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A hindcast of the Bohai Bay oil spill during June to August 2011

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Abstract

An operational three-dimensional oil spill model is developed by the National Marine Environmental Forecasting Center (NMEFC), State Oceanic Administration, China, and the model has been running for 9 a. On June 4 and 17, 2011, oil is spilled into the sea water from two separate oil platforms in the Bohai Bay, i.e., Platforms B and C of Penglai 19-3 oilfield. The spill causes pollution of thousands of square kilometres of sea area. The NMEFC's oil spill model is employed to study the Penglai 19-3 oil-spill pollution during June to August 2011. The wind final analysis data of the NMEFC, which is based on a weather research and forecasting (WRF) model, are analyzed and corrected by comparing with the observation data. A corrected current filed is obtained by forcing the princeton ocean model (POM) with the corrected wind field. With the above marine environmental field forcing the oil spill model, the oil mass balance and oil distribution can be produced. The simulation is validated against the observation, and it is concluded that the oil spill model of the NMEFC is able to commendably simulate the oil spill distribution. Thus the NMEFC's oil spill model can provide a tool in an environmental impact assessment after the event.

Key words: oil spill, hindcast, Lagrangian random walk, oil distribution, swept area

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1 Introduction

With the increasing demand for offshore oil exploration, more petroleum has been exploited and drilled from a seabed and transported by tankers. Correspondingly the threat of possible marine oil spill accidents is increasing. Accidental marine oil-spill pollution would cause damage to marine environment, the health of mankind, fisheries and so on (Wang et al., 2008; Coppini et al., 2011). The prediction of an oil spill trajectory, a contamination area and a swept area is very important for an environmental impact assessment. And numerical modelling provides an important tool to study and predict the transport and fate of the oil spills, which would assist to plan response actions in advance and minimize the loss.

Nowadays, some groups and international community have developed oil spill models and played an important role in an oil spill emergency response. GNOME (general NOAA operational modeling environment) is a publicly available oil spill trajectory model that simulates oil movement and was developed by the National Oceanic and Atmospheric Administration (Beegle-Krause 2001). It was used to simulate the oil spill trajectory of oil released from a pipeline leaking in the Gulf of Mexico and in the North Sea (Cheng et al., 2011, 2014). OSCAR (oil spill contingency and response) is a state of the art model and simulation tool for predicting the fates and effects of oil released, which has been developed by SINTEF (Stiftelsen for industriell og teknisk forskning) (Reed et al., 1999). It has been involved in and is still in use for planning, hindcasting and forecasting of accidental releases in locations such as the North Sea and Baltic Sea, the Gulf of Mexico and the Mediterranean Sea. MEDSLIK simulates the transport of the surface slick governed by the water currents and wind. The operational implementation of the MEDSLIK oil spill model during the Lebanese oil pollution crisis assisted decision makers in drawing up action plans for the clean-up operations (Coppini et al., 2011).

An operational oil spill emergence forecasting system was established in 2007 at NMEFC (National Marine Environmental Forecasting Center, China), which is capable to predict the trajectory, the swept area, and beached oil distributions and so on. The current and wind fields forcing the oil spill model are acquired from a China's global operational oceanography forecasting system (CGOFS) developed by the NMEFC. The Bohai Sea forecasting system that used in this event is a major component of CGOFS.

On June 4 and 17, 2011, the oil spill was observed from oil platforms B and C of the Penglai 19-3 oilfield, which was operated by Conoco Phillips-China Incorporation (COPC), located at 38.37°N, 120.08°E in the Bohai Sea. According to the COPC, a sum of approximate 723 barrels (115 m^3) of oil and 2 620 barrels (416

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m³) of mineral oil-based drilling mud seeped into the Bohai Sea. The average water depth of Bohai Sea is only 18 m, and water exchange capacity with the open sea is weak as a semi-closed sea. These aggravate the pollution if an oil spill occurred.

During the Penglai 19-3 oil spill accident, many researchers have forecasted the oil spill trajectories (Guo et al., 2010) and validated against satellite observations (Xu et al., 2013, 2015). Li et al. (2013a, b) analyzed the error source of spill transport modelling using the Penglai 19-3 case and identified that the wind is the major error source. The drift factor of wind and current appears to be the most relevant parameter to improve the quality of the result (Coppini et al., 2011). In this paper, a long-term simulation was carried out to analyze the swept area with the corrected wind and current, followed with validation study after the accident occurred.

2 Model and data

The hindcasting scheme is illustrated in Fig. 1. We start with the correction of wind reanalysis filed by comparing with observations. And then we obtain the current filed by forcing the POM (Princeton ocean model) circulation model with the corrected wind filed. With the above marine environmental field forcing the oil spill model, the oil mass balance and the oil distribution could be produced. It will be introduced in detail in the following subsections which including the method to produce of the wind and current field, oil spill model and model parameters.

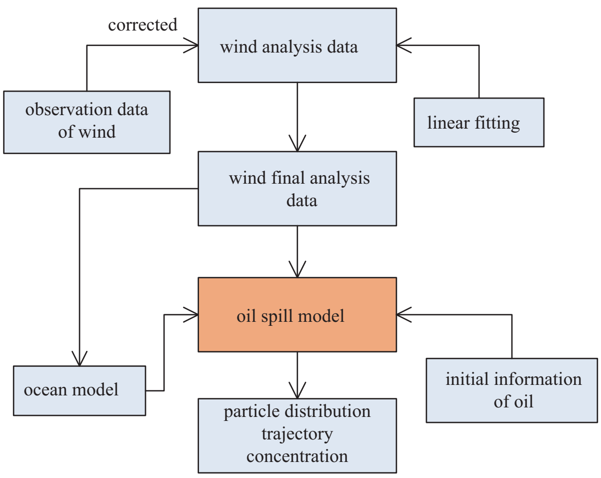

Fig. 1. The structure of hindcast simulation.

2.1 *The correction of wind analysis data*

The wind analysis data are obtained from a WRF (weather research and forecasting) model, where the initial filed and boundary condition obtained from National Centers for Environmental Prediction (NCEP) final (FNL) operational global analysis data (0.5°×0.5°). Meanwhile, the observation-nudging and the grid-nudging are used to assimilate the global telecommunication system (GTS) data.

Li et al. (2013a, b) found out that oil spill transport modelling is very sensitive to the accuracy of the wind filed. Thus we have studied this aspect carefully in this paper. Figure 2 shows the discrepancy between the model result (analysis wind) and the observational wind. The mean absolute error of a wind speed is 2 m/s and the mean absolute error of a wind direction is 47°. The analysis wind is corrected by the observational wind speed and direction received from station close to oil platform of Conoco Phillips (Fig. 3) during June to August. According to the linear fitting shown in Fig. 4, we set up a relationship, as shown by the following Eq. (1), between the corrected wind filed and the simulated one.

$$\begin{cases} u = 1.105\,3u_a - 0.383\,6, \\ v = 0.816\,9v_a + 2.335\,1, \end{cases} \tag{1}$$

where u_a is the simulated eastward component of the wind speed; v_a is the simulated northward component of the wind speed; u is the corrected eastward component of the wind speed; and v is the corrected northward component of the wind speed.

In order to present the improvement, the comparison between the wind final analysis data (corrected wind) and the observation wind is given in Fig. 5. The mean absolute error of the wind speed is 1.7 m/s and the mean absolute error of the wind direction is 43°. The improvement reduced the error of model wind outputs.

2.2 *The hindcast of ocean model*

In this paper, the Bohai operational 3-D current forecasting system of the NMEFC (BOCFS-NMEFC) is used to supply the current velocity, which is based on POM2k. The BOCFS-NMEFC is forced by an open boundary water level condition with the harmonic constant of tide from Japan (Matsumoto et al., 2000). Sixteen main constituents of tide are added to the open boundaries. The current forecasting model uses a uniform grid (2.5′×2.5′) in the Cartesian coordinate system. It covers a region bounded by latitudes ranging from 37° to 41°N and longitudes ranging from

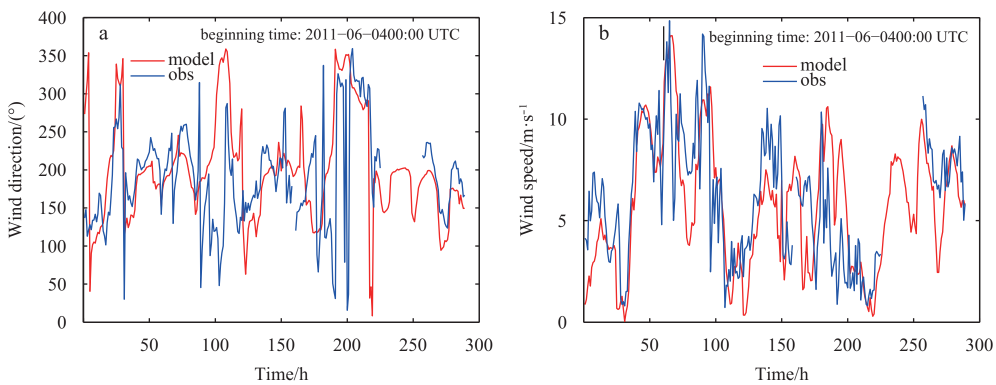

Fig. 2. Comparison of wind analysis data and observation wind.

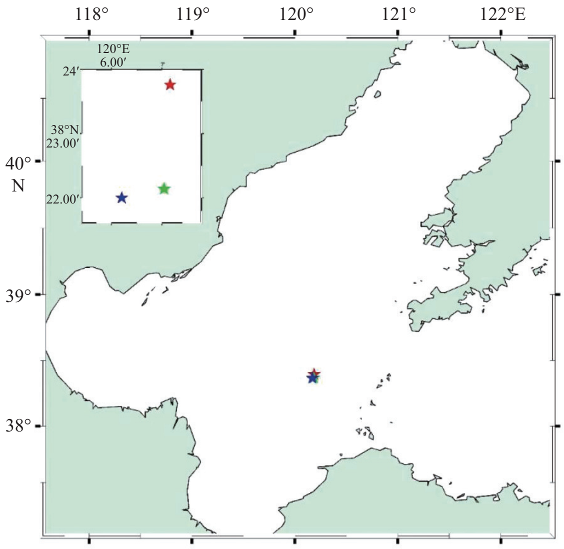

Fig. 3. The location of Penglai 19-3 oil platform (the red star is Penglai 19-3B, the green star is Penglai 19-3C) and observation station of wind near the oil filed (the blue star).

117.5° to 122.5°E. The further description can be found in the paper by Liu et al. (2005). The forecasting results are available on website of the NMEFC every day from 2003. The BOCFS-NMEFC has been running stably for 12 a, and the forecasted currents and sea surface temperatures were verified every month. Tide simulation has been verified by comparing the forecasting water level with the observational water level (Liu et al., 2005).

2.3 *NMEFC oil spill model*

During an oil spill accident, it is most concerned in the oil trajectory, concentration distribution, swept region and so on. The oil spill model would produce the above when the initial information of spilled oil is known, such as oil type, when and where the spill occurred, oil mass leaked and duration. The NMEFC have developed its own oil spill forecasting system since 2007.

An oil spill convection and diffusion model has been widely adopted to simulate the movement of spilled oil in the marine environment, which is based on the oil particle tracking in Lagrangian frame of reference. The turbulent diffusion is handled by a random walk model. An oil parcel concept is a general approach. It is assumed that spilled oil is composed by a large number of particles with equal mass (Johansen, 1984, 1987; Elliott et al., 1986) and subject to wind, current, waves and turbulent diffusion. The velocity of oil particle is calculated as

$$u_0 = u_c + \alpha(u_{10}\cos\beta - v_a\sin\beta) + u_w + u', \tag{2}$$

$$v_0 = v_c + \alpha(u_{10}\sin\beta + v_a\cos\beta) + v_w + v', \tag{3}$$

$$w_0 = w_c + w_{ok} + w', \tag{4}$$

where u_0 and v_0 are the horizontal velocities of the oil particles;

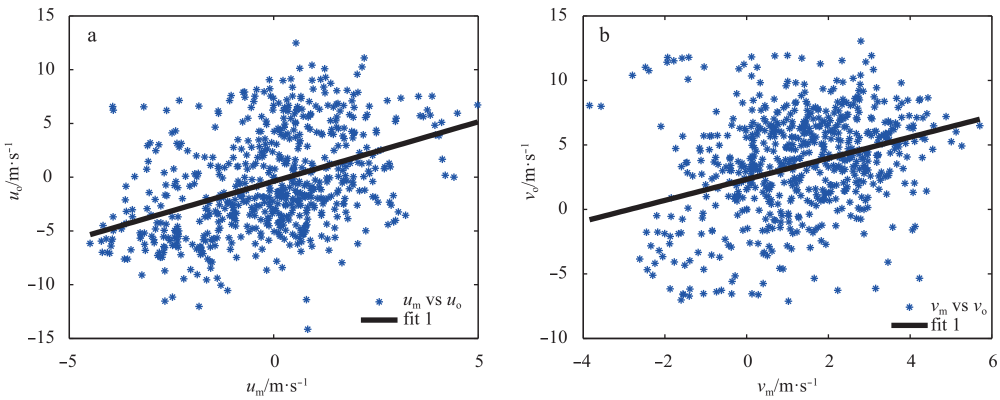

Fig. 4. Linear fitting of model result and observation (u_m and v_m are eastward and northward components of wind speed from model, respectively, and u_o and v_o are eastward and northward components of the wind speed from observation).

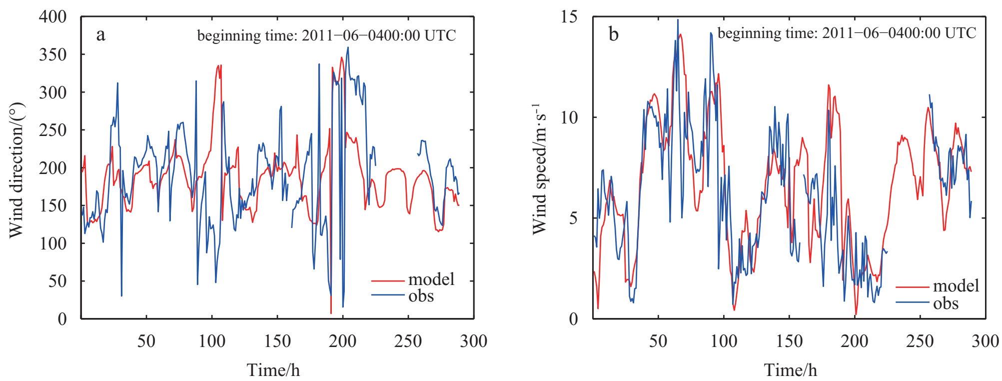

Fig. 5. Comparison of wind final analysis data (corrected wind) and observation wind.

w_0 is the vertical velocity of the oil particles. The first terms on the right hand side of Eqs (2)–(4) represent the impacts of the ocean current on the oil particle, which derived from the ocean model. u_c and v_c are the horizontal components of current and w_c is the vertical component of current. The second terms on the right hand side of Eqs (2) and (3) represent the wind drift effects on the oil particles u_{10} and v_{10} are the wind velocities at 10 m above the sea surface. α means the coefficient of the wind drift and β is the deviation angle. According to the suggestion of Li et al. (2013a, b), α=0.02 and β=0 was chosen in this paper. u_w and v_w are the velocities due to nonlinear waves. It can be ignored as the nonlinear effect can be weakened when oil slick covers the sea surface, which increases the surface tension and the smoothness. w_{ok} is the vertical velocity due to buoyancy of the oil particles, which is given by the Stokes law:

$$\begin{cases} w_{ok} = \dfrac{gd^2(1-\rho_0/\rho_w)}{18\nu} & (d \leqslant d_c), \\ w_{ok} = \sqrt{\dfrac{8}{3}gd(1-\rho_0/\rho_w)} & (d > d_c), \end{cases} \tag{5}$$

$$d_c = \frac{9.52\nu^{2/3}}{g^{1/3}(1-\rho_0/\rho_w)^{1/3}}, \tag{6}$$

where d is the diameter of oil particle and d_c is the critical diameter; ν=1.31 mm^3/s, is the seawater viscosity; g is the gravity; ρ_0=830 kg/m^3 and ρ_0=1 025 kg/m^3, are oil and seawater density, respectively.

The turbulent velocities (u', v', w') can be calculated with a random walk technology:

$$u' = \xi\sqrt{c'A_h/\Delta t}\cos(2\pi\xi), \tag{7}$$

$$v' = \xi\sqrt{c'A_h/\Delta t}\sin(2\pi\xi), \tag{8}$$

$$w' = \xi\sqrt{c'K_v/\Delta t}, \tag{9}$$

where ξ is the standard Gaussian white noise with unit intensity and null mean; A_h is the horizontal diffusion; K_v is the vertical diffusion; Δt is the time step; and c' is a constant. The horizontal diffusion is regarded as Fick diffusion, and take k_{ve} (vertical eddy viscosity) as K_v. The vertical eddy viscosity is semi empirically coefficient derived from the Reynolds stresses due to surface waves (Ichiye, 1967):

$$k_{ve} = 0.028\frac{H_s^2}{T}e^{-2\kappa z}, \tag{10}$$

where H_s is the significant wave height; κ is the wave number; T is the average period; and z is the depth where the oil particle is located.

2.4 *The parameter of oil spill model*

The first oil spill occurred at Penglai 19-3B oil platform (Fig. 3) on June 4, 2011 and was controlled on June 16. Another oil spill occurred at the other platform Penglai 19-3C (Fig. 3) on June 17, 2011 and was in control on June 19. From July 15, some spilled oil was observed near two oil platform successively, but it was not included in model because of quick response. The duration of crude oil released is 13 d (4–16) and 3 d (17–19) when simulating the Penglai 19-3B case and Penglai 19-3C case, respectively. The model was run from June 4 and June 17 to August 31, respectively (Table 1).

Table 1. Information on the two simulations performed in the present study

Oil platform	Period	Duration/d	Amount released/tons
Penglai 19-3B	4 Jun. to 31 Aug.	13	200
Penglai 19-3C	17 Jun. to 31 Aug.	3	200

Considering the inaccuracy of spilled location, all oil particles were initially distributed randomly in two circles cantered at Penglai 19-3B and Penglai 19-3C with radius of 25 m. We assume the total mass of spilled oil to be 200 t and the density to be 830 kg/m^3. Fifty oil particles were released every10 min.

3 The hindcast analysis

The hindcast analysis, shown in Figs 6–8, indicated that the oil from two platforms B and C moves to the northwest of the oil platform, where the Bohai Bay, and the Liaodong Bay were affected successively. The influenced sea area is about 7 800 km^2 including most of the Bohai Bay, the Laizhou Bay and the Bohai Strait. The affected area is located in the northwest of the Bohai Sea, including coastal cities (Qinhuangdao, Leting, Changli, Dongdaihe) of Hebei Province and Liaoning Province. The total beached length is about 160 km as shown in the red color along coast of Fig. 8.

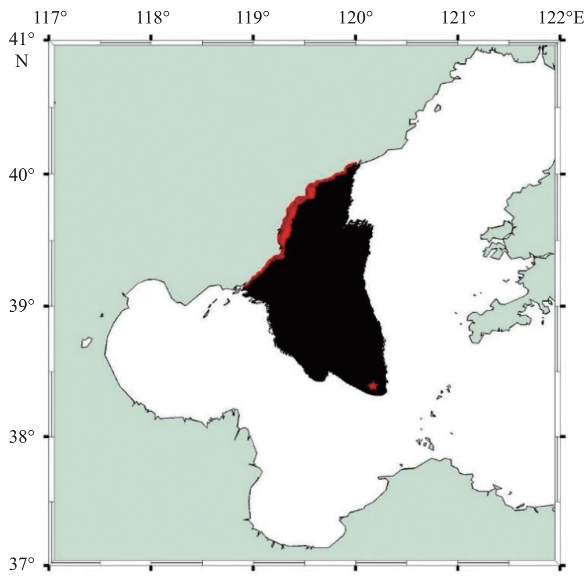

Fig. 6. The swept area of hindcast from the Penglai 19-3B.

The hindcast results indicated that the spilled oil first arrives shoreline on June 29 near Tangshan and then reaches to the Dongdaihe Coast on July 11. It was consistent with the findings from oil fingerprinting identification of spilled oil from the Penglai 19-3 platform. The place where the oil beached is consistent with the one reported, but the model gave an earlier date than actual one. The time when the two separated oil spill beached the shoreline is different in the hindcast analysis. Oil from 19-3B arrived Tangshan on June 29 and reached to Dong-

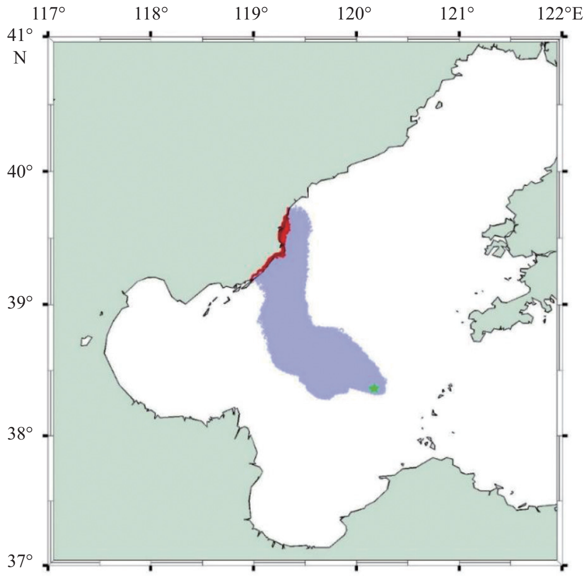

Fig. 7. The swept area of hindcast from the Penglai 19-3C.

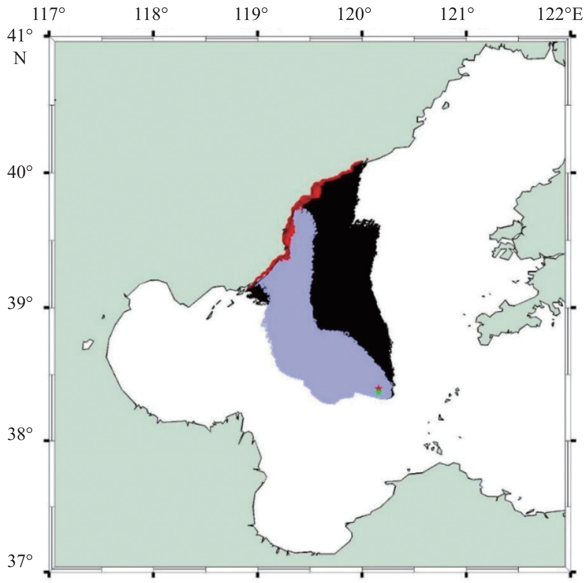

Fig. 8. The swept area of hindcast (the black is the swept area released from the Penglai 19-3B and the purple is the swept area released from the Penglai 19-3C).

daihe 12 d later (July 11). Oil from 19-3C arrived at Tangshan coast before July 9. At the end of the simulation period, i.e., on August 9, almost all oil reached to the coast. Although the convection direction of oil spilled from two platforms are same, the swept area and effected coastline are different. Oil spilled from 19-3B drifted further to the north and effected longer coastline and larger sea area than oil spilled from 19-3C (Figs 6 and 7).

Figure 9 shows the polluted region reported in the China Marine Environment Quality Bulletin from June to August in 2011. It is mapped using monitoring data which distributed in the Bohai Sea. The area in dark brown represents that the water is polluted heavily, and it mainly scatters around the oil platform and some appears in the northwest of the platform. The area in yellow represents the slightly polluted water, which is located in

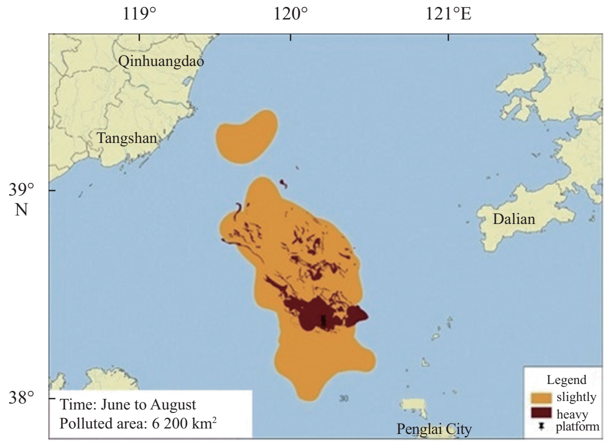

Fig. 9. Observation from the China Marine Environment Quality Bulletin (2011).

the northwest of the platform.

Comparing the simulated swept area in Fig. 8 with the observations in Fig. 9, it is found as follows: the pattern of two regions is very similar; the direction and extent of oil transport are the same; the direction of oil convection is northwest of the Penglai 19-3 the platforms in the simulation; but there is oil slick observed travelling to the south of platforms, which is not reflected in the hindcast results. The simulated polluted region is 7 800 km^2, which is larger than observed 6 200 km^2. Because there is not enough monitoring sites in the Bohai Sea to observe oil pollution, the model result is always larger than the observation.

Some of early predictions may be in error due to the lack of observational data (Proctor et al., 1994). We can conclude the hindcast result is in accord with the observation. And the long-term hindcast simulation could reproduce the transport of spilled oil in reality. Thus the NMEFC's oil spill model could provide a tool in an environmental impact assessment after the event.

4 Conclusions

In this paper, a long-term hindcast simulation for the Bohai oil spill accident in 2011 is carried out to study the behaviour and fate of the spilled oil in the marine environment. The wind field plays an important role in trajectory modeling, thus linear fitting is adopted to correct the wind data. It is a key factor to force the oil spill mode with the corrected wind and current in order to reproduce the oil distribution. The long-term hindcast simulation produced a polluted sea area of about 7 800 km^2 and polluted coast of about 160 km. Owing to the lack of monitoring, the polluted area is larger than the observation and the contaminated coastline where concentrated more than 50% poulation of province (Yang et al., 2012) is also not reflected in the observation. But the long-term hindcast simulation provied the polluted sea area, the contaminated coastline, the time of oil beached, especialy for serious oil spill accident.

Long time predictions may be in error due to the accumlation error of a numerical integration during a model calculation and it can not represent the real scene of oil spill. The long-term hindcast which assimilated observation data can reduce the modeling error.

In general, the long-term hindcast simulation proposed in this paper could provide scientific bases for government in the environmental impact assessment after the event. It is concluded that the hindcast result is consistent with the observation.

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