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# A modified probabilistic oil spill model and its application to the Dalian New Port accident

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ABSTRACT

We employ a partial-condition designated probabilistic oil spill model based on a Lagrangian particle technique to simulate the Dalian New Port oil spill accident. By correlating the model with aerial images and field observations of oil slicks on the sea surface, the model is applicable for evaluating the probability spatial scattering of the area polluted by the spilled oil. Evidence shows that multiple simulations under specified conditions fit the real distribution and behavior of oil slicks more accurately than those from fully random initial conditions. The findings suggest that the effects of seasonal variations in wind and current dynamics within tidal cycles on spill distribution should be taken into account for estimating the impact of potential oil spills in the North Yellow Sea. A statistical model that considers condition selection could enhance the reliability of risk estimation and enable the application of appropriate recovery operations in contaminated seas.



## 1. Introduction

Problems from oil spill have been a major concern as they are regarded as one of the most critical forms of marine pollution (Soomere, 2011; Alves et al., 2014, 2015). The oil spill event on July 16, 2010, in Dalian New Port was the largest accidental marine oil spill in the history of China's shipping industry. It was a destructive disaster for marine ecosystems and the fishing and tourist industries. As a large oil port, the surrounding coastal environments near Dalian New Port still face the threat of a potential oil spill. After this disaster, oil spill transport models, offering reliable slick trajectory information, should be utilized to form the basis of future risk forecasts. Oil trajectory forecasting is a critical factor in oil recovery and protection decisions. A large number of deterministic models have evolved from two-dimensional trajectory-type models to three-dimensional models that include both transport and fate processes (ASCE, 1996; Azevedo et al., 2014). In fact, the physical processes acting on the spilled oil are complex, even chaotic, and environmental data are not sufficiently precise, so uncertainty in the trajectory forecast is inevitable (Fingan, 2011).

The statistical models provide a new way to predict the trajectory of oil spills while including uncertainty, which seems more appropriate in regard to the problem of risk forecasting a spill event that has not yet taken place (Sebastião and Soares, 2007). Therefore, the environmental impact assessment tool oil spill risk analysis (OSRA) model was developed to estimate the probabilities of the occurrence and contact of an oil spill from prospective commercial oil operations on the outer continental shelf of the United States (Price et al., 2003), which produced statistical patterns similar to those displayed in the Deepwater Horizon Oil Spill surveys using historical current and wind data (Ji et al., 2011). Stochastic oil spill prediction assumes that the laws governing spilled oil behavior of spilled oil are entirely deterministic, but seeks solutions corresponding to probabilistic statements of the initial and boundary conditions. To evaluate the potential impacts and natural resource damages resulting from oil pollution, probabilistic modeling techniques were adopted to estimate the underlying impacts resulting from oil spills by calculating the oil trajectory, surface distribution, shoreline deposition, and mass balance of fuel components in various environmental mediums

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(McCay et al., 2004). The combination of GIS and multivariate statistical techniques was utilized to identify and delineate areas of overlap from multiple spill sources (Guillen et al., 2004). This probabilistic model succeeded in providing the areas that had a high probability of being impacted by a particular spill, but failed to predict the arrival time for a particular location (Díaz et al., 2008). The reliability of a statistical oil spill response model is validated by means of actual oil slick observations reported after the Prestige wreckage and the trajectories of drifter buoys (Abascal et al., 2010). Soomere et al. (2011) employed a statistical analysis of Lagrangian trajectories of pollution transport to optimize marine fairways to minimize the risk to high-risk resources. Alves et al. (2014) presented an innovative three-step model to assess the shoreline and offshore susceptibility to oil spills, and it was successfully applied in the Eastern Mediterranean Sea based on a series of oil spill simulations (Alves et al., 2015). Delpeche-Ellmann and Soomere (2013) adopted a Lagrangian transport model and statistics to investigate the possibility of marine protected areas at risk of contaminants released along a major fairway in the Gulf of Finland. In their study, the hypothetical spill event was a completely random occurrence over a longer period of time, while the seasonal and inter-tidal variations were less pronounced. Otero et al. (2014) analysed the coastal exposure to potential oil spills from various corridors under a wide range of scenarios, pointing out that the National Park of the Atlantic Islands would require protective actions in 24–48 h. Ciappa and Costabile (2014) investigated the oil pollution risk in the central Mediterranean and found that the risk area extended further offshore in winter than in summer. Goldman et al. (2015) created seasonal maps of the probability of oil spill pollution and discussed seasonal variability in the probability distribution and oil states. In fact, not only the local winds but also current patterns determine the short-term trajectory of spilled oil. More factors than only seasonal variations should be taken into account, especially neap-spring tidal cycle and flood-ebb fluctuations in coastal waters (Eide et al., 2007).

Oil spills occur at different moments, in different locations, with different magnitudes, even with different chemical compositions. Simultaneously handling these drastically different classes of information is extremely difficult; nevertheless, it is feasible to reduce the complexity of an operation for a real accident regardless of the last three types of uncertainty (Fingan, 2011). Analysing the sensitivity of various initial and boundary conditions, not only enables a determination of the significance of various environment variables but also probably reduces the number of random scenarios to the same precision. Another issue with the statistical oil spill model is that it should be run numerous times (with up to hundreds of scenarios) to obtain accurate results. All of the aforementioned probabilistic models were built based on structured grids, and a densified grid over all regions can give rise to intensive computational burden. The adoption of unstructured grids offers a good alternative without sacrificing computational efficiency (Zhang and Baptista, 2008).

The purposes of this study are: (1) to verify the reliability of a probabilistic oil spill model by applying it to a real event and (2) to improve its accuracy by setting specific environmental conditions. Following the Introduction, Section 2 describes the basics of the partial-condition designated probability statistical oil spill model. In Section 3, we discuss its application to the Dalian New Port accident. Section 4 presents the conclusions. In summary, this work addresses the following two questions:

a) Can reliable probabilistic spill models be applied to real events?
b) To what extent can specific environmental data improve the accuracy of the models?

## 2. Methods and materials

### 2.1. Model domain & environmental factors

Geographically, the port of Dalian is located on the boundary between the southern region of the Liaodong Peninsula and the North Yellow Sea (Fig. 1). The hydrodynamic computational unstructured grid resolution varies from approximately 2 km in the outer open seas to less than 50 m around the spill site. The region is characterized by the typical medium latitude monsoon climate, which consists of cold, dry winters and hot, wet summers. As a major seaport of North China, Dalian is responsible for rapid economic growth, while it also suffers from severe oil spills, such as Maya 8, 1990; Ya He, 2001; Arteaga, 2005; and most recently, the Dalian New Port accident, 2011 (Guo and Wang, 2009; Xu et al., 2012; Guo et al., 2014).

On 16 July 2010, while unloading oils at the Dalian New Port, an explosion in the pipe gallery caused by an operation failure ignited a fireball that was visible from several miles away. To avoid the fire detonating the surrounding storage tanks, 35,000 t of crude oil were spilled into the sea, drifting over 200 $km^2$ during the next week (Xu et al., 2012). To encompass the maximum range that oil slicks can reach, the computational domain covers the whole Bohai Sea and the North Yellow Sea. The unstructured grid method is adopted to refine the local area near the spill source and environmentally sensitive targets. A link to an environmental dynamic model is of vital importance for numerical oil spill models because the surrounding meteorological and hydrological conditions determine the trajectory and distribution of the spilled oil (Alves et al., 2014, 2015; Coppini et al., 2011). The wind data is obtained from re-analysis data based numerical results outputted by the Weather Research & Forecasting Model (WRF) covering 20°–52 °N and 117.5°–152 °E and ranging from January 1, 1998, to December 31, 2012. The wind fields are in high temporal and spatial resolution (3-hour time interval, and a horizontal resolution of 0.1° by 0.1°), which is sufficient to represent spatial and time variations of the spilt oil trajectories. The other critical role, that of the current, is acquired from the SELFE-SWAN coupled model, which is driven by synoptic winds, tidal forces, and surface wave effects (Zhang and Baptista, 2008; Booij et al., 1999). The hydrodynamic model open boundary is driven by water level changes, which is computed from eight harmonic constituents (M2, S2, N2, K2, K1, O1, P1, Q1), compiled in a database NAO.99 (Matsumoto et al., 2000). The coupled model incorporates three-dimensional wave–current interactions, so the surface wave information is obtained simultaneously, which is the dominant factor propelling surface oil into the water column. The applicability of the wave–current coupled model has already been demonstrated in Guo et al. (2014).

### 2.2. Oil particle model

Regarding the released oil as a larger number of particles that are tracked individually has been widely adopted and is known as the oil particle model. In the particle-based approach, the movements of oil spill are computed by means of the transport forced by the advective forces (currents, winds, and surface waves) and turbulent diffusion. The advective velocity of an oil particle is calculated by:

$$\vec{U}_a = \vec{U}_{cr} + C_{wind} D_{wind} \vec{U}_{wind} + \vec{U}_{wave} \tag{1}$$

where $\vec{U}_{cr}$ is the water current velocity interpolated from the hydrodynamic model, $\vec{U}_{wind}$ is the wind velocity at 10 m above the water surface, and $C_{wind}$ is the wind drift factor. $D_{wind}$ is the transformation matrix used to account for the wind deflection