Bohai and Yellow Sea Oil Spill Prediction System and Its Application to Huangdao ‘11.22’ Oil Spill Incident

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Abstract. Marine oil spill has deep negative effect on both marine ecosystem and human activities. In recent years, due to China's high-speed economic development, the demand for crude oil is increasing year by year in China, and leading to the high risk of marine oil spill. Therefore, it is necessary that promoting emergency response on marine oil spill in China and improving oil spill prediction techniques. In this study, based on oil spill model and GIS platform, we have developed the Bohai and Yellow sea oil spill prediction system. Combining with high-resolution meteorological and oceanographic forecast results, the system was applied to predict the drift and diffusion process of Huangdao ‘11.22’ oil spill incident. Although the prediction can’t be validated by some SAR images due to the lack of satellite observations, it still provided effective and referable oil spill behavior information to Maritime Safety Administration.

1. Introduction

Marine oil spill has deep negative effect on both marine ecosystem and human activities. In recent years, due to China’s high-speed economic development, the demand for crude oil is increasing year by year in China, and leading to the high risk of marine oil spill. On 22th November 2013, the oil spill incident occurred in Jiaozhou Bay, which was caused by a rupture and subsequent explosion of a crude oil pipeline, seriously affected local fisheries, aquaculture, tourism and shipping industry and caused huge economic losses to Huangdao. Therefore, it is necessary that promoting emergency response on marine oil spill in China and improving oil spill prediction techniques. Recently, scientific studies on marine oil spill prediction techniques play a key role to ensure that the emergency plans can be implemented successfully. Apparently, different oil spill prediction modelling systems have been developed during the past two decade years[1-10] and the state of the art in oil spill modeling has been reviewed by various authors[11]. Some sophisticated modelling systems e.g. OILMAP[12], GNOME[13], OSCAR[14], OSIS[15], MEDSLIK II[16] and MOTHY[17] have been widely adopted in the oil spill prediction and response for the coastal countries. A new oil spill transport and fate model OILTRANS developed by Barry et al.[18], which forms the basis of a newly developed operational oil spill forecasting system for Irish waters, consists of a set of algorithms based on the most widely used equations and empirical datasets to quantify the processes of advection, diffusion, mechanical spreading, evaporation, dispersion and emulsification. The model was applied to simulate the case of the accidental release of Mazut heavy crude oil in the Celtic Sea on 14th February 2009[18]. Generally, the oil transportation is affected by marine environmental dynamic factors as well as the physicochemical properties of oil. Marine environmental dynamic factors e.g. surface winds, water currents can be forecasted by high-resolution meteorological or oceanographic forecast.
model. Therefore, the accuracy of marine environmental forecasting is extremely important to oil transportation. In other words, it has been apparent that the prediction accuracy of oil transportation depends heavily on the selection of meteorological or oceanographic forecast model.

In this study, based on oil spill model and GIS platform, we have developed the Bohai and Yellow sea oil spill prediction system. Combining with high-resolution meteorological and oceanographic forecast results, the modelling system was applied to predict the drift and diffusion process of Huangdao ‘11.22’ oil spill incident. The system showed good performance in oil spill behavior prediction. Details of the system are described in Section 2, and details of model application are described in Section 3.

2. Modelling system and methods
The Bohai and Yellow sea oil spill prediction system consists of a meteorological forecast model, an oceanographic forecast model, an oil spill model and GIS platform. The meteorological and oceanographic forecast models have been coupled for data information exchange. The outputs from the meteorological model can provide free surface boundary conditions to drive the oceanographic model. Meanwhile, the results from meteorological and oceanographic models can provide marine environmental information to the oil spill model for prediction. Figure 1 showed the structure and work flow of the modelling system.

![Figure 1. The structure and work flow of the Bohai and Yellow sea oil spill prediction system](image)

2.1. Meteorological forecast model WRF
In this study, we used WRF (Weather Research and Forecasting Model) as the meteorological forecast model of the modelling system. This model is a fully compressible, non-hydrostatic model. Its vertical coordinate is a terrain-following hydrostatic pressure coordinate. The grid staggering is the Arakawa C-grid. This model uses the Runge-Kutta second and third order time integration schemes and second to sixth order advection schemes in both horizontal and vertical directions. It uses a time-split small step for acoustic and gravity-wave modes. The dynamics conserves scalar variables[19]. Due to the shared source codes and quick version update, WRF is widely used in meteorological forecasting and numerical studies.

In the meteorological forecast model, we have developed a triple-nested simulation scheme for high-resolution forecast. In this scheme, we designed the first layer nested area with coarse grid (33km) to simulate the large-scale weather phenomenon over the East Asia domain including the Bohai and Yellow Sea. Then we designed the second layer nested area with higher grid resolution (11km) to
simulate the general weather phenomenon over the Bohai and Yellow Sea. Finally, we designed some third layer nested areas with highest grid resolution (3km) to simulate the weather phenomenon over the focused areas in the Bohai and Yellow Sea. Figure 2 showed the wind forecast in WRF.

![Figure 2. The wind forecast in WRF](image)

2.2. oceanographic forecast model FVCOM
In this study, we used FVCOM (Finite Volume Coastal Ocean Model) as the oceanographic forecast model of the modelling system. This model consists of momentum, continuity, temperature, salinity and density equations and is closed physically and mathematically using turbulence closure sub models. The horizontal grid is comprised of unstructured triangular cells and the irregular bottom is presented using generalized terrain-following coordinates[20]. This model 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 FVCOM 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[21].

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

In the oceanographic forecast model, the grid resolution in most of computing areas is 10km. But for the irregular and complex geometries and priority areas, e.g. coastal areas, harbors and the adjacent waters around oil drilling platforms, the grid was refined to 100m, further to 50m (in Figure 3). Apparently, the refined grid could well describe the real terrain of the Bohai and Yellow Sea. When
the model running, the surface atmospheric forcing was provided by WRF, and the tidal forcing at open boundaries were provided by the Oregon State University Tidal Data Inversion Software (TPXO7.2) and global tide forecast model[22].

2.3. Oil spill model
In the oil spill model, we adopted the empirical formula developed by Lehr et al.[23] to simulate oil spreading. In this formula, the oil slick area is represented as:

\[ S = \frac{1}{4\pi MN} \]  

where \( S \) is oil slick area, \( M \) and \( N \) are lengths of the minor and major ellipse axis respectively, given by:

\[ M = 1.13 \left[ \frac{\rho_o - \rho_v}{\rho_v} \right]^{1/3} V_0^{1/3} t^{1/4} \]  
\[ N = M + 0.0034 U_{wind}^{3/4} t^{3/4} \]

where \( \rho_v \) is water density, \( \rho_o \) is oil density, \( V_0 \) is the initial volume of spilled oil, \( t \) is the time after oil slick commences spreading (min), \( U_{wind} \) is 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 \( X = \frac{n}{M} \cos \theta \) and \( Y = \frac{m}{N} \cos \theta \). Then the oil particle is displaced outwards with the same elliptical angle \( \theta \), as follows[23]:

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

In the oil spill model, the drift and diffusion of spilled oil is solved by tracking a mass of oil particles equivalent to oil slicks. The position of each particle is affected by surface winds, water currents and turbulent dispersion. The forecast model solves the following equation:

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

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

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

where \( \bar{V}_{Current} \) is surface current velocity, \( \bar{V}_{Wind} \) is the wind speed at 10m height, \( C_D \) is the wind drag coefficient. The turbulent diffusive velocity is calculated by Monte Carlo sampling in the range of velocities \([\pm V_D, V_D]\), which are proportional to the diffusion coefficients. The velocity fluctuation at each time step \( \Delta t \) is defined as:

\[ |V_D| = \sqrt{\frac{6D}{\Delta t}} \]

where \( D \) is the diffusion coefficient.

Since no weathering process has been considered in the oil spill model, the initial version of the Bohai and Yellow sea oil spill prediction system can’t provide oil weathering prediction. We will develop an advanced version coupled with oil weathering formulas in the future.
2.4. GIS platform
Since GIS can integrate a large number of marine, coastal, and oil production or transportation data, in the Bohai and Yellow sea oil spill prediction system, we developed component GIS embedded with DLL based on ArcEngine controllers under Visual Studio.net program language circumstance. Based on the GIS platform, some oil spill information such as wind speed, wind direction, water current velocity, water current direction, oil production or transportation can be displayed quickly. Once oil spill has occurred, the vector maps will be analysed to see what the major concerns are. Figure 4 showed the information about water currents on GIS platform.

![Figure 4. The information about water currents on GIS platform](image)

3. Application to Huangdao ‘11.22’ oil spill incident

3.1. Model Validation

3.1.1. Validation of WRF. In this work, the wind speed observation from the XMD marine observation station near Qingdao were used to validate the forecast results from WRF. As shown in Figure 5, statistical analysis showed that the root mean square error (RMSE) of wind speed was less than 1.64 m/s (Figure 5a), and the RMSE of the wind direction was less than 33 degrees (Figure 5b). As can be seen, the forecasted wind speed and direction agreed with the observations very well.

![Figure 5. Statistical analysis of the predicted wind and observations from the XMD marine observation station near Qingdao](image)

3.1.2. Validation of FVCOM. In this work, observations from some stations including the surface current velocities and direction as well as tidal elevations, were used to validate the forecast results. Table 1 showed the phase and amplitude comparisons between observations and model results. In Tab.1, the RMSE of the amplitude was between 3.54–7.71 cm, and the bias of the phase was between 5.23–10.36 degrees. Above all, the simulation have good agreement with the tidal observation, which can prove the reliability of model forecasting.
Moreover, the simulated tidal elevations on November, 2013 were selected for the further validation. As shown in Figure 6, the elevation from the model (blue solid line) were also in good agreement with observation (red point). The tidal elevations were generally well forecasted.

**Figure 6.** The tidal elevation comparison between the model outputs and observation  
(Blue solid line: observation; Red point: model outputs)

### 3.2. System application
In this paper, the Bohai and Yellow sea oil spill prediction system was used to predict the oil drift and diffusion after Huangdao ‘11.22’ oil spill occurred. Figure 7 showed the drift and diffusion of spilled oil at different times. In Figure 8 (a) and (b), after the oil spill occurred, under the impact of surface currents and winds, the oil began to move to the north in Jiaozhou Bay. 27 hours later, due to the current direction reversion, the oil moved to the southeast with diffusion (Figure 8 (c)). It is apparent that the spilled oil began to moved slowly out of Jiaozhou Bay and oil-shoreline interaction occurred. 49 hours later, as shown in Figure 8 (d), a mass of oil diffused in Jiaozhou Bay. Meanwhile, diffusing oil slick was adsorbed on Huangdao and Tuandao under the effect of surface wind and currents. 71 hours later, as shown in Figure 8 (e), after long time of drift and diffusion, the oil pollution distributed throughout Huangdao and the areas near Fushan Bay. Although this prediction can’t be validated by some SAR images due to the lack of satellite observations, it still provided effective and referable oil spill behavior information to Maritime Safety Administration.

Figure 7. Oil spill drift and diffusion at different times
4. Conclusions and outlook
In this study, based on oil spill model and GIS platform, we have developed the Bohai and Yellow sea oil spill prediction system. Combining with high-resolution meteorological and oceanographic forecast results, the modelling system was applied to predict the drift and diffusion process of Huangdao ‘11.22’ oil spill incident. The prediction showed after 71 hours of drift and diffusion, the oil pollution distributed throughout Huangdao and the areas near Fushan Bay. Although this prediction can’t be validated by some SAR images due to the lack of satellite observations, it still provided effective and referable oil spill behavior information to Maritime Safety Administration. Since no weathering process has been considered in the oil spill model, the initial version of the Bohai and Yellow sea oil spill prediction system can’t provide oil weathering prediction. We will develop an advanced version coupled with oil weathering formulas in the future.

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