Three-dimensional numerical simulation for transport of oil spills in seas

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Received 18 January 2007; accepted 8 December 2007
Available online 15 December 2007

Abstract

This study extends previous two-dimensional research [Wang, S.D., Shen, Y.M., Zheng, Y.H., 2005. Two-dimensional numerical simulation for transport and fate of oil spills in seas. Ocean Engineering 32, 1556–1571] to three dimensions in order to investigate the vertical dispersion/motion of the spilled oil slick, which is a more realistic model of the motion of the spilled oil. To this end, a three-dimensional (3-D) model, based on the particle approach, is developed for simulating oil spill transport and fate in seas. The amount of oil released at sea is distributed among a large number of particles tracked individually. These particles are driven by a combination of water current, wave- and wind-induced speed and move in a 3-D space. Horizontal and vertical diffusion are taken into account using a random walk technique. The model simulates the most significant processes which affect the motion of oil particles, such as advection, surface spreading, evaporation, dissolution, emulsification, turbulent diffusion, the interaction of the oil particles with the shoreline, sedimentation and the temporal variations of oil viscosity, density and surface tension. In addition, the processes of hydrolysis, photodegradation and biodegradation are also considered in this model. The model has been applied to simulate the oil spill accident in the Bohai Sea.

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Keywords: Oil spills; Oil particles; 3-D; Transportation; Transformation; Weathering; The Princeton Ocean Model (POM)

1. Introduction

Oil spills resulting from tanker traffic, offshore drilling and accidents are likely to increase as the demand for petroleum and its products continues to rise. An oil spill accident can cause serious problems to the ocean environment and the health of mankind through its contamination. Therefore, a real-time prediction of oil spill transport and fate is very important for clean-up operations and to estimate its impact on the marine environment.

Many processes, such as advection, turbulent diffusion, surface spreading, evaporation, dissolution and emulsification (see Fig. 1), may influence the transport of oil spill. When liquid oil is spilled on the sea surface, it spreads and forms a thin film, the so-called oil slick. The movement of oil particles is governed by the advection and turbulent diffusion due to current, wave and wind actions. The slick spreads over the water surface due to a balance between gravitational, viscous and surface tension forces, while composition of the oil changes from the initial time of the spill. Depending on turbulence, the formation of an oil-in-water or a water-in-oil emulsion may take place. It is assumed that such a formation occurs within days after the initial spill.

After an oil spill, oil particles can stay in the water column for a long time and pollute the underlying water environment. In the last three decades, many investigators have studied the transport and fate processes of oil spills based on the trajectory method (Mackay et al., 1980; Huang, 1983; Shen et al., 1986; Shen and Yapa, 1988; Yapa et al., 1994; Spaulding, 1995; Lonin, 1999; Chao et al., 2001). Among these oil spill models, many of them focus on the surface movement of oil spills. There has been little published research on the vertical distribution of oil
droplets. Fig. 1 shows a sketch of the important transport and weathering processes (Rasmussen, 1985) which affect the oil spreading following a spill. Fig. 2 shows that a particle spending a higher proportion of time in the surface layers is advected further due to the effects of the wind and waves. It is important to note that the advection forces are independent of each other so that the wind and waves can act in the direction same or opposite to the tide. The amount of time that each particle remains on the surface layer is, in turn, determined by the balance between the buoyancy and the vertical diffusion rate. Therefore, droplets of higher buoyancy spend proportionately more time on the surface layers and are advected further due to the surface currents. The spreading of the oil slick is a three-dimensional (3-D) process controlled by the droplet size distribution and shear diffusion processes.

In this paper, a Lagrangian discrete particle algorithm has been applied to simulate the transport and fate of the oil droplets; and $u_L$ is the buoyancy velocity of oil droplets and is described in Section 2.6.

### 2. Mathematical model

#### 2.1. The lagrangian discrete particle algorithm

In the Lagrangian discrete particle algorithm, the spilled oil on a sea surface is divided into a large number of small particles of equal mass under the influence of regular movement of the media with the velocity components $\langle u(x,y,z,t) \rangle$, $\langle v(x,y,z,t) \rangle$ and $\langle w(x,y,z,t) \rangle$, the buoyancy velocity of oil droplets $u_L$ and the turbulent fluctuations $\langle u'(x,y,z,t) \rangle$, $\langle v'(x,y,z,t) \rangle$ and $\langle w'(x,y,z,t) \rangle$. The coordinates $X$, $Y$ and $Z$ of oil particles can be determined by the following:

$$
\frac{dX}{dt} = \langle u \rangle + u', \quad \frac{dY}{dt} = \langle v \rangle + v', \quad \frac{dZ}{dt} = \langle w \rangle + w' + u_L,
$$

where $\langle u \rangle$, $\langle v \rangle$ and $\langle w \rangle$ are drift velocities of oil particles which represent the drift due to the combined effect of the wind, current and waves on the surface layer as well as in the water column; $u'$, $v'$ and $w'$ are the turbulent fluctuations of the velocity which simulate the turbulent diffusion of the oil droplets; and $u_L$ is the buoyancy velocity of oil droplets and is described in Section 2.6.

#### 2.2. Sea current simulation

Since the water current affects both the advection and the spreading of an oil slick, it is necessary to determine the distribution of both the magnitude and the direction of the current. The Princeton Ocean Model (POM) (Mellor, 1998) is used for this purpose.

#### 2.2.1. Basic equations of the internal model

A sigma coordinate is used for the vertical coordinate and the horizontal grid uses a curvilinear orthogonal coordinate:

$$
\frac{\partial D U}{\partial x} + \frac{\partial D V}{\partial y} + \frac{\partial U \omega}{\partial \sigma} + \frac{\partial \eta}{\partial t} = 0,
$$

$$
\frac{\partial UD}{\partial t} + \frac{\partial U^2 D}{\partial x} + \frac{\partial UVD}{\partial y} + \frac{\partial U \omega}{\partial \sigma} - fVD + gD \frac{\partial \eta}{\partial x}
= \frac{\partial}{\partial \sigma} \left[ \frac{K_M \partial U}{D \partial \sigma} \right] + \frac{\partial}{\partial \sigma} \left[ 2AMD \frac{\partial U}{\partial x} \right] + A_M D \left( \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right),
$$

$$
\frac{\partial VD}{\partial t} + \frac{\partial UVD}{\partial x} + \frac{\partial V^2 D}{\partial y} + \frac{\partial V \omega}{\partial \sigma} + fUD + gD \frac{\partial \eta}{\partial y}
= \frac{\partial}{\partial \sigma} \left[ \frac{K_M \partial V}{D \partial \sigma} \right] + \frac{\partial}{\partial \sigma} \left[ 2AMD \frac{\partial V}{\partial y} \right] + A_M D \left( \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right),
$$

Following model. The developed model has been applied to simulate the spreading of the oil spill in Bohai Sea.
\[ \frac{\partial q^2 D}{\partial t} + \frac{\partial Uq^2 D}{\partial x} + \frac{\partial Vq^2 D}{\partial y} + \frac{\partial q^2}{\partial \sigma} = \frac{\partial}{\partial \sigma} \left[ K_\sigma \frac{\partial q^2}{\partial \sigma} \right] \]
\[ + 2K_M \frac{D}{D} \left[ \left( \frac{\partial U}{\partial \sigma} \right)^2 + \left( \frac{\partial V}{\partial \sigma} \right)^2 \right] \]
\[ + \frac{2g}{\rho_0} K_H \frac{\partial \rho}{\partial \sigma} - \frac{2Dq^3}{B_1} + \frac{\partial}{\partial \sigma} \left(DA_H \frac{\partial q^2}{\partial x} \right) \]
\[ + \frac{\partial}{\partial \sigma} \left(DA_H \frac{\partial q^2}{\partial y} \right). \] (5)

\[ \frac{\partial q^2 D}{\partial t} + \frac{\partial Uq^2 D}{\partial x} + \frac{\partial Vq^2 D}{\partial y} + \frac{\partial q^2}{\partial \sigma} = \frac{\partial}{\partial \sigma} \left[ K_\sigma \frac{\partial q^2}{\partial \sigma} \right] \]
\[ + 2K_M \frac{D}{D} \left[ \left( \frac{\partial U}{\partial \sigma} \right)^2 + \left( \frac{\partial V}{\partial \sigma} \right)^2 \right] \]
\[ + \frac{2g}{\rho_0} K_H \frac{\partial \rho}{\partial \sigma} - \frac{2Dq^3}{B_1} + \frac{\partial}{\partial \sigma} \left(DA_H \frac{\partial q^2}{\partial x} \right) \]
\[ + \frac{\partial}{\partial \sigma} \left(DA_H \frac{\partial q^2}{\partial y} \right), \] (6)

where \( \omega \) is the velocity component normal to sigma surfaces. The transformation to the Cartesian vertical velocity is

\[ W = \omega + U \left( \frac{\partial D}{\partial x} + \frac{\partial \eta}{\partial \sigma} \right) \]
\[ + V \left( \frac{\partial D}{\partial y} + \frac{\partial \eta}{\partial \sigma} \right) + \frac{\partial D}{\partial t} + \frac{\partial \eta}{\partial t}. \] (7)

\( A_M \) is the horizontal diffusivity

\[ A_M = C \Delta x \Delta y \left[ \left( \frac{\partial U}{\partial \sigma} \right)^2 + \frac{1}{2} \left( \frac{\partial V}{\partial \sigma} + \frac{\partial U}{\partial \sigma} \right)^2 + \left( \frac{\partial V}{\partial \sigma} \right)^2 \right]^{1/2}, \] (8)

where values of \( C \), in the range 0.10–0.20 seem to work well. \( E_t, E_v \) and \( B_l \) are close constants of the mode; \( q^2/2 \) is the turbulence kinetic energy; \( q^2l \) is the turbulence length scale; and \( \rho \) is the density of seawater. Turbulent close parameters (\( K_M, K_H, K_\sigma \)) have been given by Mellor (1998).

2.2.2. Basic equations of the external model

By integrating Eqs. (2)–(4) along the vertical direction, an equation for the surface elevation and two momentum equations can be written as

\[ \frac{\partial \eta}{\partial t} + \frac{\partial D \tilde{U}}{\partial x} + \frac{\partial D \tilde{V}}{\partial y} = 0, \] (9)

\[ \frac{\partial D \tilde{U}}{\partial t} + \frac{\partial D \tilde{U}^2}{\partial x} + \frac{\partial D \tilde{V}}{\partial y} - fD \tilde{V} \]
\[ + gD \frac{\partial \eta}{\partial x} = -\langle wu(0) \rangle + \langle wu(-1) \rangle \]
\[ + \frac{\partial}{\partial x} \left[ 2A_M D \frac{\partial \tilde{U}}{\partial x} \right] + \frac{\partial}{\partial y} \left[ A_M D \left( \frac{\partial \tilde{U}}{\partial y} + \frac{\partial \tilde{V}}{\partial x} \right) \right]. \] (10)

\[ \frac{\partial D \tilde{V}}{\partial t} + \frac{\partial D \tilde{U} \tilde{V}}{\partial x} + \frac{\partial D \tilde{V}^2}{\partial y} + fD \tilde{U} \]
\[ + gD \frac{\partial \eta}{\partial y} = -\langle wv(0) \rangle + \langle wv(-1) \rangle \]
\[ + \frac{\partial}{\partial x} \left[ 2A_M D \frac{\partial \tilde{V}}{\partial x} \right] + \frac{\partial}{\partial y} \left[ A_M D \left( \frac{\partial \tilde{U}}{\partial y} + \frac{\partial \tilde{V}}{\partial x} \right) \right]. \] (11)

The overbars denote vertically integrated velocities such as: \( \tilde{U} \equiv \int_{-1}^{0} U d\sigma \). \( A_M \) can be obtained from Eq. (8) and here the velocities are depth-averaged current velocities.

2.2.3. Boundary conditions

The vertical boundary conditions for Eq. (2) are

\[ \omega(0) = \omega(-1) = 0. \] (12)

The boundary conditions for Eqs. (3) and (4) are

\[ \frac{K_M}{D} \left( \frac{\partial U}{\partial \sigma} + \frac{\partial V}{\partial \sigma} \right) = -\left( \langle wu(0) \rangle, \langle wv(0) \rangle \right), \quad \sigma \to 0, \] (13)

where the right-hand side of Eq. (13) has the input values of the surface turbulence momentum flux, and

\[ \frac{K_M}{D} \left( \frac{\partial U}{\partial \sigma} + \frac{\partial V}{\partial \sigma} \right) = -C_s[U^2 + V^2]^{1/2}(U, V), \quad \sigma \to -1, \] (14)

where \( C_s = \max[k^2/\ln^2(z/z_0), 0.0025] \), \( k = 0.4 \) is the von Karman constant and \( z_0 \) is the roughness parameter.

The horizontal boundary conditions can be written as follows: open boundary: \( \eta = \eta(x, y, \xi); \) close boundary: \( \eta = 0. \)

2.3. Advection velocity

The drift velocity of the surface oil is the result of the combined action of wind, current and waves and can be written as follows (Zhang et al., 1991):

\[ \langle u \rangle = u_w \Delta u_w + \Delta w_c + u_{wave}, \]
\[ \langle v \rangle = u_w \Delta v_w + \Delta w_c + u_{wave}, \quad \langle w \rangle = w_c, \] (15)

where \( u_w \) and \( v_w \) are the wind velocities at 10 m above the water surface; \( u_c, v_c \) and \( w_c \) are the surface water current velocities, which can be obtained from the POM; \( u_{wave} \) is the wave-induced velocity and described in the following section; \( u_w \) is the wind drift factor, usually taken as 0.03 (Stolzenbach et al., 1977); and \( u_c \) is the factor that accounts for the contribution of the drift of the oil slick on the water surface due to the current and is selected as 1.1. \( D \) is the transformation matrix which allows introducing a deviation angle (Zhang et al., 1991):

\[ D = \begin{bmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{bmatrix}, \] (16)

where \( \theta = 40^\circ - 8\pi \sqrt{u_{w_c}^2 + v_{w_c}^2} \) when \( 0 \leq \sqrt{u_{w_c}^2 + v_{w_c}^2} \leq 25 \text{ m/s} \) and \( \theta = 0 \) when \( \sqrt{u_{w_c}^2 + v_{w_c}^2} > 25 \text{ m/s} \).

The drift velocity of the oil droplets in the water column is the result of the combined action of the current and
waves and can be calculated as
\[
\langle u \rangle = u_c + u_{\text{wave}}, \quad \langle v \rangle = v_c + u_{\text{wave}}, \quad \langle w \rangle = w_c,
\]
where \( u_c, v_c, w_c \) and \( u_{\text{wave}} \) are the same as in Eq. (15).

2.4. The net current speed due to waves—Stokes waves

Stokes showed that a mean forward velocity \( u_{\text{wave}} \) existed and was associated with free surface wave motion. This forward velocity was calculated as
\[
u_{\text{wave}} = \frac{k \omega H_x^2}{8 \sinh^2(kh)} \cos(2kz_0),
\]
where \( u_{\text{wave}} \) is the net wave current velocity at depth-\( z \) below the mean surface, \( \omega \) is the angular frequency (2\( \pi/ \)wave period), \( k \) is the wave number (2\( \pi/ \)wave length), \( z_0 \) is the vertical coordinate of oil droplets measured upwards from the still water surface, \( H_x \) is the significant wave height and \( h \) is the water depth. The formula, presented here, gives the mass transportation velocity of a single Stokes wave.

2.5. Turbulent diffusion

The turbulent diffusive transport is generally calculated using a random walk technique. Based on Fischer et al.’s (1979) study, the fluctuation velocity components \( u', v' \) and \( w' \) are calculated as
\[
u' = R_n \sqrt{4K_x/\Delta t} \cos(\phi), \quad v' = R_n \sqrt{4K_y/\Delta t} \sin(\phi), \quad w' = R_n \sqrt{2K_z/\Delta t},
\]
where \( \Delta t \) is the time step; \( R_n \) is a normally distributed random number with a mean value of 0 and a standard deviation of 1. The directional angle \( \phi \) is assumed to be a uniformly distributed random angle in the interval 0–\( \pi \); \( K_x \) is the turbulent diffusivity of the \( x \)-direction (\( x = x, y \) \( \text{(Sayre and Chang, 1969)} \). In the horizontal direction, \( K_x \) and \( K_y \) are constant. In the vertical direction, \( K_z \) can be expressed as \( \text{(Johansen, 1982)} \)
\[
K_z = 0.028 \left[ \frac{H_x^2}{T} \right] e^{-2kz},
\]
where \( T \) is the wave period, \( k \) is the wave number (2\( \pi/ \)wave length), and \( z \) is the vertical coordinate of oil droplets.

2.6. Vertical mixing

The buoyancy velocity of oil droplets is determined by their size, seawater viscosity and the density difference between seawater and oil droplets. The critical diameter of oil droplets is calculated by the following formula (Lou et al., 2001):
\[
d_c = \frac{9.52 v^{2/3}}{g^{1/3}(1 - \rho_o/\rho_w)^{1/3}}.
\]

For small oil droplets \( d < d_c \), Stokes law gives the steady buoyancy velocity
\[
u_{L_S} = g d_i^2 (1 - \rho_o/\rho_w)/18v.
\]
For large oil droplets \( d \geq d_c \), Reynolds law gives the steady buoyancy velocity
\[
u_{L_R} = \sqrt{\frac{8}{3} g d_i(1 - \rho_o/\rho_w)},
\]
where \( v \) is the seawater viscosity, \( \rho_o \) and \( \rho_w \) are the oil and seawater density, respectively. Delvigne (1994) and Delvigne and Sweeney (1989) conducted a series of laboratory investigations and found that the distribution of vertical diffusion oil droplets’ diameter was a normally distributed random number with a mean value of 250 \( \mu \)m and a standard deviation of 75 \( \mu \)m.

Other factors, such as mechanical spreading, shoreline boundary conditions, evaporation, dissolution and emulsification, which affect the spreading and motion of a spilled oil slick, can be found in Wang et al. (2005). As the spilled oil is emulsified, its density, surface tension and viscosity may change. Such factors and changes were simulated in the calculation using the method of Bommelé (1985) and Buchanan (1987); see Wang et al. (2005) for details.

3. Application of the model to the oil spill accident in the Bohai Strait

A 3D oil spill model is developed based on the above analytical formulation and used to simulate the oil spill accident which occurred in Bohai Strait. The simulated results of the oil slicks after the spillage are presented and discussed.

3.1. The incident

On 8 June 1990, two ships collided in the Bohai Strait (38°32’48”N, 120°56’42”E) at 2:00 a.m. (Beijing time) with one seriously damaged and its tank broken. Until 14 June, the amount of heavy fuel released continuously from the broken tank was estimated to be of the order of 250–350 tons. At the same time, aerial surveys were carried out by a team of Chinese experts and the distribution of the spilled oil on the sea surface issued (Figs. 8 and 9, Zhang et al., 1991). Some environmental factors observed by a monitoring vessel in the accident site indicated that the speed of wind, blowing from the south, did not exceed 4 m/s and the wave height was around 0.5 m during those days. After 15 June, the oil spill continued but the survey had to be cancelled due to very bad weather conditions. The Bohai Sea is a semi-enclosed sea located in the North of China and connected to the Yellow Sea via the Bohai Strait. The maximum depth is observed to be 70 m near the north of strait. The Bohai Sea contains three main bays: Liaodong Bay to the northeast, Bohai Bay to the west and Laizhou Bay to the south. Fig. 3 shows the computational topography.
3.2. Input data

A uniform grid (5 km × 5 km) and the Cartesian coordinate system are used. Firstly, data (from tide table 1990) at two prediction stations (Table 1) are used in the hydraulic model (POM) for validating its reliability and applicability. The duration of the simulation is 8 days, starting from 8 June 1990 at 2:00 when the accident occurred. It is assumed from the observations that during this period of time 1000 oil particles were released. The time interval between two releases has been set as 1 h and 100 oil particles were released each time. The input data are summarized in Table 2. The wind speed is 3 m/s and it is assumed that the wind blew from SSW. The mean wave height in the Bohai Sea is adopted and the value of \( H_s \) is 0.6 m.

3.3. Results and discussion

Figs. 4 (ebb phase) and 5 (flood phase) show the simulated current field on 10 June 1990 (2 days after oil spill). The results show that the tide current reaches the maximum speed at around 38°50′N, 121°E. This location

![Fig. 3. The computational topography of the Bohai Sea.](Image)

![Fig. 4. Computational tidal currents on 10 June 1990 at 6:00.](Image)

Table 1

<table>
<thead>
<tr>
<th>Stations</th>
<th>North latitude</th>
<th>East longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bayuquan</td>
<td>40°18′</td>
<td>122°5′</td>
</tr>
<tr>
<td>Dalian</td>
<td>38°55′</td>
<td>121°40′</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Simulation time (days)</th>
<th>Spill time step, Δt (min)</th>
<th>Initial oil particle number, ( N_0 )</th>
<th>Sea bed deposition coefficient, ( \beta ) (s⁻¹)</th>
<th>Emulsification coefficient, ( \gamma ) (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>15</td>
<td>Release 100 at 1 h intervals during duration</td>
<td>( 10^{-5} )</td>
<td>( 10^{-6} )</td>
</tr>
<tr>
<td>Resurfacing coefficient, ( \alpha )</td>
<td>Buoyant velocity, ( V_b ) (m/s)</td>
<td>Air temperature (°C)</td>
<td>Water viscosity, ( \nu_w ) (m²/s)</td>
<td>Total spilled volume (m³)</td>
</tr>
<tr>
<td>1.0</td>
<td>0.00254</td>
<td>10.0</td>
<td>( 1.311 \times 10^{-6} )</td>
<td>300.0</td>
</tr>
<tr>
<td>Oil type</td>
<td>Ice cover condition</td>
<td>Wind velocity 0–192 h, 3.0 m/s from SSW</td>
<td>Spill location 38°32′48″N, 120°56′42″E</td>
<td>Spill condition Continuous spill, duration = 10 h</td>
</tr>
<tr>
<td>Heavy fuel (sp. gr. = 0.965)</td>
<td>Open water</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Oil viscosity, ( \nu_0 ) (m²/s)</th>
<th>Surface tension, ( \sigma ) (N/m)</th>
<th>Evaporation parameters ( C, T_0 ) (°K)</th>
<th>Solubility parameter, ( \alpha ) (day⁻¹)</th>
<th>Solubility parameter, ( K_{S0} ) (g/m²·h⁻¹)</th>
</tr>
</thead>
<tbody>
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<td>( 8.6 \times 10^{-4} )</td>
<td>0.02</td>
<td>7.88, 465</td>
<td>0.423</td>
<td>0.0184</td>
</tr>
</tbody>
</table>
roughly coincides with the accident place, indicating that
tide current may exert a significant effect on the spreading
of the spilled oil. Figs. 5–7 show the comparison between

![Fig. 5. Computational tidal currents on 10 June 1990 at 12:00.](image)

![Fig. 6. Comparison of elevation between simulated and predicted at Bayuquan.](image)

![Fig. 7. Comparison of elevation between simulated and predicted at Dalian.](image)


the simulated elevation and the data from the tide table at
Bayuquan and Dalian stations, respectively. It can be seen
that the simulated elevation agrees well with the predicted
one. Figs. 8 and 9 show the observed distribution of the
spilled oil slick on 12 and 15 June, respectively. Figs. 10
and 11 show the simulated distribution of the oil slick
on 12th and 15th, respectively. Comparison of Figs. 10
and 11 reveals that there exists an eastward movement of
the simulated oil slick, which agrees with the main tendency
of the spreading of the observed oil slick (see Figs. 8 and 9).
Both the observed (Figs. 8 and 9) and the simulated
(Figs. 10 and 11) results demonstrate that the spilled oil
slick area at the sea surface decreases with time (from 12 to 15 June), which indicates that some oil slick has either evaporated or dissolved and moved downward. Figs. 12 and 13 show the simulated vertical distribution of oil droplets. Unfortunately, there is no observed vertical distribution of oil slick for comparison. Nevertheless, the results show that it is possible to predict the transport of the spilled oil slick on the sea surface using this model. Even with the rather poor information about wind conditions provided, it can give, at least, a first-order prediction of the oil slick displacement. With the improvement of the reliability of external information such as wind conditions, better-simulated results may be achieved.

4. Conclusion

A description of a 3-D model for simulating oil spill transport and fate in seas has been presented in this paper. The model is based on the particle approach. The amount of oil released at sea is distributed among a large number of particles tracked individually. These particles move in a 3-D space. They are driven by water current, wave- and
wind-induced speed when they are on the water surface, while they move vertically in the water column due to the buoyancy. Horizontal and vertical diffusion have been taken into account using a random walk technique. The vertical distribution of the oil droplets in the water column has been presented. Three weathering processes, namely emulsification, dissolution and evaporation, which modify the characteristics of the surface oil, have been simulated. The model has been applied to an oil spill incident that occurred in the Bohai Strait (China). The numerically simulated results appear realistic. The simulated trajectories of the spilled oil slick were similar to the observed moving tendency of the slick although rather poor wind data were provided. The simulated results could be improved if more accurate environmental data were provided. The validation of the model results for spreading and aging processes was not carried out as there were no observational data to verify. Further studies are needed to better understand the various mechanisms dominating the behavior of the spilled oil, and to work out more realistic expressions for different factors that influence the behavior of spilled oil spreading. In general, the simulated results show that the model is useful for investigating the behavior of oil spreading, advection, turbulent diffusion, evaporation and dissolution on the water surface. It is a useful tool to estimate the impact of the spilled oil on the marine environment.

Acknowledgments

This research is sponsored by the National Basic Research (973) Program of China under Grant no. 2006CB403302 and by the National Natural Science Foundation of China under Grant no. 50779006. Comments and suggestions made by anonymous reviewers have significantly improved the quality of the paper.

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