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STUDY ON THE IMPACT OF COASTAL MARINE DYNAMIC FACTOR COUPLING INTERACTION ON MATERIAL TRANSPORT AND DIFFUSION

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Abstract. This study is focused on combining a coastal high-resolution (2′×2′) two-dimensional coupled wave-tide-surge interaction model, including three main physical mechanisms with a material transport and diffusion model to study the law of material transport and diffusion. The experimental results from material transport and diffusion show the law of material transport and diffusion driven by background current fields simulated by the coupled wave-tide-surge model is clearly different from those driven by background current fields simulated by the pure tide-surge, and more different from traditional conditions driven only by tidal currents.

Key words: Coupled model; Material transport and diffusion law; Coastal area

1. INTRODUCTION

In recent years studies on material transport and diffusion have gained rapid development due to increasing coastal marine environmental problems. Also the continuous improvement of computer performance has made the numerical modelling into the key tool of forecasts of marine environmental conditions. Some developed countries have definitely regulated their environmental evaluation system and regarded numerical forecast method and experimental modelling method together as the main approach to make environmental prediction. Researchers (Li and Chen 1989; Wu 1994,1997; Lardner and Song 1991; Sommeijer and Kok 1995; Sankaranarayanan 1998;Lei Kuen 2000;Han Guan 2000;Jiang Donghui 2001;Jiang Wensheng 2000,2001) from home and abroad have made many numerical studies on pollutant and material transport and diffusion, including numerical method and diffusion coefficient. However, past studies on background currents driving material transport and diffusion mainly focused on tidal currents , and almost no coupled wave-tide-surge background currents were taken into account. Actually, when wind exists, the dynamical processes such as waves and tide-surges happen simultaneously, and thus their generation inevitably interrelates. Under the conditions of large wind , the background currents of coupling interaction between waves and tide-surge motion in the coastal area will determine material transport and dynamic balance. As a result, only when the coupling interaction between wave and tide-surge motion is taken into consideration, can actual marine environmental dynamic fields be obtained to further study the law of material transport and diffusion.

The focus of this study is the law of material transport and diffusion under the background currents of wave-tide-surge interactions in the coastal region. 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, the coupling simulations are validated and the law of material transport and diffusion are studied .

2. COUPLED WAVE-TIDE-SURGE MODEL AND MATERIAL TRANSPORT AND DIFFUSION MODEL

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:

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

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

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

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

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:

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

the momentum equations are

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

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

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 $10\,\mathrm{m}$ reference height. In this study, a conventional approach C_d, following Hsu (1986), is assumed to 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).For the consideration of 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) :

$$z_o = 3.7 \times 10^{-5} \frac{u_{10}^2}{g} \left(\frac{c_p}{u_{10}}\right)^{-0.9} \tag{10}$$

C_d can be obtained by：

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

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

When we don’t consider wave-current interactions, bottom stress is assumed to be,

$$\vec{\tau}_b = \rho_w \gamma |\vec{u}| \vec{u} \quad , \gamma = \frac{ng}{c_z^2} \tag{12}$$

where c_z 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 wave-current interaction bottom stress is used in this study and the detailed description is refered to Signell et al. (1990).

2.3 TWO-DIMENSIONAL DEPTH-AVERAGE SEDIMENT ADVECTION-DIFFUSION EQUATION

$$\frac{\partial (HC)}{\partial t} + \frac{\partial (HuC)}{\partial x} + \frac{\partial (HvC)}{\partial y} = \frac{\partial}{\partial x}\left(K_x H \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial y}\left(K_y H \frac{\partial C}{\partial y} \right) + HS_m \tag{13}$$

where $H = \zeta + h$ is the total depth, C, u, v, K_x and K_y are all depth-average values. Diffusion coefficients are given by

$$K_x = \frac{(\alpha U^2 + \beta V^2) H \sqrt{g}}{C\sqrt{U^2 + V^2}} \tag{14}$$

$$K_y = \frac{(\alpha V^2 + \beta U^2) H \sqrt{g}}{C\sqrt{U^2 + V^2}} \tag{15}$$

where C is Chezy-Manning coefficient and according to Elder，$\alpha = 5.93$，$\beta = 0.23$。

2.4. INITIAL AND BOUNDARY CONDITIONS

Initial conditions are that currents and surface elevation are zero,

$$\zeta = u = v = C = 0 \tag{16}$$

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

Along the open boundary, given concentration C_{Bi} , then set $C_i = C_{Bi}$;otherwise set $\frac{\partial^2 C}{\partial n^2} = 0$ .For solid boundary, set $\frac{\partial C}{\partial n} = 0$.

3. NUMERICAL STUDY OF THE LAW OF MATERIAL TRANSPORT AND DIFFUSION IN THE COUPLED BACKGROUND FIELDS IN THE COASTAL AREA

The coastal area, with buoy location at • as shown in Fig. 1, is the focus of this study. This area can be characterized as continuous erosion and deposit. Therefore there is a big challenge both for the study of material transport and diffusion in this region, particularly in severe storms. The focus of this study is to probe into the law of material transport and diffusion, in the context of a coupled wave-tide-surge interaction model and a material transport and diffusion model. A secondary objective is to offer a feasible analysis for the set-up of a coupled wave-current-sediment model to study the unique phenomena of continuous erosion and deposit in this coastal region.

3.1 CASE DESCRIPTIONS

One storm case occurred 1-2 April 1999, where synchronic in situ measured wave ,current and elevation data were collected from the buoy site, 38°13′N, 118°19′E, shown in Fig. 1. The wind fields were prepared by the Ocean University of China. Resolution grids for the wave model are 2′×2′,and the tide-surge model and material transport and diffusion model are also implemented on the 2′×2′ grid for the entire Bohai Sea. The validation and results can be analyzed by comparing results from uncoupled and coupled model simulations and measurement.

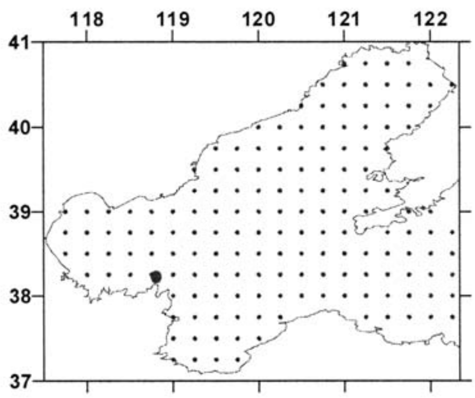

Fig. 1 The Bohai and Huanghe Delta coastal area, with buoy location •. The actual resolution is 2′ in the computations for the entire Bohai Sea.

3.2 STUDY ON LAW OF MATERIAL TRANSPORT AND DIFFUSION

In the first place validations of coupled model are made and detailed description and analysis are refered to Yin et al.(2002b). Basically, the results simulated by the coupled wave-tide-surge model agree better with the measured values than uncoupled model results, particularly for peak storm conditions, which laid sound foundation for the further study of law of material transport and diffusion. Fig. 2-5 show comparisons of currents simulated by the coupled wave-tide-surge model and uncoupled model in the coastal area. From the comparisons, it can be seen that the currents are different, particularly in the near shore, which will determine the difference of law of material transport and diffusion.

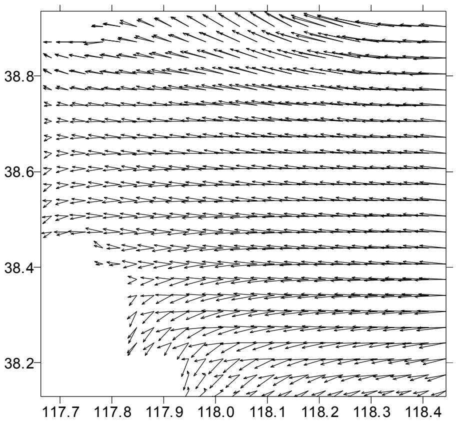

Fig. 2 Comparisons of simulated currents from coupled and uncoupled model for 01UTC 01 April 1999

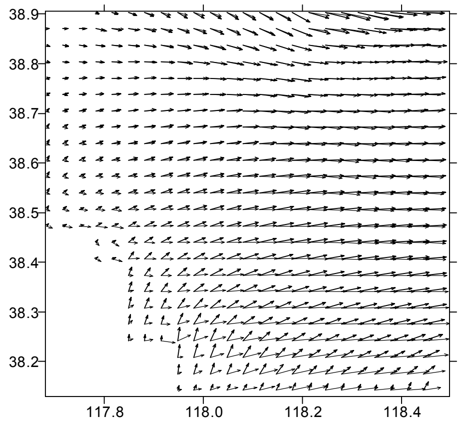

Fig. 3 For the 07UTC 01 April 1999

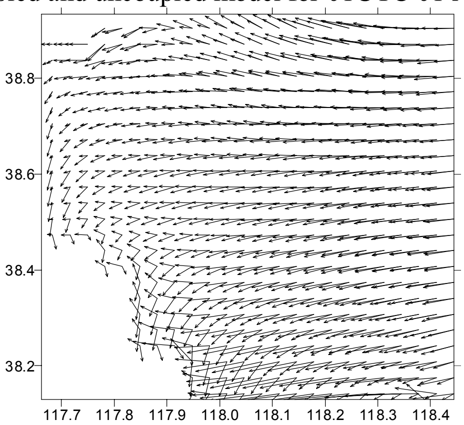

Fig. 4 For the 15UTC 01 April 1999

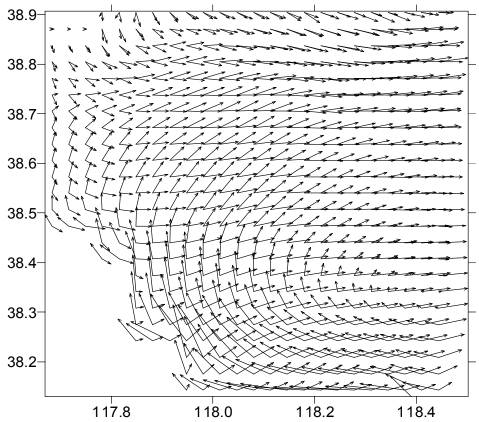

Fig. 5 for the 22UTC 01 April 1999

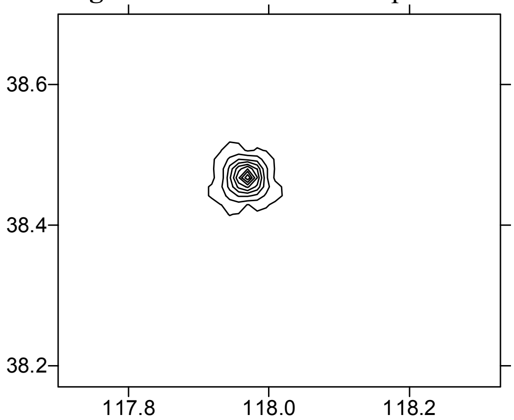

Fig. 6a 01UTC 01(coupled model)

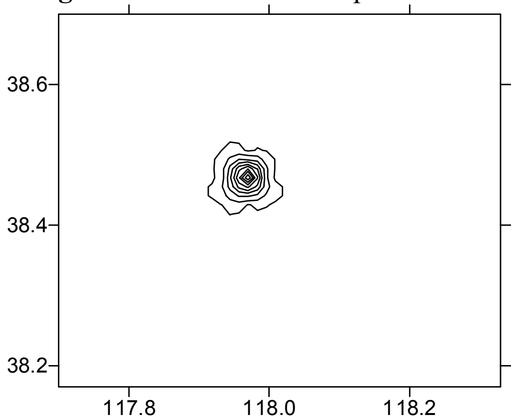

Fig. 6b 01UTC(uncoupled model)

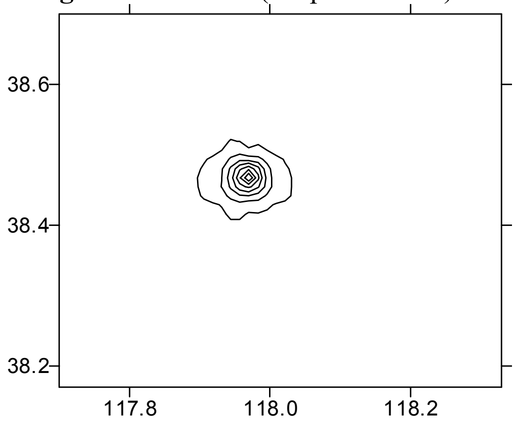

Fig. 7a 22UTC 01 (coupled model)

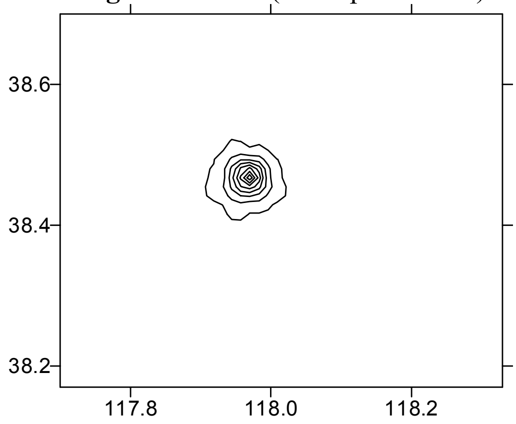

Fig. 7b 22UTC 01 (uncoupled model)

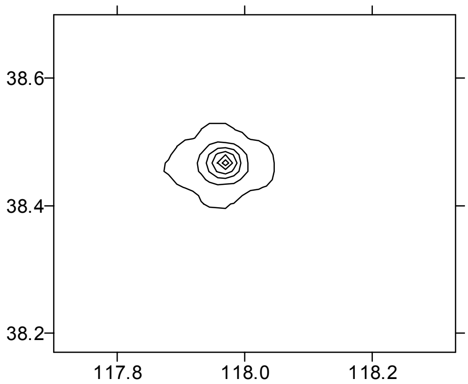

Fig. 8a 8UTC 01 (coupled model)

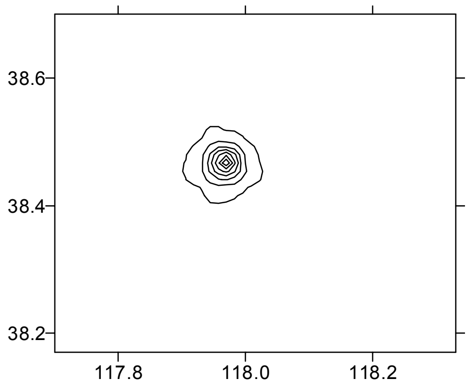

Fig. 8b 38UTC 01 (uncoupled model)

To investigate the law of material transport and diffusion driven by background currents simulated by coupled model and uncoupled model, set a point source of unit concentration at 38°28′N,117°58′ (depth is 7.4m,near the shore). From the Fig. 2-3 and Fig. 6, we can see that at the beginning the current difference is small due to small wave influences and the transport and diffusion of the point source also show similar situation; but Fig. 4-5 show that with the growth of waves, wave-current interaction becomes more obvious in shallow water and thus results in the change of current structures which cause the variation of point source transport and diffusion. Fig. 7 show the transport and diffusion of point source computed by the coupled model and uncoupled model begin to change clearly. The point source driven by background currents computed by coupled model begins to quicken its transport and diffusion in the direction of west-east, and the speed of transport and diffusion driven by the background currents computed by the uncoupled model changes little. With the elapse of time, the extent of transport and diffusion of the point source becomes larger and larger. Fig. 8 show the patterns of transport and diffusion after 38 hours and indicate the clearly different law of transport and diffusion driven by background currents computed by coupled model and uncoupled model. Furthermore, these results show when there exists wind, waves and storm surges as well as their coupling interaction will change tidal current field, thus affecting material transport and diffusion, and when there exists large wind, the stirring action of waves will become stronger and their coupling background current may play a decisive role on the material transport and diffusion of coastal study area. Because the coupled model gave better agreement with the measurement, the law of material transport and diffusion obtained by it is more reasonable and practical. In addition, this study has laid foundation for the establishment of coupled wave-current-sediment model to simulate the continuous erosion and deposit in the coastal area.

4. CONCLUDING REMARKS

The focus of this study is combining a coastal high-resolution (2′×2′) two-way coupled wave-tide-surge interaction model, including the radiation stress, wave-age dependent surface wind stress and wave-current interaction bottom stress mechanisms with a material transport and diffusion model to study the law of material transport and diffusion. Comparisons and analysis of simulated results considered one moderate storm cases for the Bohai coastal area. We show that the law of material transport and diffusion simulated by the coupled wave-tide-surge model is clearly different from that simulated by uncoupled model, which show when there is wind, the existence of waves changes the structure of tide-surge currents ,resulting in the change of material transport and diffusion., and which is more clearly different from those with only traditional tidal current considered. As a result, in the computation of coastal material transport and diffusion, the coupled background current field from waves and tide-surge motion should be taken into account.In addition, this study has laid foundation for the establishment of coupled wave-current-sediment model to simulate the continuous erosion and deposit in the coastal area of Bohai.

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