害。对它们的精确预测和预报对沿岸海洋灾害的风险评估及海洋工程的设计具有极其重要的社会和经济价值。过去人们大多对波浪和风暴潮

单独进行预报。实际上, 风既产生浪又产生风暴潮, 因此它们的产生必然存在相互作用。本研究的目的是要建立一个渤海高分辨率的双向耦合的海浪和潮汐风暴潮数值模式, 研究各耦合机制的影响, 以期为黄河三角洲沿岸风暴潮海浪漫堤、漫滩风险评估提供更为准确的海浪风暴潮预测预报结果。

作者在研究中基于国际上先进的第三代海浪数值模式和潮汐风暴潮模式, 建立了渤海 $2' \times 2'$ 的海浪和潮汐风暴潮耦合数值模式。耦合模式充分考虑了三个主要耦合物理机制: 依赖海浪状态的表面风应力, 波-流相互作用底应力和辐射应力。波浪模式主要基于国际上第三代 WAM 模式, 并对其进行了浅水效应的改进, 以包括浅水深度破碎引起的能量耗散; 潮汐风暴潮模式计算中开边界考虑了 10 个主要分潮 K_1 , O_1 , P_1 , Q_1 , M_2 , S_2 , N_2 , K_2 , S_{sa} , S_{sa} 。依赖海浪状态的表面风应力取自 Done lan 等 (1993) 的结果, 波-流相互作用底应力取自 Signell 等 (1990) 对 Grant and Madsen (1979) 简化的结果, 辐射应力以海浪谱表示。耦合计算中, 两个模式通过三个耦合机制双向传递所需参量。

运用胜利油田中心一号观测的 2 个同步浪、潮、流资料对所建的耦合模式进行了检验, 并通过耦合和非耦合模式结果的对比对各耦合机制的影响效应进行分析研究。研究表明, 不同物理机制对波高的影响主要由能量方程中以辐射应力表示的波流相互作用所决定; 在波-潮耦合作用中, 依赖波令的表面风应力和辐射应力对水位是正效应, 而波流相互作用底应力对水位是负效应。三个物理机制的综合净效应是正, 可增加水位达 25 cm。比较显示, 耦合模式的结果无论对波高还是水位都比非耦合模式的结果好, 特别在峰值处。

本研究显示耦合模式的结果将改进海浪和风暴潮的模拟精度。所建立的耦合模式将对渤海海浪和风暴潮预报精度的提高, 以及为黄河三角洲近岸海浪和风暴潮灾害的风险评估, 提供更可靠的参数, 具有重要的价值。