Numerical simulation study on drift and diffusion of Dalian Oil Spill

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Abstract. Marine oil spill has long-term harmful impact on both marine ecosystem and economics. Recently as the increase in China’s rapid economic growth, the demand for energy is increasing, leading to the high risk of marine oil spill pollution. So it is essential that we improve emergency response capacity in marine oil spill pollution and develop oil spill prediction and early warning in China. In this study, based on Lagrange tracking approach, we have developed an oil spill model. Combining with high-resolution meteorological and hydrodynamic model, the oil spill model was applied to predict the drift and diffusion processes of Dalian oil spill. The predicted results are well agreed with the analyzed synthetic aperture radar (SAR) image, and provided effective oil spill behaviour prediction to Shandong Maritime Safety Administration.

1. Introduction

Marine oil spill has long-term harmful impact on both marine ecosystem and economics. In recent years, as the increase in China’s rapid economic growth, the demand for energy is increasing, leading to the high risk of marine oil spill pollution. On July 16, 2010, an oil spill occurred in Dalian Xingang Port, leading to more than 1500 tons of oil spilled into the water. The spill has seriously affected local fisheries, aquaculture, tourism and shipping industry and caused huge economic losses to Dalian. Therefore, it is essential that we improve emergency response capacity in marine oil spill pollution and develop oil spill prediction and early warning in China.

Most of studies on the oil spill prediction and early warning have been focused on the development of oil spill model. It’s the fact that many different oil spill models have been developed during the past 20 years [1-11] and the state of the art in oil spill modeling has been reviewed by various authors [12, 13]. The publicly available oil spill trajectory model GNOME, which was developed by the Hazardous Materials Response Division (HAZMAT) of the National Oceanic and Atmospheric Administration Office of Response and Restoration (NOAA OR&R), can be used to calculate a ‘best guess’ of an oil spill’s trajectory and the associated uncertainty in that trajectory during marine oil spill response [14]. In addition, another sophisticated operational oil spill model systems e.g. OSIS [15], OSCAR [16], OILMAP [13], MOTHY [17], BOOM [18] and TESESO [19] have played a key role in the oil spill response for different countries. Generally, as a focused process, the transport of oil spill is affected by marine dynamic environment changes as well as the physicochemical properties of oil slicks. The marine dynamic environment information e.g. winds, water currents which can be forecasted by numerical models. Therefore, the accuracy of marine dynamic environmental forecasting is extremely
essential for the oil spill prediction. In other words, it has become apparent that the prediction accuracy of oil spill model depends on the selection of meteorological or hydrodynamic model. In this paper, based on Lagrange tracking approach, we have developed an oil spill model. Combining with high-resolution meteorological and hydrodynamic model, the oil spill model was applied to predict the drift and diffusion process of Dalian oil spill on July 16, 2010. By comparing the model results with the Radarsat-2 satellite image provided by Shandong Maritime Safety Administration, the model showed good performance in oil spill behavior prediction. Details of the model are described in Section 2, and details of model application are described in Section 4.

2. Models and methods
In this paper, the meteorological and hydrodynamic models have been coupled for high efficient information exchange. The outputs from the meteorological model can provide free surface boundary conditions to drive the hydrodynamic model. Moreover, the outputs from meteorological and hydrodynamic models can provide marine dynamic environment information to the oil spill model for prediction. Figure 1 showed the workflow of the models.

![Figure 1. The workflow of the models.](image)

2.1. Meteorological model

![Figure 2. A triple-nested simulation scheme in WRF](image)

In this paper, WRF (Weather Research and Forecasting Model) was selected as the meteorological forecast component. This model can accurately describe the physical processes in weather system changes. In addition, due to its open source and quick update performance, WRF is widely used in domestic and international institutes and universities [20].
In this work, a triple-nested simulation scheme is adopted for high-resolution weather forecast. As shown in Figure 2, the first nested area D01 with coarse grid resolution (36km) was designed to forecast the large-scale weather phenomenon over the whole East Asia and its adjacent seas. The second nested area D02 with higher grid resolution (12km) was designed to forecast the weather phenomenon over the China Seas. Finally, the third nested areas D03, D04 as well as D05 with highest grid resolution (4km) was designed to forecast the weather phenomenon over the key waters in the China Seas, among which, D03 is for the Bohai Sea and North Yellow Sea. Local high-resolution meteorological forecast has been realized for harbors, waterways and areas with high-risk of oil spill.

2.2. Hydrodynamic model
In this paper, FVCOM (Finite Volume Coastal Ocean Model) was selected as the hydrodynamic forecast component. As we know, the forecasted hydrodynamic information are commonly provided by structured grid ocean models based on the finite difference method. These systems are generally adequate in the open sea or shelf waters, where the geometry is regular or smooth[21]. However, for irregular and complex geometries, e.g. coastal areas, these operational tools are not sufficient to provide information concerning the fundamental variables controlling the oil spill event and to forecast the oil dispersion. FVCOM is solved numerically by a second-order accurate discrete flux calculation in the integral form of the governing equations over an unstructured triangular grid. The ability of the model in accurately solving scalar conservation equations in addition the topological flexibility provided by unstructured meshes and the simplicity of the coding structure have made this model ideally suited for many coastal and interdisciplinary scientific applications[22].

![Figure 3. The grid configuration for the Bohai Sea domain](image)

In this work, the grid resolution in most of computing areas was 10km. But in the irregular and prioritized areas, e.g. coastal areas, harbours and the adjacent waters around oil drilling platforms, the grid resolution was refined to 100m and further to 50m (in Figure 3). The refined grid could reflect the topography in the Bohai Sea. The atmospheric forcing at sea surface was provided from WRF, while the tide forcing at open boundaries consisted of tidal elevations and barotropic velocities for 8 major tide constituents, which are obtained from the Oregon State University Tidal Data Inversion Software (TPXO7.2) and global barotropic tide model[23].

2.3. Oil spill model
In this paper, the spreading empirical formula developed by Lehr et al.[24] has been adopted. In this formula, the area of oil slick can be represented as:

$$S = \frac{1}{4\pi MN}$$

(1)

where $S$ is the area of oil slick, $M$ and $N$ are the lengths of the minor and major ellipse axis respectively, given by:
\[ M = 1.13 \left( \rho_s - \rho_o \right)^{1/3} V_0^{1/3} t^{1/4} \]  
\[ N = M + 0.0034 U_{\text{wind}}^{4/3} t^{3/4} \]

where \( \rho_s \) is the water density, \( \rho_o \) is the oil density, \( V_0 \) is the initial volume of oil spill, \( t \) is the time after the oil slick commences spreading (min) and \( U_{\text{wind}} \) is the wind speed. Let the concentric and similar ellipse on which the particle is located have major and minor axes \( n \) and \( m \), with \( \frac{m}{M} = \frac{n}{N} \). 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, here write \( X = n \cos \theta \) and \( Y = m \cos \theta \). Then the oil particle is displaced outwards with the same elliptical angle \( \theta \), as follows [24]:

\[ \Delta X = \Delta n \cos \theta = \Delta n \left( \frac{X}{n} \right) = X \left( \frac{\Delta N}{N} \right) \]
\[ \Delta Y = \Delta m \sin \theta = \Delta m \left( \frac{Y}{m} \right) = Y \left( \frac{\Delta M}{M} \right) \]

In this paper, based on Lagrange tracking approach, we have developed an oil spill model. The drift and diffusion of oil is solved by tracking a large number of oil particles equivalent to oil slicks. The position of each particle is affected by surface winds, currents and turbulent dispersion. The numerical model solves the following equation:

\[ \frac{d\vec{x}}{dt} = \vec{V}_A(x_i, t) + \vec{V}_D(x_i, t) \]

where \( \vec{V}_A \) is the advective velocity; \( \vec{V}_D \) is the diffusive velocity; \( \vec{x}_i \) is the particle position. \( \vec{V}_A \) is calculated as the linear combination of current velocity and wind speed as follows:

\[ \vec{V}_A = \vec{V}_{\text{Current}} + C_D \vec{V}_{\text{Wind}} \]

where \( \vec{V}_{\text{Current}} \) is the surface current velocity; \( \vec{V}_{\text{Wind}} \) is the wind speed at 10m height over sea surface;

\( C_D \) is the wind drag coefficient. The turbulent diffusive velocity is calculated by Monte Carlo sampling in the range of velocities \([-V_D, V_D]\), which are proportional to the diffusion coefficients. The velocity fluctuation at each time step \( \Delta t \) is defined as:

\[ |\vec{V}_D| = \sqrt{\frac{6D}{\Delta t}} \]

where \( D \) is the diffusion coefficient. It is worth mentioning that there is no weathering process was considered in this oil spill model, so a more advanced version will be developed in the future.

3. Model Validation

3.1. Validation of meteorological model

In this work, the wind speed observation from the marine observation station near Dalian XingangPort were adopted to validate the meteorological model results. As shown in Figure 4, statistical analysis showed that the root mean square error (RMSE) of wind speed was less than 1.85 m/s (Figure 4a), and the RMSE of the wind direction was less than 31 degrees (Figure 4b). Both the model results and observation showed a similar variation trend and strength especially in the first 24th hours. It was concluded that the meteorological inputs were reliable.
3.2. Validation of hydrodynamic model

In this work, observations from three stations including the surface current velocities and direction as well as tidal elevations, were adopted to validate the model results. Table 1 showed the related information of each station.

| Number | Name | Longitude   | Latitude   |
|--------|------|-------------|------------|
| 1      | LTS  | 121° 05’   | 38° 27’   |
| 2      | CSJ  | 122° 44’   | 37° 25’   |
| 3      | LQS  | 123° 48’   | 34° 02’   |

Figure 4. Statistical analysis of the predicted wind and observations from the marine observation station near Dalian Xingang Port (Blue line: observation; Red line: model results)

Figure 5. The current velocities (left) and direction (right) from the model and observations at different station
(Blue solid line: observation; Red point: model outputs)
As shown in Figure 5, from 0:00 July 10, 2010 to 1:00 July 11, 2010 the surface current velocities (left) and direction (right) from the numerical model (red point) were in good agreement with the observation (blue solid line) at different stations. It was obvious that the model could produce reliable prediction of the current velocity and direction.

Moreover, the simulated tidal elevations on November, 2010 were selected for the further validation. As shown in Figure 6, the elevation from the model outputs (blue solid line) were also in good agreement with observation (red point).

### 3.3. Surface water currents

It is showed the simulated surface water currents forced by winds and tides near Dalian at different times in Figure 7. Obviously, the essential formation of water current is reversing currents, and the direction changes of water current occur at the time of high or low tide. The maximum current velocity is rapidly generated when the rate of tidal level rising or ebb reached maximum.

![Figure 7. The simulated surface water currents near Dalian at different times](image)

### 4. Model application

In this paper, the oil spill model was used to predict the oil drift and diffusion after Dalian oil spill occurred. And the prediction were compared with the Radasat-2 synthetic aperture radar (SAR) image.
SAR data have a significant role in remote sensing-based slick detection. The visibility concept of the oil slick in a SAR image is a function of the reduced radar backscatter from the surface[25, 26]. Recently, some new approaches for utilizing RADARSAT data for oil slick detection have been explored and effectively improve the emergency response capacity in marine oil spill[26, 27].

Figure 8 showed the drift and diffusion of spilled oil at different times. After the oil spill occurred, under the impact of surface currents and winds, the oil began to move to the southwest (Figure 8 (a)). 12 hours later, due to the current direction reversion, the oil moved to the northeast with diffusion (Figure 8 (b)). 18 hours later, the oil drifted by the northern side of Xiaoshan Island and entered into Dalian Bay (Figure 8 (c)). 28 hours later, the oil moved to the north and entered into Dayao Bay with oil-shoreline interaction (Figure 8 (d)). 48 hours later, as shown in Figure 8 (e), a large amount of oil passed through Sanshan Channel and began to invade Dalian Bay. Meanwhile, the oil reached to the coast of Dashan and Sanshan Island. 72 hours later, shown in Figure 8 (f), after long time of drift and diffusion, the oil pollution distributed throughout Dayao Bay, Xiaoyao Bay and the waters near Dalian Bay.

Figure 8. Oil spill drift and diffusion at different times

Figure 9 (a) showed that 84 hours later, the oil pollution distributed throughout Dayao Bay, Xiaoyao Bay and the waters near Dalian Bay, and the calculated pollution area reached 184km². In
Figure 9 (b), the Radasat-2 SAR image provided by Shandong Maritime Safety Administration showed the extracted oil spill distribution near Dalian waters and the calculated pollution area was 195km². The comparison displayed that the prediction results are well agreed with the satellite observation.

Figure 9. The predicted oil spill distribution after 84 hours (a) and the Radasat-2 SAR image (b)

5. Conclusions and outlook
In this paper, based on Lagrange tracking approach, we have developed an oil spill model. Combining with high-resolution meteorological and hydrodynamic model, the oil spill model was applied to predict the drift and diffusion processes of Dalian oil spill. The prediction results showed after 72 hours of drift and diffusion, the oil pollution distributed throughout Dayao Bay, Xiaoyao Bay and the waters near Dalian Bay. The prediction is well agreed with the analyzed SAR image, and provided effective oil spill behavior information to Shandong Maritime Safety Administration. However, in this oil spill model no weathering equation has been coupled, so we will develop a more advanced version in the future.

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