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A numerical oil spill model based on a hybrid method

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ABSTRACT

The purpose of this paper is the development of a hybrid particle tracking/Eulerian–Lagrangian approach for the simulation of spilled oil in coastal areas. Oil discharge from the source is modeled by the release of particles. When the oil slick thickness or the oil concentration reaches a critical value, particles are mapped on slick thickness or node concentrations, and the calculations proceed in the Eulerian–Lagrangian mode. To acquire accurate environment information, the model is coupled with the 3-D free-surface hydrodynamics model (POM) and the third-generation wave model (SWAN). By simulating the oil processes of spreading, advection, turbulent diffusion, evaporation, emulsification, dissolution and shoreline deposition, it has the ability to predict the horizontal movement of surface oil slick, the vertical distribution of oil particles, the concentration in the water column and the mass balance of spilled oil. An accidental oil release near Dalian coastal waters is simulated to validate the developed model. Compared with the satellite images of oil slicks on the surface, the numerical results indicate that the model has a reasonable accuracy.

1. Introduction

Accidental oil spills have the potential to cause serious impact on the marine environment so that considerable amounts of work have been directed towards understanding and quantifying the spill processes in order to develop spill models to predict the trajectory and fate of spilled oil. When liquid oil is spilled on the sea surface, it spreads to form an oil slick whose movement is governed by the advection and turbulent diffusion due to current and wind action. Both Eulerian methods (EMs) and Lagrangian methods (LMs) for solution of the advection–diffusion equation have been adopted in the oil spill problems. Application of the Eulerian method for water quality studies appears to be used more frequently because of the increasing need to couple the transport models with (Eulerian) hydrodynamic models. Despite the fact that the most predictive of contaminant movement in aquatic environment adopt EM, oil spill transport models have been an exception to utilizing LM (ASCE, 1995; Reed et al., 1999). Maybe due to this long tradition, Fay's empirical formulas from layer-averaged Navier-Stokes equations and their later derivatives are still sometimes considered as the state-of-the-art in oil slick modeling literature. A previous work (Bennett and Clites, 1987) showed that the Euler methods could cause erroneous drifts in particle trajectories for non-uniform flow fields. Since Elliot et al. (1986) applied the random walk particle tracking (RWPT) for the description of oil droplet movement within the water column, RWPT has been applied widely in oil spill models. However, a shortcoming of RWPT is that the particle number must be restricted. The oil droplet diameter distribution is observed within the range 10–1000 μm, so the number of oil particles is very large. On the assumption that the diameter of all the particles is 1000 μm, 1 m^3 oil is divided into about 1.91×10^9 particles, it is impractical to save and track the history of so many particles in personal computers. Recognizing the great contribution of high-powered computational facilities for rapid evaluation of the slick movement, existing oil spill models must be updated with modern computational techniques for more accurate prediction of the fate of the spilled oil. A drawback of traditional EMs is that they do not directly resolve dispersion phenomena in a physical point resulting numerical diffusion. In order to avoid explicit treatment of the advection terms, Eulerian–Lagrangian methods (ELMs) have been developed for coastal dispersion modeling in advection-dominated systems, which decouple the transport equation into two parts and solves advection and diffusion processes separately (Oliveira and Baptista, 1998). Reported results from ELM show that wiggles and numerical damping can be greatly reduced, but these methods are still known to give erroneous results in regions with high concentration gradients (Suh, 2006). Particular emphasis is given on the simulation of oil spill sources (e.g., tankers) whose spatial extend is small compared to the computational grids. In order to use the advantages of both models, one is sometimes compelled to use a computational scheme that integrates two methods.

A hybrid method combined with particle tracking and Eulerian–Lagrangian methods to solve the oil transport problem seems more promising. The RWPT method is adopted in the vicinity of the high

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oil concentration regions, while the ELMs are employed to describe the thinner oil slick thickness on the surface and the oil concentration in the deeper water column, both of which are the advection-dominated characteristics. Continuous exchange occurs between the surface slick and suspended oil. A mathematical accurate description of the oil particles vertical movements based on the Langeven equation is given with wave actions taken into consideration. As an integrative numerical oil spill model, it also includes the other important processes, e.g., surface spreading, evaporation, dissolution, emulsification and shoreline deposition, which modify oil as it drifts.

This paper is structured as follows: the most important processes affecting oil spill transport and fate in the marine environment are given in Section 2. In Section 3, the numerical oil spill model structure is described. In section 4, an example of the model application is given.

2. Oil spill processes

The transport and fate of spilled oil in water are dominated by several physical, chemical and biological processes. In this section, some of the available algorithms describing physical and chemical weathering processes are described. The objective of this model is developed for short-term tactical forecasting. Photochemical reactions and biodegradation can change the character and reduce the amount of oil over a long period of time, but they are not taken into consideration in this paper. The transport and fate of spilled oil are governed by horizontal spreading of the surface slick due to gravity, inertia, viscous and surface tension forces; the advection due to currents and wind; dispersion and mixing due to turbulent diffusion, breaking waves, shear and buoyancy; mass transfer and change in physicochemical properties of oil due to weathering processes such as evaporation, emulsification, and dissolution; and interaction of oil with shoreline.

2.1. Spreading

Spreading is the horizontal expansion of an oil slick due to mechanical forces such as gravity, inertia, viscous, and interfacial tension and turbulent diffusion . Even though the classical spreading equations developed by Fay form the basis for the most spreading algorithms in use today, it is widely recognized that oil spreading cannot be fully explained by these equations. Lehr et al. (1984) proposed an elongated ellipse along the direction of the wind model to account for the observed non-symmetrical spreading of oil slicks:

$$Q = 1.13[(\rho_w - \rho_o)/\rho_o]^{1/3} V_0^{1/3} t^{1/4} \tag{1}$$

$$R = Q + 0.0034 W^{4/3} t^{3/4} \tag{2}$$

where Q is the length of the minor axis, R is the length of the major axis, ρ_w is the water density, ρ_o is the oil density, V_0 is the initial volume of spill, W is the wind speed and t is the time.

Let the concentric and similar ellipse on which the particle is located have major and minor axes r and q, with $q/r = Q/R$. It is assumed that on any time step, the inner ellipse of particles moves outwards with the outer elliptical boundary of the mini spill, in proportion to the ratio of the axes of the inner ellipse to those of the outer.

If the coordinates of the particle relative to the principal axes of the ellipse are (X, Y), whose x-axis is selected in the direction of the wind, we write $X = r\cos\theta$, $Y = r\sin\theta$. Then the particle is displaced outwards with the same elliptical angle θ, that is,

$$\Delta X = \Delta r\cos\theta = \Delta r(X/r) = X(\Delta R/R) \tag{3}$$

$$\Delta Y = \Delta q\sin\theta = \Delta q(Y/q) = Y(\Delta Q/Q) \tag{4}$$

2.2. Advection and horizontal turbulent diffusion

Advection is a physical process dominated by winds, currents and waves. The advection of surface oil is caused by the forces of surface current and wind drag on oil, while the advection of suspended oil is the movement of oil droplets entrained in the water column due to the water current.

The traditional advective velocity of each surface particle $\vec{U}_r$ can be computed as

$$\vec{U}_r = K\vec{V} + K_w\vec{U}_w \tag{5}$$

where $\vec{V}$ is the surface water current velocity, it can be obtained from 3-D hydrodynamic model; $\vec{U}_w$ is the wind velocity at 10 m above the water surface; K is the current factor, usually selected as 1.0; and K_w is the wind drift factor, usually adopted as 0.03. As for the oil particle in the water column, the wind drift component is ineffective.

By appreciating the governing equations of 2-D RWPT, Dimou (1989) noted that the deterministic velocity comprises three parts: the real advective velocity $\vec{U}_r$, an artificial velocity due to the rate of change of the horizontal dispersion coefficient, and another artificial velocity due to uneven bathymetrical changes. As for the oil transport on the sea surface, the former artificial component is not negligible.

$$U_x = u + \frac{\partial D_{xx}}{\partial x} \tag{6}$$

$$U_y = v + \frac{\partial D_{yy}}{\partial y} \tag{7}$$

where U_x and U_y are the deterministic velocities of each particle in the x and y directions, respectively; u and v are the component velocities of $\vec{V}$ in the x and y directions, respectively; D_{xx} and D_{yy} are the x and y directional diffusivities, respectively.

In addition to the regular movements due to the mean current, oil droplets experience a random walk procedure due to the turbulent diffusion. The stochastic velocity is correlated with the time scale and the diffusion coefficient.

Combining the above two processes, the horizontal displacement of each particle at every time step can be expressed as (Al-Rabeh et al., 1989)

$$\Delta X = U_x\Delta t + [R]_{-1}^{1}\sqrt{6D_{xx}\Delta t} \tag{8}$$

$$\Delta Y = U_y\Delta t + [R]_{-1}^{1}\sqrt{6D_{yy}\Delta t} \tag{9}$$

where $[R]_{-1}^{1}$ is the uniform distribution random number in the interval -1 to 1; ΔX and ΔY are the displacements of each particle in the x and y directions, respectively; and Δt is the interval time.

2.3. Vertical dispersion

The process by which wind-driven breaking and non-breaking waves spilt the surface oil layer into droplets and then propel them into the water column is called natural dispersion. Tkalich and Chan (2002) proposed that the rate of oil entrainment from slick to the water column can be scaled as

$$\lambda_{ow} = \frac{k_e\omega\gamma H}{16\alpha L_{ow}} \tag{10}$$

where λ_{ow} is the entrainment rate; k_e is the coefficient evaluated from experiments, usually 0.3–0.5; ω is the wave frequency; γ is the dimensionless damping coefficient; H is the significant wave height; α is coefficient concerning the mixing depth of the individual particles; and L_{ow} is the vertical length-scale parameter.

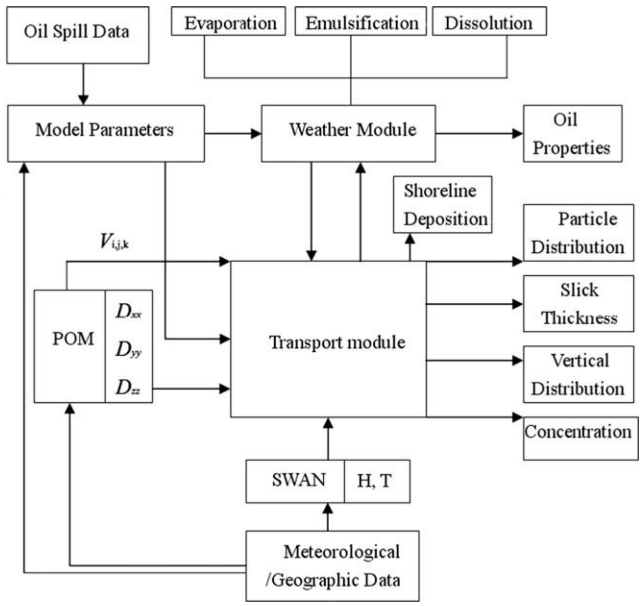

Fig. 1. Schematic of the numerical model.

Based on the laboratory data (Delvigne and Sweeney, 1988), the intrusion depth z_H that the oil droplet may penetrate is assumed as

$$z_H = (1.5 + 0.35 * [R]_{-1}^{1})H \tag{11}$$

2.4. Evaporation

Evaporation is a crucial process that changes oil mass and physicochemical properties during the first hours of an oil spill. The rate of evaporation is determined by the physicochemical properties of the oil as well as sea water temperatures, winds and other processes such as spreading and emulsification.

The most frequently used equation to predict evaporation loss is proposed by Stiver and Mackay (1984):

$$F_E = \frac{T_s}{BT_G} \ln\left[\frac{BT}{T}\frac{K_a t}{h}\exp\left(A - \frac{BT_0}{T}\right) + 1\right] \tag{12}$$

where F_E is the fraction evaporated; T_s is the sea temperature; T_0, T_G, A and B are constants derived from distillation data; K_a is the mass transfer coefficient for evaporation; and h is the slick thickness.

2.5. Dissolution

Although it is considered that oil spilled on the sea surface will go much faster into evaporation than solution, the soluble oil components (in particular the aromatic compounds) can bring disaster to biologic life form a toxicological point of view. In this oil spill model, the mass of soluble is negligible compared to the dispersed oil droplet near the surface but of the same order of magnitude in the deeper water. The rate of dissolution is written as (Cohen et al., 1980)

$$D_t = K_d A_s D \tag{13}$$

where D_t is the total dissolution rate of the oil slick; K_d is a dissolution mass transfer coefficient; A_S is the slick area; and D is the oil solubility in water.

2.6. Emulsification

Emulsification is the process of the formation of water-in-oil emulsions that change the properties and characteristics of oil to a large degree. The rate of water incorporation increases as the water content in emulsion increases, so it is usual to characterize the emulsification degree. Most models that incorporate the phenomenon use an equation proposed by Mackay et al. (1980)

$$Y_w = K_b\left[1 - \exp\left(\frac{-2\times 10^{-6}}{K_b}(1+W)^2 t\right)\right] \tag{14}$$

where Y_w is the fractional water content and K_b is the mousse viscosity constant.

2.7. Oil–shoreline interactions

An oil slick may deposit or reenter into the sea after reaching a shoreline. There are several factors affecting the result, including oil properties, shoreline types, onshore currents driven by wind stress and tidal currents. A model incorporating all these factors is almost impossible due to limited data available.

Oil may be brought to and deposited along the shoreline, and re-entrained into the water. So far, the simulation of the oil–shoreline interaction is primarily through empirical formulation because of complex processes and limited available data. A parameter oil-holding capacity, which means how much oil will retain per unit area on a given type shoreline, is defined to quantify the interaction of oil with the shoreline. Once the shoreline oil-holding capacity is reached, oil will undergo longshore transport processes. Based on Humphrey's study (1993), the maximum beach capacity for oil can be expressed as

$$Q_{max} = L_s W_s D_s \eta_{eff} \tag{15}$$

where Q_{max} is the maximum capacity of a beach for oil; L_s, W_s and D_s are, respectively, the length, width and depth of sediments on the beach; and η_{eff} is the effective porosity of the sediments on the beach (0.12–0.46).

3. Oil spill model

The model simulates the processes of surface spreading, advection, and diffusion, while other weathering processes, including evaporation, dissolution and emulsification, are simultaneously considered.

The geographic data and oil properties can be stored in the data base in advance. When an oil spill accident happens, data such as spill location, duration and oil volume as well as meteorological information are input into the model. The hydrodynamic submodel *viz.* Princeton Ocean Model (POM) is operated ahead of the calculation oil movements for supplying the latter with necessary data and parameters. Considering wave special actions on vertical dispersion, we use a third-generation wave model Simulated WAves Nearshore (SWAN) to simulate wind-generated surface gravity waves.

The overall structure of this model is illustrated in Fig. 1.

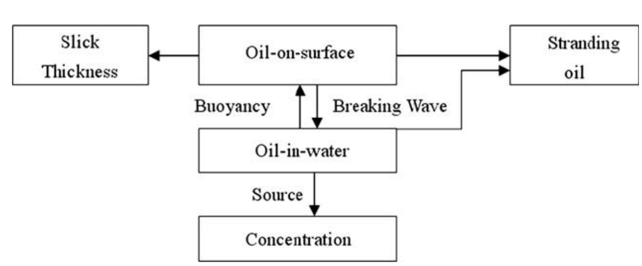

Fig. 2. Oil transfer chart.

3.1. Environmental conditions module

Accurate environment information is essential for the reliable prediction of the transport and fate of oil pollution, so forecasting these dynamic factors accurately is the base of the oil spill model. The fate of oil at sea is determined by the environmental conditions as well as by the physicochemical properties. The latter are relatively settled if the spilled oil is certain, while the former are space and time dependent of which the most dynamic three factors are sea winds, water currents and waves. Forecasting these dynamic factors accurately is the base of the numerical oil spill model.

The sea wind field can be obtained from a deterministic archive of recorded winds. If archive is not available, an alternative method is to make use of statistical descriptions of the wind field which have traditionally been provided by wind roses. The disadvantage of the wind rose is that it does not contain information on the time variability of the wind such as the duration of oil spill accidents and the probability of the transition between wind directions. However, these deficiencies can be remedied through the determination of the dominant time scales and the derivation of a direction transition matrix that describes the probability of two specified wind directions following in succession (Elliott, 2004).

The background ocean current is represented based on the Princenton Ocean Model. The POM is a free-surface, sigma-coordinate and primitive equation model, which is based on the finite difference discretization of the dynamical equations and splits computations between the so-called 'internal' and 'external' modes. POM provides not only the mean current velocity field but also the horizontal diffusion coefficients computed from the Smagorinsky formula and the vertical diffusivity obtained from the level 2.5 turbulence model. The detail of the numerical code can be found in Blumberg and Mellor (1987).

Errors may occur during directly evaluating wave parameters from empirical formulas, wave spectral numerical model is adopted to offer wave conditions with enough resolution and accuracy. SWAN (Simulating WAves Nearshore) is a well-known numerical wave model for computing random, short-crested waves in coastal areas, for its ability to take into account of the shallow water effects of triad wave–wave interactions and depth-induced wave breakings. In SWAN, the evolution of wave spectrum is described by the action balance equation rather than the energy transport equation, because the wave action density spectrum is conserved in the presence of currents, but the energy density spectrum is not. Detailed descriptions of the numerical solutions to the equation were given by Booij et al. (1999).

3.2. Transport module

A 3-D hybrid transport model is developed to predict the oil trajectory in the sea waters.

The spilled oil is labeled in five interacted phases: particle-on-surface, continuous slick-on-surface, particle-in-water, concentration-in-water and oil-at-shoreline. The relations of the five phases are figured in Fig. 2.

3.2.1. Simulation of sea surface oil

A hybrid particle tracking/Eulerian–Lagrangian method is developed for the simulation of surface oil slick: oil discharge from the source is modeled by the release of particles. The particle tracking approach is used for the simulation of oil slick movement within the thick portion, whose extent is small compared to the computational domain. When the thickness of the slick reaches a terminal value, particle locations are mapped on node thicknesses, and the calculations proceed in the Eulerian–Lagrangian mode.

Once spilled onto the sea surface, the oil trajectory is simulated by the RWPT. Combining the effect of spreading, advection and diffusion, the displacements of each particle are given by Eqs. (3), (4), (8) and (9), respectively.

Under natural conditions, when the slick approaches a terminal thickness, particle locations should be mapped onto node oil thickness. Slick thickness in grid cells is calculated by

$$h = \sum \frac{V_i}{\Delta A} \tag{16}$$

where ΔA is the area of the grid cell and V_i is the volume of the sea surface particles in the cell.

Computations then proceed with an Eulerian–Lagrangian model on the oil dynamics equations on the surface which is given as

$$\frac{\partial h}{\partial t} + \frac{\partial h(u + \tau_x/f)}{\partial x} + \frac{\partial h(v + \tau_y/f)}{\partial y} = \frac{\partial^2 D_s h}{\partial x^2} + \frac{\partial^2 D_s h}{\partial y^2} + R_h \tag{17}$$

where τ_x/f and τ_x/f are the shear stresses due to wind in the x and y directions; $D_s = gh^2(\rho_w - \rho_o)\rho_o/\rho_w f$ is the oil slick diffusion coefficient; f is the 'oil film-water surface' friction coefficient; g is the

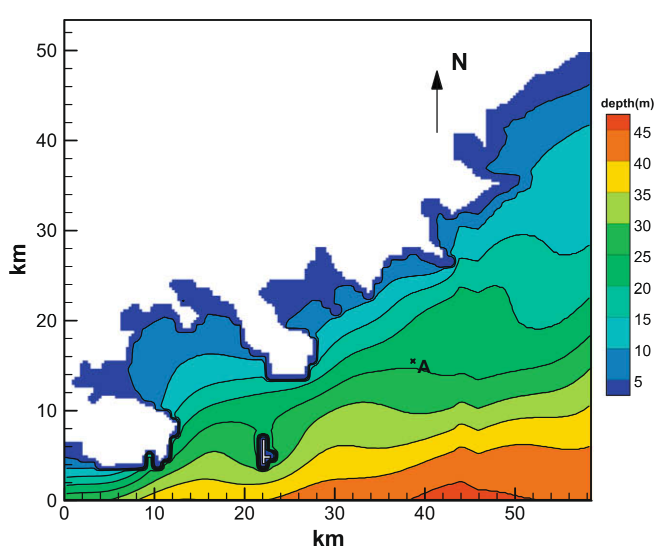

Fig. 3. Computational domain of Dalian coastal waters.

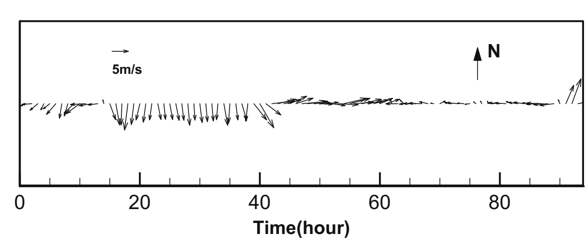

Fig. 4. Time history of wind speed (m/s) (2/4/2005–5/4/2005).

Table 1
Input parameters used in oil spill model.

Properties	Parameters
Location	38.96°N, 121.98°E
Release situation	Accidental ship leakage
Spill rate	30 m^3/h
Spill duration	6.8 h
Sea temperature	4 °C
Oil density	889 kg m^{-3}
Oil viscosity	0.16 kg m^{-1} s^{-1}
Terminal thickness	0.1 mm

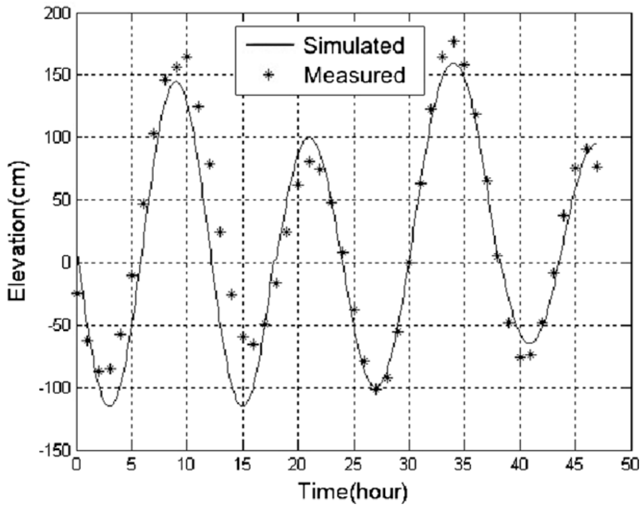

Fig. 5. Comparisons of surface elevations between the model simulation and the observation at the station (9.6, 4.8) (3–4 April 2005).

acceleration due to gravity; and R_h is the physical–chemical kinetic terms.

3.2.2. Simulation of oil in water column

Due to breaking waves and turbulence in ambient water, the slick may split into droplets and penetrate into the water column. As for the submerged oil droplets, their horizontal movements are analogous to the ones on the surface. The Langeven equation is employed to determine vertical particle movements using stochastic perturbations from Markov's chain for deceleration (Lonin, 1999):

$$\frac{dZ}{dt} = w + w_o + w' \tag{18}$$

where Z is the vertical coordinate; w is from the hydrodynamic model by interpolating the vertical flow velocity from the model finite-different grid; w_o is the rise velocity; w' is the turbulent fluctuation in the vertical direction.

The component of the oil droplet emergence velocity w_o is depended on the droplet size and defined by (Proctor et al., 1994)

$$w_o = \begin{cases} \frac{gd^2(1-\rho_o/\rho_w)}{18\upsilon} & \text{for } d \leqslant d_C \\ \left(\frac{8}{3}gd(1-\rho_o/\rho_w)\right)^{1/2} & \text{for } d > d_C \end{cases} \tag{19}$$

where d is the droplet diameter and υ is the water viscosity.

The critical diameter d_C is given by the expression

$$d_C = \frac{9.52\upsilon}{g^{1/3}((1-\rho_w)/\rho_o)^{1/3}} \tag{20}$$

The turbulent hydrodynamic model characteristics, together with the vertical shear gradient, provide additional information to compute the vertical fluctuation w':

$$\frac{dw'}{dt} = -aw'(t) + b\xi \tag{21}$$

where $\xi(t)$ is the standard Gauss' "white noise" with the unit intensity and the mean value; a and b are coefficients determined by covariance and dispersion of the stochastic process $w'(t)$.

Most of the oil droplets resurface back, but some of the smaller ones diffuse downward and become permanently incorporated into the water column.

Hydrocarbon concentrations in grid cells are calculated by

$$C = \sum \frac{M_i}{\Delta A Z_i} \tag{22}$$

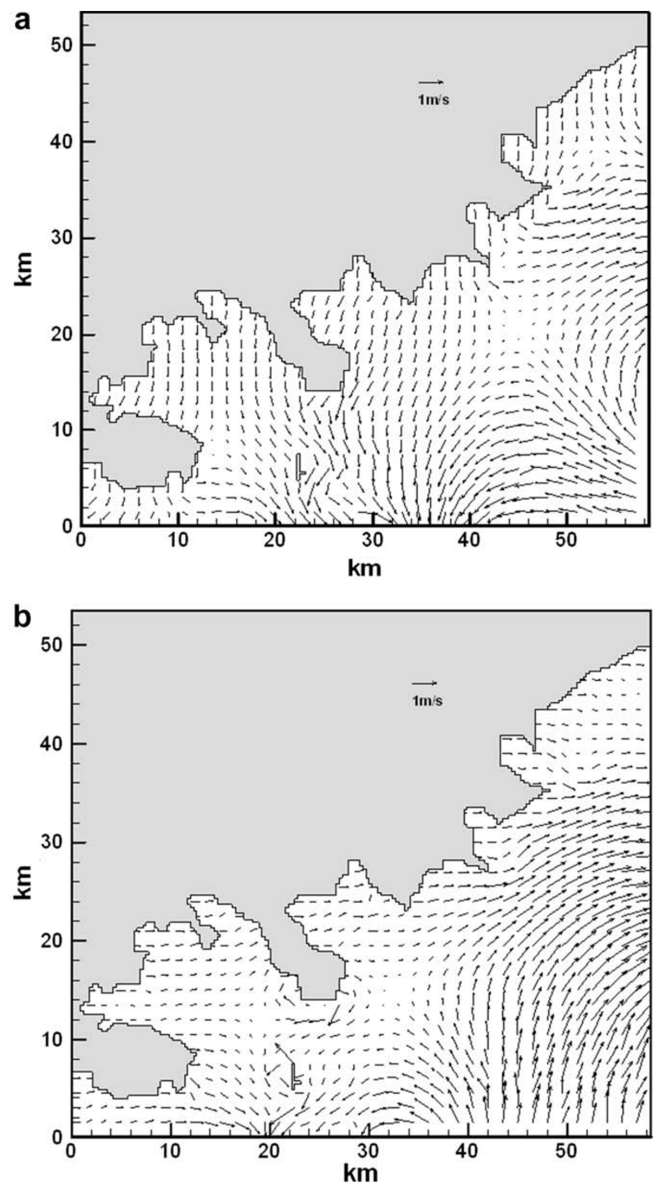

Fig. 6. Velocity field on sea surface 1 h (a) and 24 h (b) after the spill.

where M_i is the mass of submerged particles in the cell and Z_i is the mixing depth of the individual particles.

The oil concentration transport equation is given by

$$\frac{\partial C}{\partial t} + \frac{\partial(uC)}{\partial x} + \frac{\partial(\nu C)}{\partial y} + \frac{\partial(wC)}{\partial z} = \frac{\partial}{\partial x}\left(D_{xx}\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_{yy}\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_{zz}\frac{\partial C}{\partial z}\right) + S \tag{23}$$

where S represents point sources/sinks. ELMs are utilized to this equation, which split the transport equation into a pure advection part that is solved by the backwards method of characteristics and a pure diffusion part that is solved by central difference schemes.

3.3. Weathering module

The behavior of spilled oil depends not only on the prevailing conditions but also on the physicochemical properties of the oil itself. While the former are site and time dependent, the latter change while interacting with each other with oil movements. A weathering model keeps track of the changes in the composition due to loss of volatile and soluble fractions and formation of a water-in-oil emulsion.

The evaporation process, together with dissolution and the mouse formation, leads to an increase in the volume:

$$V = V_0[1 - (F_E + F_D)]/[1 - Y_W] \tag{24}$$

where V is the oil volume and F_D is the fraction dissolved.

The evaporation process, together with solution and the mouse formation, leads to an increase in the density. It may be calculated by (Buchanan and Hurford, 1988)

$$\rho_R = Y_w\rho_w + (1 - Y_w)(\rho_o + K_bF_E) \tag{25}$$

where ρ_R is the density of the remaining oil.

Evaporation and emulsification also cause an increase in viscosity, which is computed by the subsequent equation:

$$\mu = \mu_0 \exp\,[K_cF_E]\exp\left[\frac{2.5Y_w}{(1 - K_bY_w)}\right] \tag{26}$$

where μ is the mousse viscosity, μ_0 is the parent oil viscosity, K_c is the oil dependent constant that varies between 1 and 10 (Mackay et al., 1980).

4. Application

As Dalian Port is the transshipment hub of oil products for Northeast Asia, the risk of oil spills in Dalian coastal region has increased, with the frequent movement of oil tankers. Fig. 3 shows the computational zone. It covers an area of 58.8 km by 50.1 km bounded by latitudes 38°50′N to 39°15′ and longitudes 121°30′ to 122°10′. There are three open boundaries in the west, south and east and one island in the domain. The water depth ranges from 1 m to 46 m.

The Portuguese oil tanker Arteaga, carrying 119,574 tons of crude oil, ran aground about 11:30 a.m. near the new port of Dalian and spewed 180.5 tons crude oil into local waters on 3rd April 2005. Point A is the location of the oil spill accident (x = 38.7 km and y = 15.5 km). The wind data in computational region are obtained from field measurements (Fig. 4). The oil data were obtained from some measurements and oil property databases. The parameters used in the oil spill model are presented in Table 1.

4.1. Simulation of 3-D tidal currents and wind waves

The flow fields are simulated-based POM, which uses a uniform grid (300 m × 300 m) and the Cartesian coordinate system. The horizontal model grid cells are 196 (x axis) × 167 (y axis), and there are 15 vertical σ levels.

As shown in Fig. 5, the water surface elevations from the numerical model are in good agreement with the observed data. Surface drift currents generated by wind and tide are presented in Fig. 6. The water surface elevations as well as the tidal currents are generally well predicted. The wave parameters, including significant wave height and mean wave period, are shown in Fig. 7 at the beginning of the spill.

4.2. Simulation of the transport of the surface oil slick

Fig. 8 demonstrates the comparison of the movements of the oil on the sea surface obtained from the numerical model and observed from the satellite images. Only the slick thicker than 0.3 μm could be detected in the satellite images, so the outline of simulated results is chosen 0.3 μm. It can be seen that the major movement direction and polluted area of the oil slick from the model are generally in agreement with the observed results.

4.3. Simulation of the oil concentration distribution

Based on the oil concentration, equation can be solved by coupling with the flow field. Similar to the 3-D hydrodynamic model, the water body is divided into 15 layers and the exchange of oil by turbulence, wave actions and buoyancy between the neighboring two layers is computed. Fig. 9 shows the slick thickness on the surface, and Fig. 10 the concentration at different layers. Fig. 11 presents the vertical distribution of particles. Due to the buoyant effect, most particles will resurface after entrained into the water column. With the formation of breaking waves, upper layer of the water column becomes well mixed to the depth of approximately significant wave height. The turbulent mixing force may propel a few oil particles deeper into the water column, reducing their opportunity to resurface back. In this model, these particles will be mapped into the local node concentration which is described by the advection–diffusion equation then. As illustrated, the oil concentration becomes smaller and smaller with an increase in water depth. More than 90% of oil stays in the upper layers (about 0–3 m under the water surface), which means that the upper water is the most polluted area after the first few hours following a spill accident.

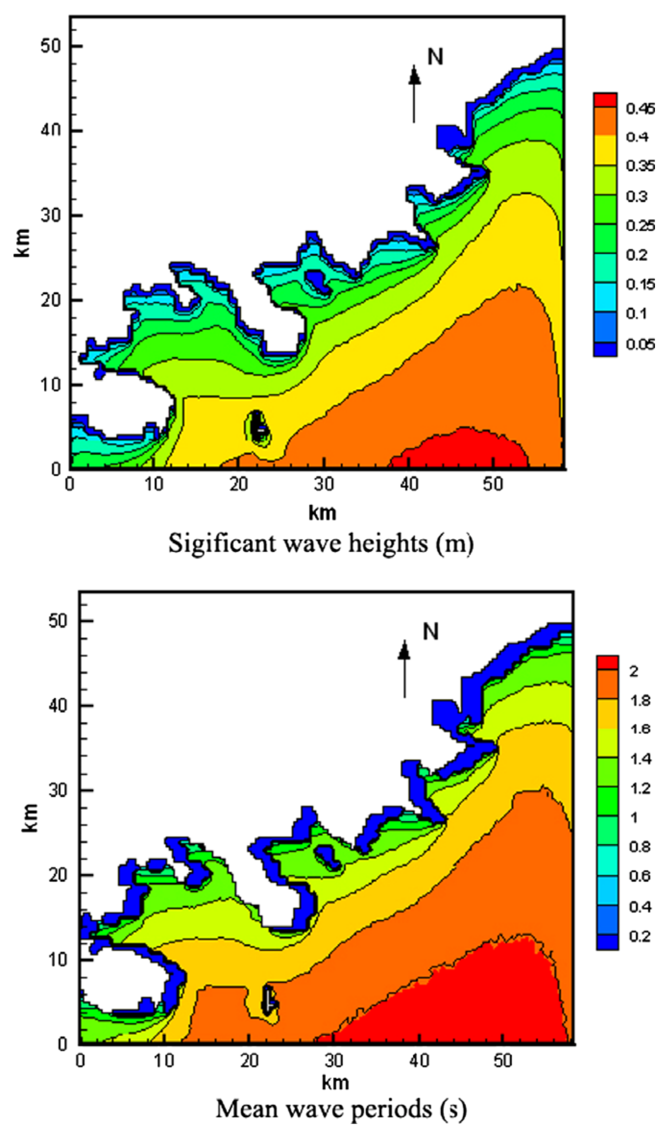

Fig. 7. Isolines of wave parameters at the beginning of the spill.

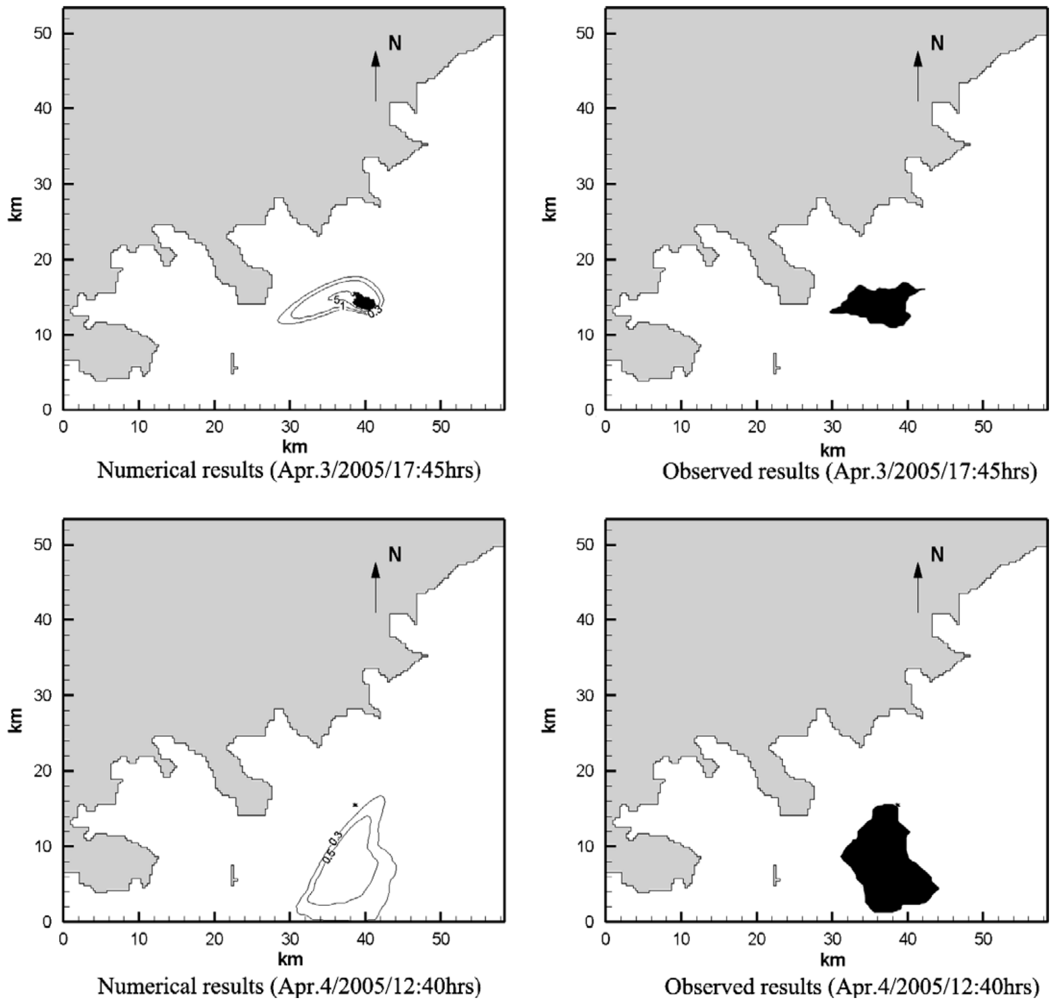

Fig. 8. Comparisons of oil slick on sea surface.

4.4. Mass distribution of the spilled oil

Fig. 12 shows the mass balance of this oil spill. It can be observed that evaporation is the primary initial process involved in the removal of oil from sea. During the first day, about 30% of the oil evaporates. Due to dissolution and dispersion, about 13.3% of the oil is dissolved and dispersed in the water column.

5. Conclusion

A 3-D hybrid model has been developed to simulate the transport and fate of the oil spilled from tanker. To reduce computing time in particle tracking models and numerical errors in concentration models, the following computational framework is devised to achieve effective and accurate trajectory results: spill source is simulated by the introduction of particles. Each particle advects and diffuses independently, and when the particles are so dispersed that the oil concentration or the surface slick thickness reaches the critical value they are mapped onto the numerical grid by identifying the concentration or the slick thickness at each node. RWPT scheme is applied in regions with high oil concentration; as for the regions where particles have been projected, Eulerian–Lagrangian scheme is exploited to compute node value. Combining with the 3-D hydrodynamic submodel in coastal waters, the model is capable of providing the reasonable prediction of the spill trajectory. Besides the transport processes, the fate processes are also taken into account. The combination of incident-specific environmental data and spilled oil characters allows the

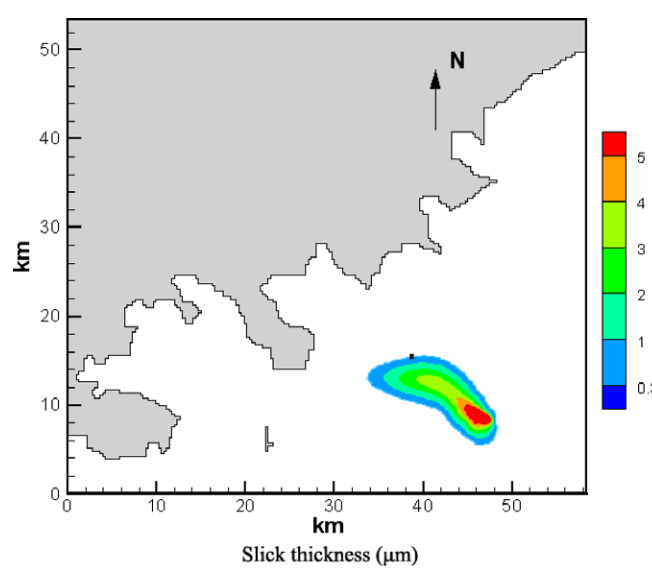

Fig. 9. Slick thickness after 10 h.

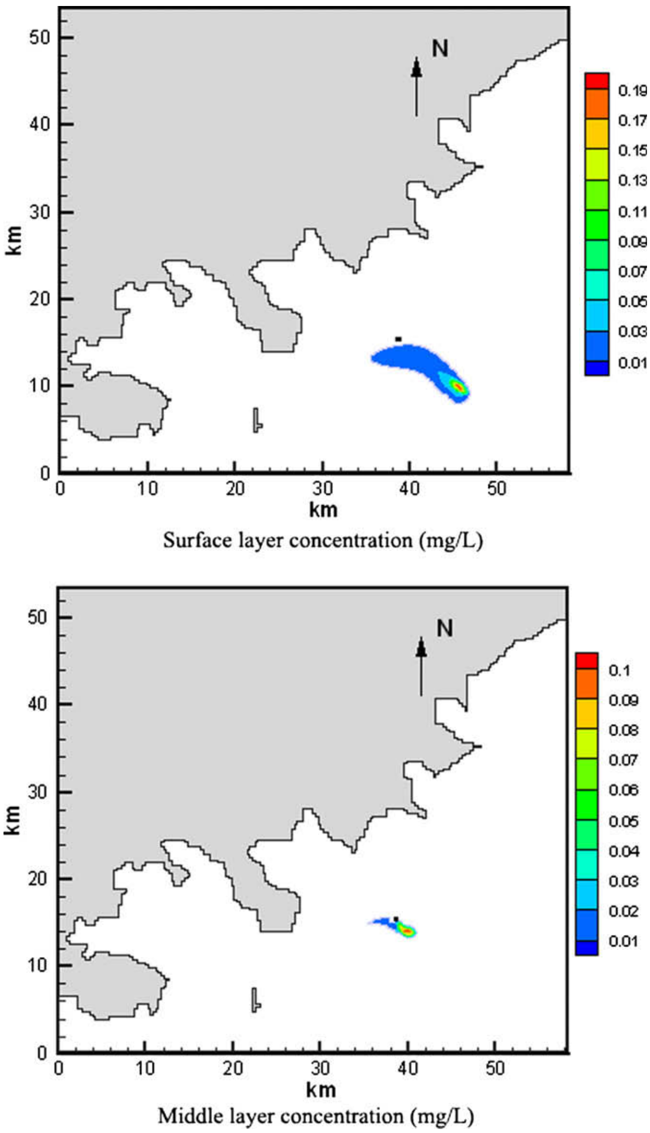

Fig. 10. Concentration distribution after 10 h.

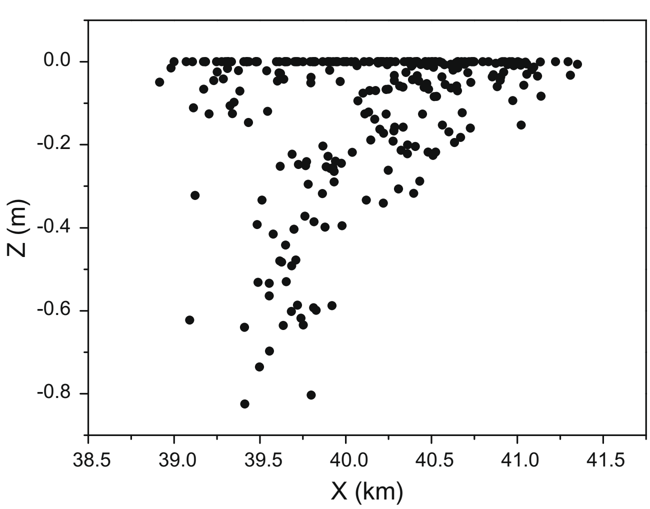

Fig. 11. Vertical oil distribution near sea surface after 10 h ($Y = 14$ km).

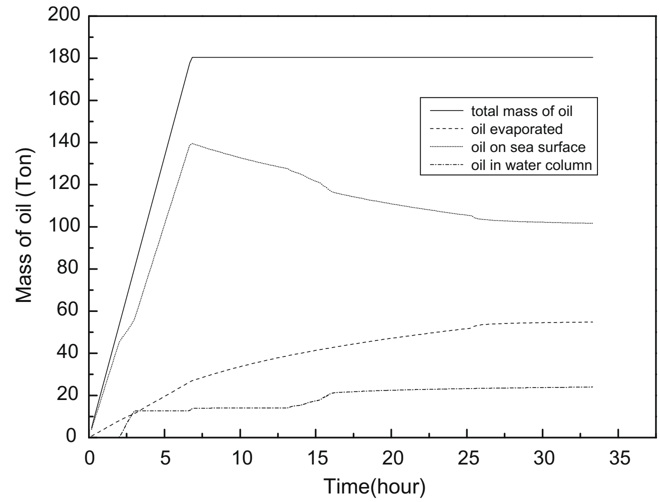

Fig. 12. Calculated oil mass balance.

precise descriptions of primary fate processes including evaporation, dissolution, emulsification and shoreline deposition. Results for the case study indicate that the model has the ability to predict reasonable the trajectory and fate of oil spills with reasonable accuracy over a relatively short period. This numerical model is suitable to be applied in environmental risk assessments and to help make decisions to contain, control and clean up accidental oil spills.

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