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Modelling of oil spill trajectory for 2011 Penglai 19-3 coastal drilling field, China

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ABSTRACT

An oil particle trajectory model was developed and was applied to the 2011 Penglai 19-3 subsurface oil spill in the Chinese Bohai Sea. The three dimensional model simulated ocean currents fields and utilised meteorology data from the local measurement station to drift spilled oil. In such a model, the movement of the particles as the sum of deterministic advection and random diffusion were determined by using the Lagrangian algorithm. The simulation fitted well with observations of actual oil sightings, which showed that oil particles spread southeast/eastward to the Bohai Strait, China. This estimation agreed with actual official combat activities near the spill site during the month of the June–July, 2011.

1. Introduction

On the 4th June 2011, oil was observed on the surface of coastal waters near platform B, latitude 38°N longitude120.0°E, a nearshore oil drilling field named Penglai 19-3 operated by ConocoPhillips China Inc. (COPC). Specific spill site was shown in Fig. 1. This accident was identified as a consequence of geological fault that opened slightly because of pressure from water injection into a subsurface reservoir during production activities [1] (see http://www.conocophillips.com.cn/EN/Response/Pages/default.aspx). According to COPC, a sum of approximate 723 barrels (115 cubic metres) of oil and 2,620 barrels (416 cubic metres) of mineral oil-based drilling mud have seeped into the Chinese Bohai Sea. By June 17, it was reported that 840 square kilometres of clean coastal water, an area to be 1.2 times the size of Singapore, were polluted.

The Chinese Bohai Sea is semi-closed with an average water depth of 18 metres. Its significant ecosystem and important economy make the Chinese Bohai Sea be highly vulnerable to any size of oil spills [2]. This Penglai 19–3 spill contained toxic substances and heavy metals, that threatened ecosystem and the livelihood of people along the Bohai coast. Dead seaweed and rotting fish have been seen and reported by XinHua News [3]. More detailed can be seen at http://en.wikipedia.org/wiki/2011_Bohai_Bay_oil_spill.

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This accident was considered as not only an ecosystem disaster, but also a complex event resulting in much concern from the public and official governments including both the North Korea and the South Korea. Firstly, the State Oceanic Administration (SOA), China was criticised to cover up the news of the oil spill for a month. As this oil spill was initially revealed via a public microblog tip-off on June 21. The domestic public was only informed about this spill on July 5, 2011, that was already 31 days after it spilled on June 4, 2011. Secondly, many Chinese environmental organizations and experts questioned the "spill amount" released by ConocoPhillips, because no third party but ConocoPhillips and the SOA attended the combat and assessment activities. Thirdly, Korea media have expressed that the spill would result in a cross-country environmental damage to both the North Korea and the South Korea, if the spilled oil flow into the Yellow Sea [3]. More detailed information can be referred to http://en.wikipedia.org/wiki/2011_Bohai_Bay_oil_spill.

Following the tragic Penglai 19-3 oil spill, oil particle trajectory simulations were developed to estimate how and where the oil might spread under the combined driving forces of current and wind. The model simulated three-dimensional oil trajectories with particles. The three dimensional model incorporated key weathering processes including evaporation, spreading, stranding, emulsification and dissolution [4,5]. A Lagrangian algorithm was introduced here to describe the movement of the particles as the sum of an advective deterministic components and an independent, random Markovian component which statistically approximates the dispersion characteristics of the environment [6,7].

2. Methodology and data

2.1. Lagrangian particle algorithm

Oil spill simulation consisted of two major parts: the hydrodynamic modelling and the particle tracking. The hydrodynamic model for the Chinese Bohai Sea was fully established by using ECOM (Estuary, Coastal and Ocean Model) with a set up of bathymetry, initially condition, open boundary and gridding. More details on ECOM can be referred by the HydroQual's website (i.e., http://www.hydroqual.com). To simulate the drift of oil slicks, a three dimensional oil transport model including a variety of processes such as spreading, stranding, evaporation and emulsion was then developed on the basis of both the hydrodynamics and the Lagrangian discrete particle algorithm. According to the Lagrangian discrete particle algorithm, the movement of a large number of small oil particles of equal mass can be driven by the media such as sea water with the velocity components $\vec{U}(x,y,z,t)$, $\vec{V}(x,y,z,t)$ and $\vec{W}(x,y,z,t)$, the buoyancy velocity of oil particles u_b and the turbulent fluctuations $\hat{U}(x,y,z,t)$, $\hat{V}(x,y,z,t)$ and $\hat{W}(x,y,z,t)$ by Xu et al. [8]. Hence, the coordinates X, Y and Z of oil particles can be written as [8],

$$\begin{cases} dX/dt = \vec{U} + \hat{U} \\ dY/dt = \vec{V} + \hat{V} \\ dZ/dt = \vec{W} + \hat{W} + u_b \end{cases} \tag{1}$$

where $\vec{U}(x,y,z,t)$, $\vec{V}(x,y,z,t)$ and $\vec{W}(x,y,z,t)$ represent the drift velocity of oil particles due to the combined forcing of wind, current and waves. u_b is the buoyancy velocity and $\hat{U}(x,y,z,t)$, $\hat{V}(x,y,z,t)$ and $\hat{W}(x,y,z,t)$ simulate the turbulent fluctuations of velocity of oil particles in the water column.

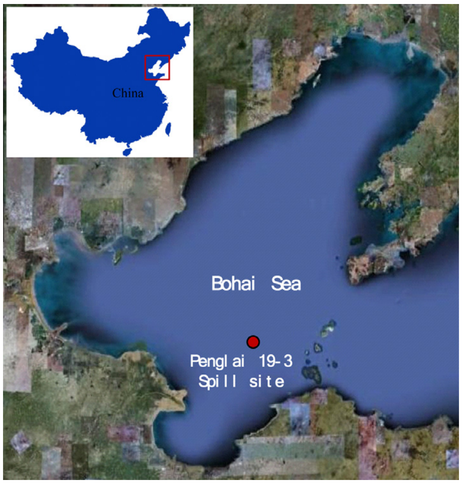

Fig. 1. The Chinese Bohai Sea and the Penglai 19-3 oil spill site. (*Note*: Google map downloaded was modified).

2.2. Advection

The drift velocity of the oil on the sea surface as well as in the water column can be determined as follows [9],

$$\begin{cases} \vec{U} = \alpha_{wind} D * U_{wind} + \alpha_c U_c + U_{wave} \\ \vec{V} = \alpha_{wind} D * V_{wind} + \alpha_c V_c + V_{wave} \\ \vec{W} = W_{wave} \end{cases} \quad (2)$$

where U_{wind} and V_{wind} are the wind velocities at 10 m above the sea surface for horizontal x and y direction, respectively. U_c, V_c and W_c are the sea current velocity for x, y, z direction, which are obtained from the ECOM. U_{wave}, V_{wave} and W_{wave} represent wave induced velocity at the direction of x, y and z, respectively. It was mentioned previously that the Chinese Bohai Sea is a C-shaped semi-enclosed sea. Compared with tidal currents and wind forcing, many literatures suggested that wave induced currents were not considered as the most dominant factor to drift the spilled oil on the sea surface. In this paper, hence we have an emphasis on tidal currents and wind as dominant driving force so that wave induced currents were ignored during simulations; α_{wind} is usually assigned as 0.03 for the drifting force of wind [10]; α_c is a contribution from currents, usually taken a value of 1.1; D is a matrix as follows [9],

$$D = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \quad (3)$$

where $\theta = 40^\circ - 8\sqrt[4]{U_{wind}^2 + V_{wind}^2}$, if wind speed is less than 25 m/s; otherwise $\theta = 0$.

2.3. Diffusion

Following Fisher et al. [11], the turbulent diffusion is calculated as,

$$\begin{aligned} \hat{U} &= R^* \cos\phi\sqrt{4K_a/\Delta t} \\ \hat{V} &= R^* \sin\phi\sqrt{4K_a/\Delta t} \\ \hat{W} &= \sqrt{2K_z/\Delta t} \end{aligned} \quad (4)$$

where Δt is the time step; R is assumed to be an independent random number with a zero mean and unit variance. ϕ is a random angle between 0 and π. K_a and K_z represent the turbulent diffusivity in the horizontal and the vertical directions, respectively. These parameters will be assumed empirically to be constants in the proceeding model for simplicity [12].

2.4. Evaporation and emulsion

Evaporation and emulsion are the most two primary processes involved in the natural reduction of oil from the sea water. Environmental condition and oil type are crucial for determining the evaporation rate of oil. The evaporation process (%Eva) for the crude oil in this paper was modelled using Fingas [13] empirical formulation as follows:

$$\%\text{Eva} = [0.165 * \%D + 0.045(T - 15)] * ln(t) \quad (5)$$

where $\%D$ indicates the distillation percentage at 180 °C; T is the water temperature and t represents time after the spill. The emulsion is the incorporation process of water into the oil slick. The natural process of emulsion within the proposed model is based on the classic work by Mackay et al. [14] who developed a relationship for fractional water content (F_{emul}) in the oil, as a function of wind velocity (w) and the maximum amount of water that oil can retain (F_{max}), as:

$$dF_{emul}/dt = F_{emul}^*(1 + w)^2(1 - F_{emul}/F_{max}) \quad (6)$$

2.5. Data and setup

The digital coastal line was extracted from National Geophysical Data Centre [15] and bathymetry data as shown in Fig. 1 was obtained by in-situ measurements and was interpolated. For a three dimensional model, rectilinear grids were generated horizontally to cover the whole domain ranging from 117.5° to 122.5° Longitude and from 37° to 41°Latitude in the local coordinate system. The grid cell was 1.67′ by 1.67′ of Longitude and Latitude, respectively. The mesh comprised 180 cells (x-direction) and 144 cells (y-direction). 10 layers were designated vertically. All wind data were downloaded from the Changdao meteorological station (See Fig. 2), which is the closest meteorological station to the spill site.

Using the Lagrangian algorithm, surface oil particles were drifted by wind and tidal Currents [16]. Within the computation model, open boundary was defined along the right most vertical line at 122.5°E. There existed two hydrology stations located in the Dachangshan island and the Jiming island along the open boundary line as shown in Fig. 3. Amplitudes and phases for four major harmonic constituents: M2, S2, K1 and O1 were obtained from these two local stations. Initial conditions for open boundary were then interpolated to drive the tide. The instantaneous water level and current speed can be calculated in the model. Surface water temperature and salinity are accurate to be an average of monthly mean surface water

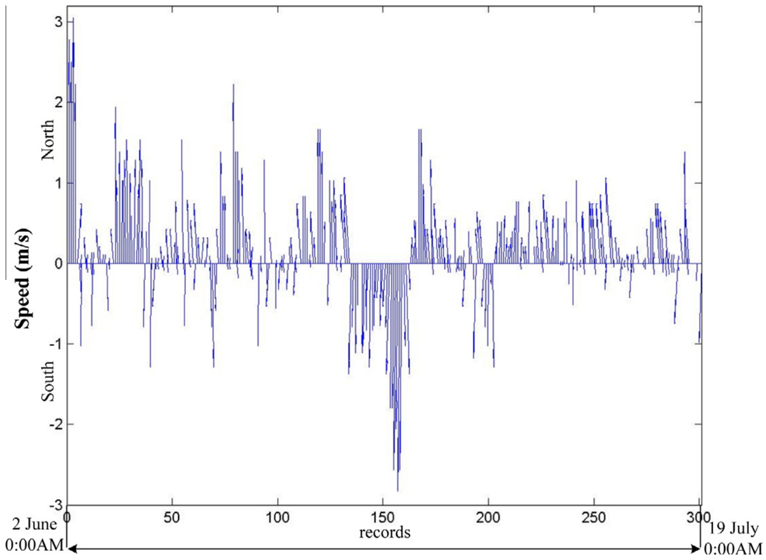

Fig. 2. Wind speed for Changdao station (actual measurements from local meteorological station as shown in Fig. 3) from June 2, 2011 to July 19, 2011. Totally, 300 records were used for driving simulation models.

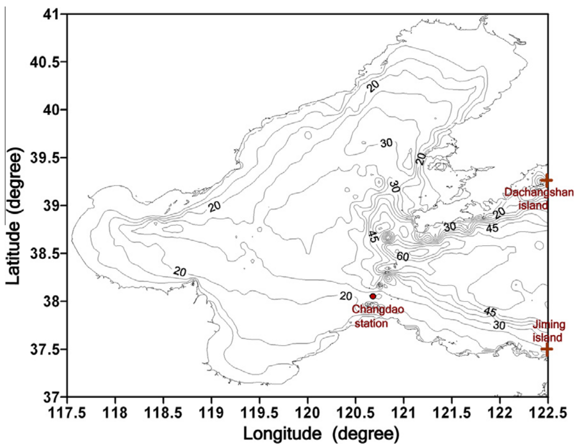

Fig. 3. Bathymetry data was in meter for the Bohai Sea, China. One meteorological station at the Bohai Strait and two hydrological stations along the open boundary at 122.5 Longitude were all marked in red. Water depth was measured in metre. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temperature and salinity, respectively for the central Bohai Sea by Mao et al. [17]. The flow in the Bohai Sea is almost completely tidal induced and for the present analysis, the density driven flows were not considered [18,19]. Oil was transported assuming neither removal of mass by cleanup nor application of dispersants [20]. Simulation duration was 46.5 days from 2 June 0:00AM to 18 July 12:00AM. The oil tracking model provided trajectory data over 44.5 days following the Penglai 19-3 oil spill in the 4th June. Spill was assumed to be continuous in a specific time duration. That is, 100 particles were released in every 180 s. Totally, there were 16,000 particles representing 3400 barrels of oil that were released. Using the Lagrangian algorithm, surface oil particles were drifted by both wind and tidal currents [21,22]. The model's setup is summarised in the following Table 1.

3. Results

Most of the wind speed in this area during the specific period was less than 3 m/s (See Fig. 3, defining the north direction as positive). Wind speed less than 3 m/s will also induce dark areas in SAR (Synthetic Aperture Radar) image, which were likely to affect the accurate detection of oil spill by remote sensing method [23,24]. Hence it further resulted in less validation of oil spill simulation.

Table 1
Inputs to simulation models.

Name	Description	Value(s)
Oil type	Heavy oil released	Statfjord
Oil density	Density of oil released	0.832 g/cm^3
Spill site	Latitude and longitude of the release	120.1°E; 38.4°N
Release depth	Depth below the water surface (m) for spill	23 metres
Spill start	Hours over which the release occurs	0:00AM at 4 June 2011
Spill end	Hours over which the release ends	8:00AM at 4 June 2011
Model time step	Time step used for model calculations	180 s
Model duration	Length of each model simulation	46.5 days
Model start	Time over which the model runs	0:00AM at 2 June2011
Tidal constituents	Amplitudes and phases of major constituents included	M2, S2, K1, O1
Number of oil particles	Number of particles released	16,000
Wind data	Wind velocity	Hourly varied wind data from local hydro-station

Note: Model starts at 0:00AM 2 June, while spill starts at 0:00AM 4 June 2011. The two days' lag is for stability of currents developed in the model.

Water level and currents were presented by the hydrodynamic modelling in this paper. To validate the hydrodynamic model, both currents and amphidromic points for M2, S2, K1 and O1 were compared with literatures. According to modelling results, the flows in the Bohai Bay, the Laizhou Bay and the northern part of the Liaodong Bay all belonged to the category of loop currents with the direction of anticlockwise, while it was reciprocating flow in the middle of Bohai Sea as shown in Fig. 4 [25]. These results agreed with many literatures [26–28]. The tidal currents in the Bohai Bay, the Liaodong Bay and the Laizhou Bay were all normally semi-diurnal tide, with a period of 12∼13 h. Such a result was consistent with the work by Huang and Huang [29]. Surface currents' speed in the Chinese Bohai Sea is relatively small, which was averaged at some 0.5 m/s.

To further validate the simulation results for hydrodynamic flow, cotidal charts for this study area were presented as shown in Figs. 5 and 6 and were compared with previous publications. M2 is an important dual-tide constituent. Totally, there were two amphidromic points detected for M2 in this study area. One was located off Qinhuangdao coast and the other was referred to the estuary of the yellow river as shown in the Fig. 5. This is consistent with publications by Sun et al. [30]. S2 had two similar amphidromic points as M2 did. K1 and O1 have similar amphidromic points, while K1 and O1 have only one amphidromic point, which was in the south-west to the Bohai Strait as show in the Fig. 6. Identification of amphidromic points for M2, S2, K1 and O1 in this paper fully agreed with literatures [30,31].

Figs. 7–11 helped us understand how the currents affected the trajectories of oil spilled. Penglai 19-3 oil spill site was close to the middle of the Bohai Sea. As mentioned above, currents in this area were grouped into reciprocating flow, which forced the oil particles move to either the west or the east direction at the early days after the spill as seen in Figs. 7 and 8. As time went on, particles as simulated in Figs. 9 and 10 generally tended to transport eastern to the Bohai Strait. That is, oil

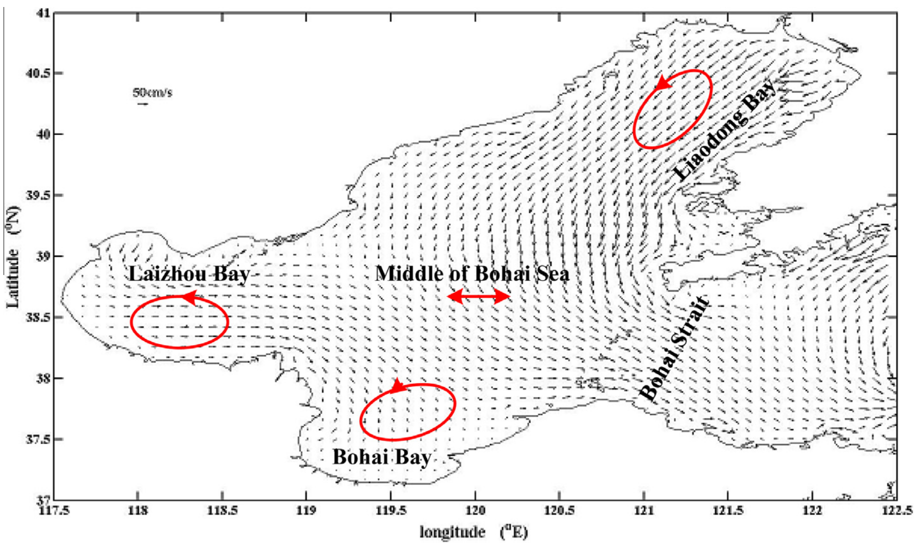

Fig. 4. Simulation of currents in the surface of the Bohai Sea at 0:00AM on the 18th July, 2011. Bohai Sea consists of four major parts. They are the Liaodong Bay, the Laizhou Bay, the Bohai Bay and the middle part of the Bohai Sea. Movements of surface currents in those four parts of the Bohai Sea are marked in red with arrow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

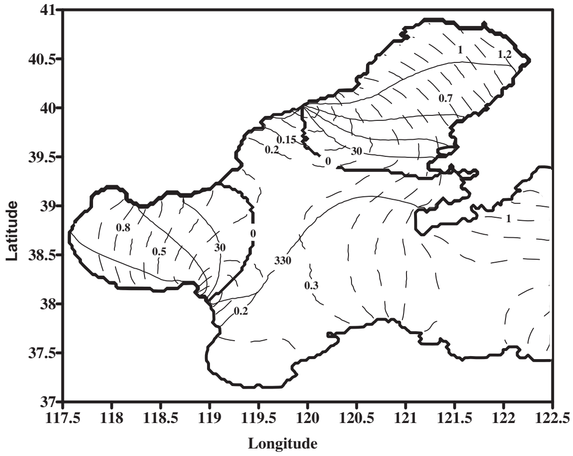

Fig. 5. Simulations of amplitudes and phases for M2 in the Bohai Sea. Dotted lines indicated amplitudes in cm and solid lines represented phases in degree. Comparison of amphidromic points of predictions against literatures [30,31] showed a close fit.

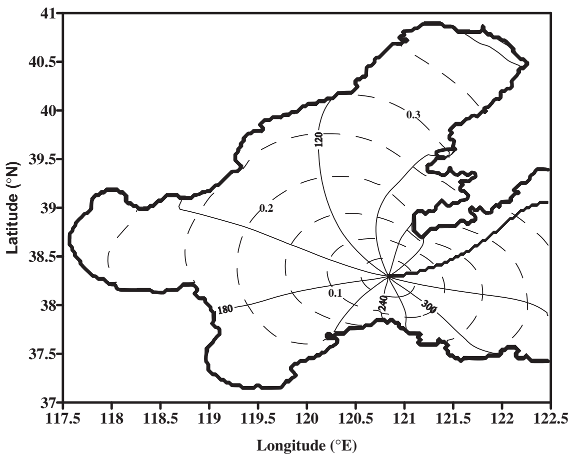

Fig. 6. Simulations of amplitudes and phases for K1 in the Bohai Sea. Dotted lines indicated amplitudes in centimetre and solid lines represented phases in degree. Consistent results can be found in historical literatures [30,31].

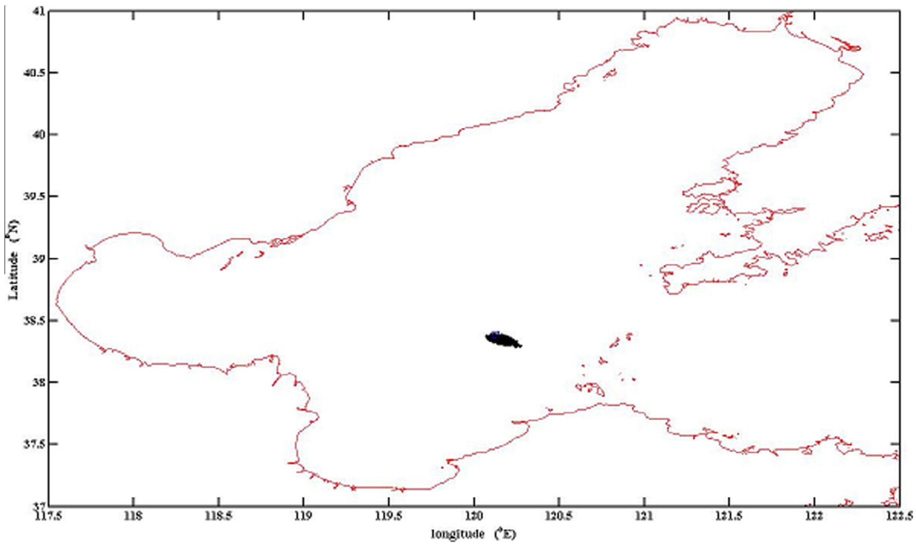

Fig. 7. Horizontal projection of simulated trajectory of spilled oil at 0:00AM on the 11th June 2011.

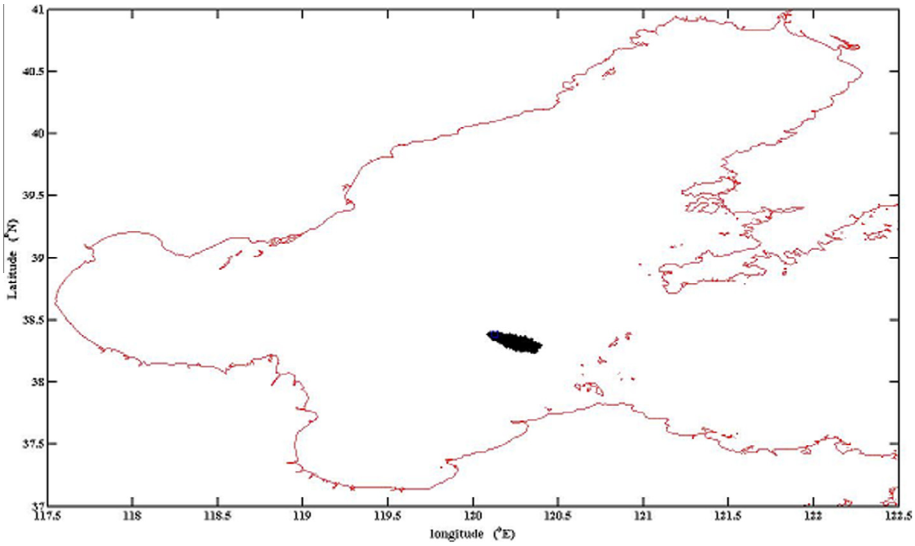

Fig. 8. Horizontal projection of simulated trajectory of spilled oil at 6:00AM on the 19th June 2011.

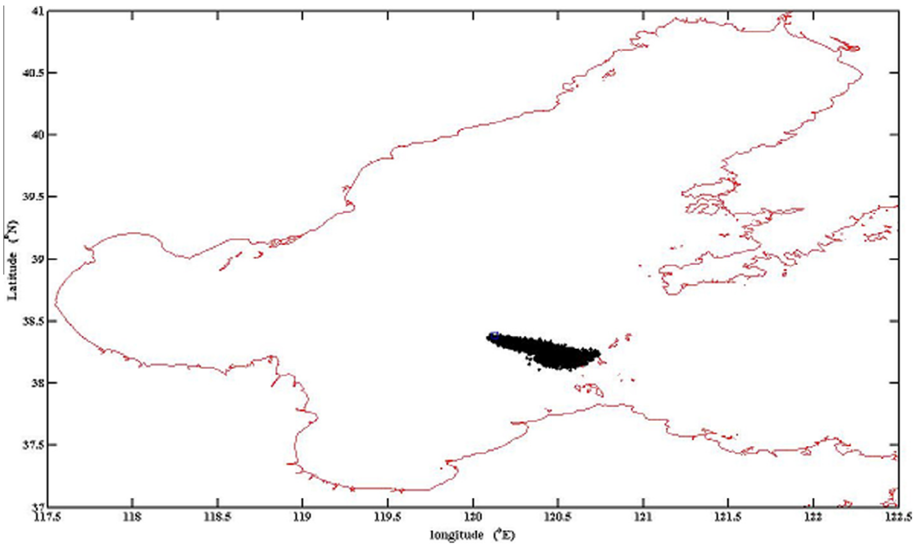

Fig. 9. Horizontal projection of simulated trajectory of spilled oil at 0:00AM on the 8th July 2011.

particles in Fig. 9 were clearly dominated by currents, which was extended to eastward past the 120.7° E in 8 July, 2011 (see Fig. 9). Spilled oil was a mixture of petroleum, hydrocarbons and drilling cuttings like 'oil-based mud' that tends to sink to the bottom of sea as shown in Fig. 10. The result revealed that the oil particles transported in both the horizontal and the vertical ways, given the assumption of the advective deterministic component and the random dispersive component. Fig. 10 showed the simulated vertical distribution of oil particles. The result demonstrated that some of the particles departed from the bottom of the sea and got into the water column, which indicated that the movement of oil particles was significantly influenced by the process of vertical diffusion and floating.

To be efficient to stop spilled oil from polluting domestic coastal areas and outer international sea (i.e., the Yellow Sea), we suggested that physical combat should be carried out in the orange marked area (as seen in Fig. 11) prior to its approaching to the Bohai Strait (i.e., 8th July, 2011 as shown in Fig. 9).

A lack of sufficient field data at the time of oil spill event often hampered the efforts to validate the oil spill modelling [32]. In case of the Penglai 19-3 oil spill, SAR image thereby allowed the comparison of predicated oil slick trajectory with the actual observations of the oil slick position. Due to the difficulty of accessing to SAR image data and extensive activities of oil combat on waters by local governments as well, we compared the simulation results with satellite image only by the 11th June, 2011. According to Fig. 12 (i.e., the observed data) showed that oil slicks were spreading in the directions of both the

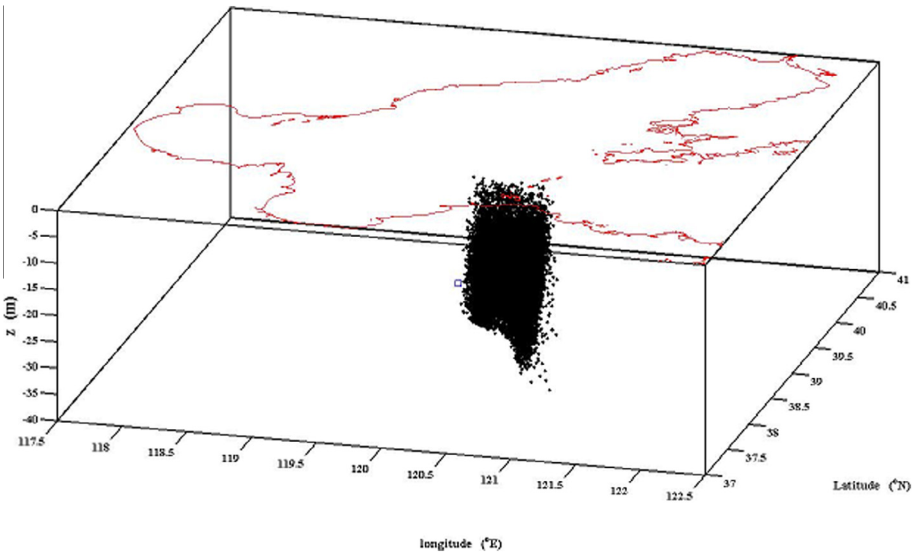

Fig. 10. Simulated three dimensional trajectory of spilled oil at 12:00AM on the 18th July 2011.

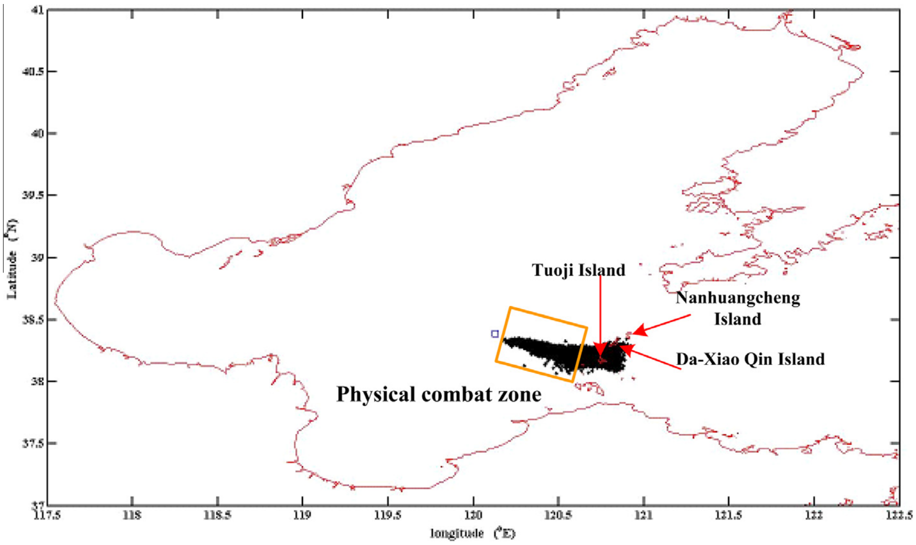

Fig. 11. Horizontal projection of simulated trajectory of spilled oil at 12:00AM on the 18th July 2011. Physical combat zone suggested was marked by the orange rectangular.

Fig. 12. ENVISAT-ASAR image by the 11th June, 2011 showed a distribution of oil slicks. Yellow cross represented the original spill site and oil slicks were identified and were marked in white solid lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

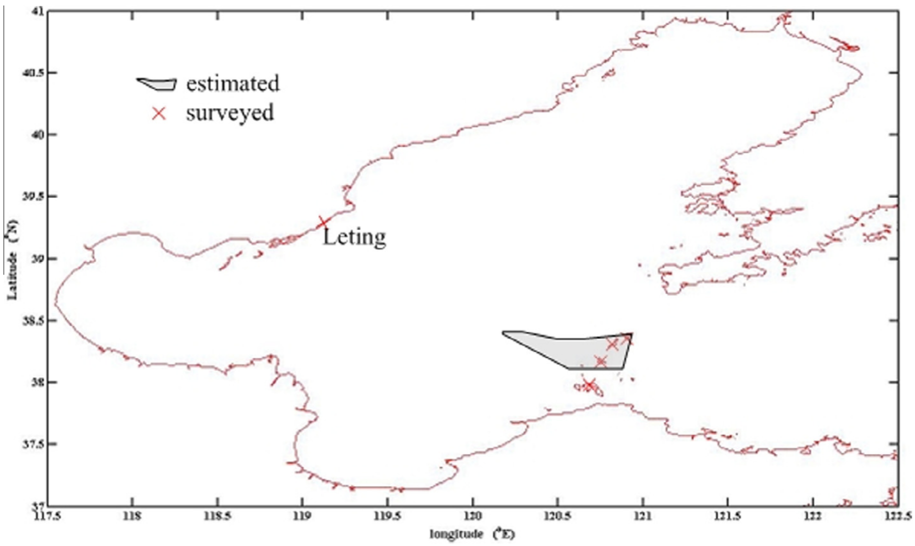

Fig. 13. Surveyed oil sightings were compared with estimations of polluted areas.

North-West and the East to the original spill site by the 11th June, 2011. Compared with results shown in Figs. 7–10, it was confirmed that simulated oil drifting mainly towards eastern was correct, while the model did not precisely simulate the spreading of oil to the direction of North-West. This would be resulted from the storm entering the Bohai Sea through the Bohai Strait at that particular period, which was discussed in a comprehensive way in the proceeding section of oil sightings.

3.1. Oil sightings

The simulation was based on an assumption that no cleanup such as combat strategy on water was carried out. That is, the Changdao islands, especially the Tuoji Island, the Da-Xiao Qin Island, the Nanhuangcheng Island would be coastal areas seriously hit by this oil spill without on-site cleanup as shown in Fig. 11. In reality, SOA (State of Oceanic Administration) and COPC (ConocoPhillips China Inc.) both have used chemical dispersants and have deployed physical measures including skimmers, absorbent booms, fishery vessels and other clean-up equipments to combat after the spilled oil was detected on sea water surface. To some extent, the combat activities disturbed the natural distribution of the oil and stopped further its spreading through the Bohai Strait to the Yellow sea, which connects to both the North Korea and the South Korea. Although combat activities reduced the impact of spilled oil on coastal environments and chemical dispersant got oil slicks disappear visibly on sea surface quickly, some serious oil sighting on coastal areas were still captured and were reported by the media. According to a report in the 27th volume of the magazine called "XinMin Weekly", it was said that oil slicks were observed by local fishermen and there were ships being busy on fighting oil on water day and night near the Tuoji Island during the early period of July, 2011. Currently, Wiki Penglai 19-3 oil spill website officially released a report that outside of the spill area, dead seaweed and rotting fish can be found around the Nanhuangcheng Island in the Shandong province. Hence, it is useful to compare the model estimates with those observations surveyed. Fig. 13 showed that model estimations were consistent with observations very well but the site of the Leting. In the Fig. 13, Leting was apparently surveyed to be one of oil sightings after the spill, while our model was not able to predict it. This was because, in this model, we did not consider an extreme condition of storm. Actually, there was one huge storm entering into the Bohai Sea through the Bohai Strait during the period between June and July, 2011. It was very likely that oil was drifted to the site of the Leting as storm was approaching to coastal zones.

4. Discussions and conclusions

At the subsurface of the Penglai 19-3 release site, oil particles' movements were controlled mainly by currents and flew southeast/eastward into the Bohai Strait. Due to the fact that spilled oil was a mixture of petroleum, hydrocarbons and drilling cuttings like 'oil-based mud', simulations showed that a majority of oil particles tended to either diffuse into water columns or to sink to the bottom of sea, which agreed fully with observations. Therefore, it was suggested to carry out physical combat in the east/southeastern sea area next to the Penglai 19-3 oil release site as marked in orange in Fig. 11 so that oil could be stopped from further polluting both domestic coastal/island areas and the outer international sea.

Some oil particles moving upward to surface were drifted by both wind and tidal currents towards the direction of the north-west during early stages/days. But wind speed was relatively low (<3 m/s) during the period of June-July, which played a relatively weak role in surface oil trajectories in such a case of the Penglai 19-3 oil spill. Especially, there existed a storm named MEIHUA to be reported to be loading the Bohai Sea through the Bohai Strait during the period of June-July. By the effect of the storm, oil was more likely to move towards north-western, which has been observed by the SAR image, but has been missed by the model simulation. That is to say, the oil surveyed to strand the coast of Leting were outside the certainty of the model estimations. Hence, the hydrodynamic model presented in the paper is suggested to make use of assimilation data for wind incorporating storm information from many meteorological stations nearby or to be coupled with a meteorological model to improve its accuracy of forecasting in the future. Moreover, storm could break big oil patch into small slices, which are much easier to move by the driving force of flow currents and wind. However, we have shown that the model prediction was credible when compared with the observed oil sightings of the actual spill and was therefore a useful tool for oil spill trajectory estimations for future oil spills in the Chinese Bohai Sea.

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