A Three Dimensional Transport Model for Oil Spills in Coastal Waters Based on Particle Approach

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***Abstract*—a three dimensional transport model based on particle approach is developed and applied for simulating oil spills at Bohai Sea, China. In such a model, the movement of the particles as the sum of deterministic advection and random diffusion are determined by exploiting the equivalency between the Ito-Fokker-Planck equation and concentration equation. Numerical experiments are further used to demonstrate the simulations of oil spills and to visualize the trajectory of oil pollution in the coastal waters driven by the force of tidal currents of Bohai Sea, China.**

Keywords-oil spills; oil particles; the Princeton ocean model

I. INTRODUCTION

Over years, shipping and offshore oil activities, two main human sources of oil on the sea surface, have caused large, spectacular, accidental oil spills. There is a long list of coastal and marine habitats and ecosystems, seabirds, mammals, fisheries and people victimized by oil pollution [1-5].

Spilled oil undergoes a number of physical and chemical changes, collectively termed weathering, when it scatters on the sea [6-8]. As predictions of probable movement, behavior and fate of oil are obviously of importance to decision making for effective oil spill combat strategies, a large number of research have been made in it [9, 10]. Oil particles could be transported under the influence of advection and dispersion of the current field, most of which are either wind driven current or tidal current or both in the water column. Focusing on the Bohai Sea, one of the most economically productive and environmentally vulnerable marine areas in China, a Langevin equation is proposed in this paper to simulate the distribution of the oil particles as the sum of deterministic advective mass and random dispersive mass. The Langevin equation could be solved by searching the equivalency between the Ito-Fokker-Planck equation and the concentration equation. A complete description of the theory can be found in Zhang [11]. The contribution of this study to the literature is an attempt to using particle tracing model for oil spill simulations in Bohai Sea, China.

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II. MATHEMATIC MODEL

2.1 POM for tidal currents

Both the advection and diffusion of particles could be influenced by currents; hence a three-dimensional ocean model is required to simulate the tidal hydrodynamics. In this study, the Princeton Ocean Model (POM) is referred. POM is a sigma coordinate model in that the vertical coordinate is scaled on the water column depth. Applying the boussinesq approximation, the governing equations of POM are as follows:

$$\frac{\partial DU}{\partial x}+\frac{\partial DV}{\partial y}+\frac{\partial \omega}{\partial \sigma}+\frac{\partial \eta}{\partial t}=0 \tag{1}$$

$$\begin{aligned}&\frac{\partial UD}{\partial t}+\frac{\partial U^2 D}{\partial x}+\frac{\partial UVD}{\partial y}+\frac{\partial U\omega}{\partial \sigma}\\&-fVD+gD\frac{\partial \eta}{\partial x}+\frac{gD^2}{\rho_0}\int_\sigma^0\left[\frac{\partial \rho'}{\partial x}-\frac{\sigma'}{D}\frac{\partial D}{\partial x}\frac{\partial \rho'}{\partial \sigma'}\right]d\sigma'\\&=\frac{\partial}{\partial \sigma}\left[\frac{K_M}{D}\frac{\partial U}{\partial \sigma}\right]+F_x,\end{aligned} \tag{2}$$

$$\begin{aligned}&\frac{\partial VD}{\partial t}+\frac{\partial V^2 D}{\partial y}+\frac{\partial UVD}{\partial x}+\frac{\partial V\omega}{\partial \sigma}\\&+fUD+gD\frac{\partial \eta}{\partial y}+\frac{gD^2}{\rho_0}\int_\sigma^0\left[\frac{\partial \rho'}{\partial y}-\frac{\sigma'}{D}\frac{\partial D}{\partial y}\frac{\partial \rho'}{\partial \sigma'}\right]d\sigma'\\&=\frac{\partial}{\partial \sigma}\left[\frac{K_M}{D}\frac{\partial V}{\partial \sigma}\right]+F_y,\end{aligned} \tag{3}$$

Where U and V are the horizontal velocity, ω is the vertical velocity at the sigma coordinate. η is the surface elevation. F_x and F_y are the horizontal diffusion term and defined according to:

$$\begin{cases} F_x = \frac{\partial}{\partial x}\left(2HA_M \frac{\partial U}{\partial x}\right) + \frac{\partial}{\partial y}\left(HA_M\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right)\right) \\ F_y = \frac{\partial}{\partial x}\left(HA_M\left(\frac{\partial U}{\partial y} + \frac{\partial V}{\partial x}\right)\right) + \frac{\partial}{\partial y}\left(2HA_M \frac{\partial V}{\partial y}\right), \end{cases} \tag{4}$$

A_M is the horizontal diffusion coefficients. Using the smagorinsky formula,

$$A_M = C\Delta x \Delta y \frac{1}{2}\left[\left(\frac{\partial U}{\partial x}\right)^2 + \frac{1}{2}\left(\frac{\partial V}{\partial x} + \frac{\partial U}{\partial y}\right)^2 + \left(\frac{\partial V}{\partial y}\right)^2\right]^{\frac{1}{2}}, \tag{5}$$

where C is the HORCON parameter. K_M is the vertical mixing coefficients which are provide by an imbedded second moment turbulence closure sub-model developed by Mellor [12]. A finite difference method is used for solving the model equations. A complete description of POM can be found in Mellor[13].

2.2 The Lagrange tracking method

In the Lagrange tracking method, a certain oil slick at the sea surface is assumed to consist of a large number of particles. The Langevin equation is introduced here to describe the movement of the particles as the sum of an advective deterministic component and an independent, random Markovian component which statistically approximates the dispersion characteristics of the environment. By exploiting the equivalency between the Ito-Fokker-Planck equation and concentration equation, the Lagevin equation can be solved and the movement of the particles can be determined.

In the coastal water, the oil spills are transported under the influence of advection and dispersion processes. The transport equation for oil spill can be written as

$$\begin{aligned} & h_1 h_2 \frac{\partial(DC)}{\partial t} + \frac{\partial}{\partial \xi_1}(h_2 U_1 DC) + \frac{\partial}{\partial \xi_2}(h_1 U_2 DC) \\ & + h_1 h_2 \frac{\partial(\omega C)}{\partial \sigma} = \frac{\partial}{\partial \xi_1}\left(\frac{h_2}{h_1} A_H D \frac{\partial C}{\partial \xi_1}\right) \\ & + \frac{\partial}{\partial \xi_2}\left(\frac{h_1}{h_2} A_H D \frac{\partial C}{\partial \xi_2}\right) + \frac{h_1 h_2}{D}\frac{\partial}{\partial \sigma}\left(K_H \frac{\partial C}{\partial \sigma}\right) \end{aligned} \tag{6}$$

C is the concentration, h1 and h2 are the metrics of the unit grid cell in the ξ_1 and ξ_2 directions, and U_1 and U_2 are the velocity components along the ξ_1 and ξ_2 directions. An equivalent formation of equation (6) is as:

$$\begin{aligned} & \frac{\partial(P)}{\partial t} + \frac{\partial}{\partial \xi_1}\left\{\frac{U_1}{h_1} + \left[\frac{1}{h_1 h_2 D}\frac{\partial}{\partial \xi_1}\left(\frac{A_H}{h_2^2} h_1 h_2 D\right)\right] P\right\} \\ & + \frac{\partial}{\partial \xi_2}\left\{\left[\frac{U_2}{h_2} + \frac{1}{h_1 h_2 D}\frac{\partial}{\partial \xi_2}\left(\frac{A_H}{h_1^2} h_1 h_2 D\right)\right] P\right\} \\ & + \frac{\partial}{\partial \sigma}\left\{\left[\frac{\omega}{D} + \frac{1}{h_1 h_2 D}\frac{\partial}{\partial \sigma}\left(\frac{K_H}{D^2} h_1 h_2 D\right)\right] P\right\} \\ & = \frac{\partial^2}{\partial \xi_1^2}\left(\frac{A_H}{h_1^2} P\right) + \frac{\partial^2}{\partial \xi_2^2}\left(\frac{A_H}{h_2^2} P\right) + \frac{\partial^2}{\partial \sigma^2}\left(\frac{K_H}{D^2} P\right) \end{aligned} \tag{7}$$

Where $P = h_1 h_2 DC$

On the other hand, the displacement of the oil particles in a random walk is governed by the non-linear langevin equation

$$\frac{d\bar{x}}{dt} = A(\bar{x}, t) + B(\bar{x}, t) Z_n \tag{8}$$

Where $\bar{x}(t)$, $A(\bar{x},t)$ and $B(\bar{x},t)$ are vectors, $\bar{x}(t)$ defines the position of an oil particle, $A(\bar{x},t)$ is the deterministic forces that advect particles, $B(\bar{x},t)$ represents the random forces that lead to particle diffusion, and Z_n is a vector of the independent random numbers with zero mean and unit variance.

If $f = f(\bar{x}, t | \bar{x}_0, t)$ is defined as the conditional probability density function for $\bar{x}(t)$ of particles whose initial position at t_0 is $\bar{x}_0$, the number density will satisfy the Ito-Fokker-Planck equation in the limit as the number of particles gets very large and the time step used to solve the conservation equation gets very small

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial x}(Af) = \nabla^2\left(\frac{1}{2} BB^T f\right) \tag{9}$$

The transport equation (7) is equivalent to the Ito-Fokker-Planck equation if $f = h_1 h_2 DC$,

$$A = \begin{bmatrix} \left[\frac{U_1}{h_1} + \frac{1}{h_1 h_2 D}\frac{\partial}{\partial \xi_1}\left(\frac{A_H}{h_2^2} h_1 h_2 D\right)\right] h_1 h_2 DC \\ \left[\frac{U_2}{h_2} + \frac{1}{h_1 h_2 D}\frac{\partial}{\partial \xi_2}\left(\frac{A_H}{h_1^2} h_1 h_2 D\right)\right] h_1 h_2 DC \\ \left[\frac{\omega}{D} + \frac{1}{h_1 h_2 D}\frac{\partial}{\partial \sigma}\left(\frac{K_H}{D^2} h_1 h_2 D\right)\right] h_1 h_2 DC \end{bmatrix} \tag{10}$$

And

$$\frac{1}{2} BB^T = \begin{bmatrix} \frac{A_H}{h_1^2} & 0 & 0 \\ 0 & \frac{A_H}{h_2^2} & 0 \\ 0 & 0 & \frac{K_H}{D^2} \end{bmatrix}$$

III. NUMERICAL EXPERIMENTS

The Bohai Sea located in the North of China with heavy sea traffic is a semi-enclosed sea contains Liaodong Bay, Bohai Bay and Laizhou Bay (Fig.1). Liaodong Bay lies in the northeast of the Bohai Sea, while Bohai Bay in the east and Laizhou Bay in the south. Due to the relatively high risk of of oil spills in Bohai Sea and vulnerability of Bohai coastal zones, the numerical experiments will be carried out in this area.

3.1 Input data

In the numerical experiments the domain of the numerical simulation is ranging from 37°N to 41°N, from 117.5°E to 122.5°E. The realistic bottom topography (Fig.1) is used to set up the model. The horizontal and vertical resolution is 2.5′x2.5′and 10 layers, respectively. The open boundary is set along the 122.5E meridian, which is about 130 km away from the Bohai strait. Along the open boundary, the constituent amplitude and lag of M_2 are added to drive the tide. According to Wang [10], on 8 June 1990, an accident of oil spill happened in Bohai Strait (38°32′48″N, 120°56′42″E)at 2:00AM (Beijing time). Until 14 June, the amount of heavy fuel released continuously from the broken tank was estimated to be 250-300 tons. The duration of the simulation is 10 days. It is assumed that 1000 particles were released during the period in the location (38°32′48″N, 120°56′42″E). The time interval between two releases was set as 1 hour and 100 oil particles were released each time.

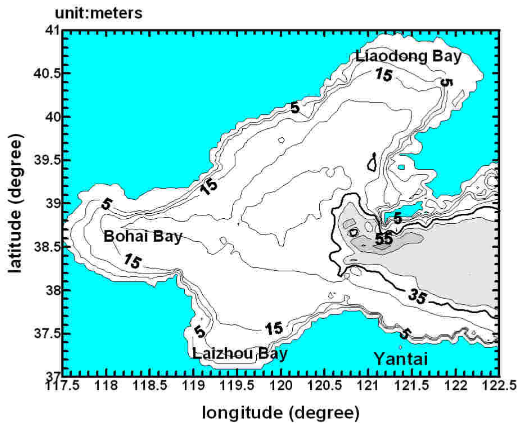

Figure 1. The topography of Bohai Sea in meter

3.2 Results and discussions

Results for currents simulation are shown in Fig.2-5 which represent tidal currents on 10 June 1990. Key findings are as follows:

(1) The tidal currents in the Bohai Bay, Liaodong Bay and Laizhou Bay are all normal semidiurnal tide ,with a period of 12~13 hours. Such a result is consistent with the work of Zhang [14];

(2) The flows in Bohai Bay, Laizhou Bay and the northern part of Liaotung Bay all belong to the category of rotating flows with the directions changing anticlockwise, while it is reciprocating flow in the middle of Bohai Sea. These results agree with historical records [15].

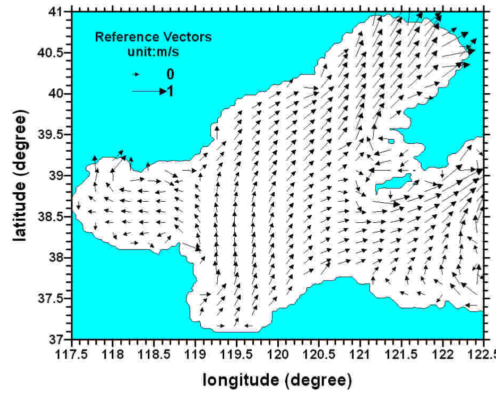

Figure 2. The computational tital currents on 11 June 1990 at 2:00

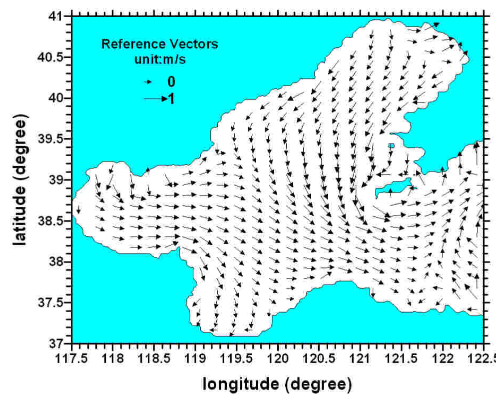

Figure 3. The computational tital currents on 11 June 1990 at 5:00

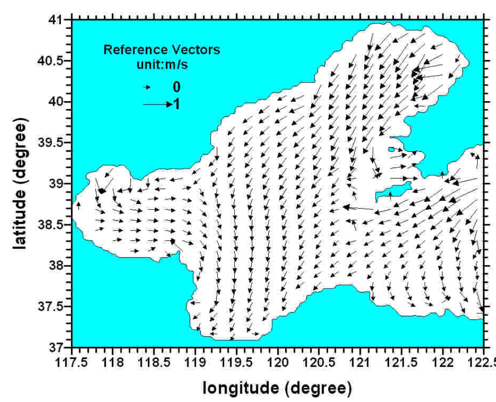

Figure 4. The computational tital currents on 11 June 1990 at 8:00

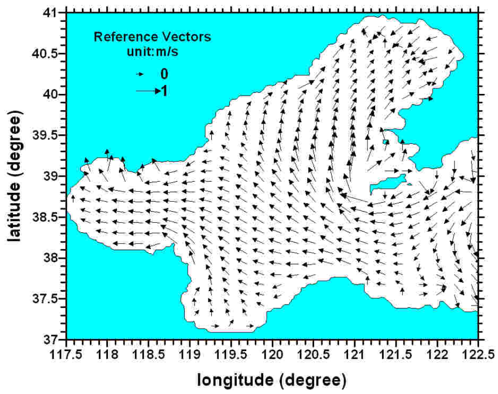

Figure 5. The computational tital currents on 11 June 1990 at 11:00

Fig.6 and 7 show the simulated distribution of the oil particles on the water surface at the first day and 8 days after the spill. The result reveals that the oil particles transport in both horizontal and vertical way, given the assumption of advective deterministic component and random dispersive component. Fig.8 shows the simulated vertical distribution of oil particles. The result demonstrate that some of the particles depart from the oil surface and get into the water column, which indicates the movement of oil particles is significantly influenced by the process of vertical diffusion.

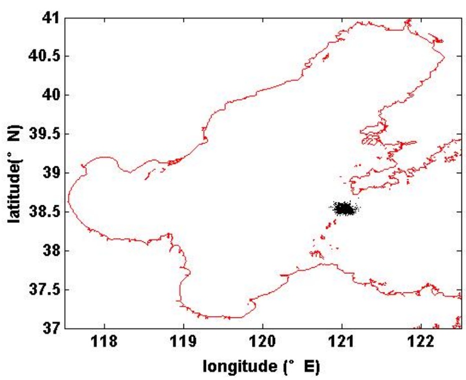

Figure 6. Distribution of oil particles on the surface water on 8 June 1990

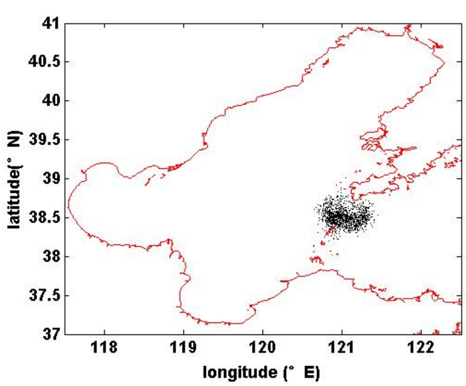

Figure 7. Distribution of oil particles on the surface water on 15 June 1990

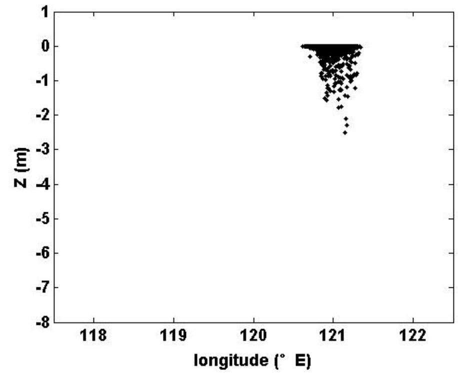

Figure 8. Vertical distribution of oil particles in the water column on 15 June 1990

IV. Conclusions

A three dimensional model for transporting oil particles caused by spills in Bohai coastal waters is presented in this paper. Based on the ' particle 'idea, a Lagrangian algorithm is used to describe the movement of the oil particles and their random walk procedure is exploited to present the diffusion of oil in water column. The numerical experiments showed in this paper demonstrate the movement of the particles as both the advection and the random diffusion in the three dimensional space which appear realistic. However, validation of the spill simulation result is currently not carried out due to the difficulties of field oil experiments. Moreover, the evaporation, emulsification and dissolution processes will be taken into account in our future work to improve this spill model.

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