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The long-term prediction of the oil-contaminated water from the *Sanchi* collision in the East China Sea

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Abstract

The condensate and bunker oil leaked from the *Sanchi* collision would cause a persistent impact on marine ecosystems in the surrounding areas. The long-term prediction for the distribution of the oil-polluted water and the information for the most affected regions would provide valuable information for the oceanic environment protection and pollution assessment. Based on the operational forecast system developed by the First Institute of Oceanography, State Oceanic Administration, we precisely predicted the drifting path of the oil tanker *Sanchi* after its collision. Trajectories of virtual oil particles show that the oil leaked from the *Sanchi* after it sank is mainly transported to the northeastern part of the sink location, and quickly goes to the open ocean along with the Kuroshio. Risk probability analysis based on the outcomes from the operational forecast system for years 2009 to 2017 shows that the most affected area is at the northeast of the sink location.

Key words: *Sanchi* collision, long-term prediction, oil spill

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1 Introduction

The oil tanker *Sanchi*, which carried a full natural-gas condensate cargo of 136 thousand metric tons from public report and renewed as 111.3 thousand metric tons on 22 January 2018 by the Ministry of Transport of the People's Republic of China, collided with the Hong Kong-flagged cargo ship *CF Crystal* at (30°42′N, 124°56′E) in the East China Sea (ECS) on 6 January 2018. Eight days later, the oil tanker sank at the location (28°22′N, 125°55′E) that about 151 nautical miles away from the collision site on 14 January. About 1 900 t of the *Sanchi*'s own fuel oil (bunker oil) and unknown amount of condensate sank along with the *Sanchi*.

The fate of these two kinds of oil brings a great challenge for the ocean environment, especially for the marine ecosystems and fisheries with large contaminated areas (Peterson et al., 2003; Alonso-Alvarez et al., 2007). The leaked oil can even affect the wind stress and then ocean surface wave and current systems (Cox et al., 2017). As the density of condensate is lower than that of sea water, and the condensate can also dissolve in water, so if no salvage by human beings, the fate of the condensate leaked from the *Sanchi* will (1) go to sea surface due to low density, and then evaporate into the atmosphere; (2) be dissolved in sea water and transported by ocean circulation; (3) expand through food web, and even affect the fishes; (4) be absorbed by various particles such as sands, chlorophyll, phytoplankton, zooplankton, etc., and finally go to sea bed as sediment contaminations. For the environment protection and pollution assessment, the prediction of the oil-contaminated area is crying needed.

The Lagrangian particle tacking method is widely used in the marine oil spill tracing in recent years (Toz and Koseoglu, 2018). In terms of the method, spilled oil is discrete into large amount of oil particles and each particle represents certain mass of oil, which will be drifted by its ambient physical environment such as the ocean current and wind (Wang et al., 2008). To predict the trajectories of the oil-contaminated water, a precise current field is strongly needed.

The oceanic surface wave-tide-circulation coupled forecasting system (OFS) developed by the First Institute of Oceanography, State Oceanic Administration (SOA), China (Wang et al., 2016; Xiao et al., 2016) has been operationally run since November 2007. Based on the OFS, the spread of nuclear radiation from the damaged Fukushima Nuclear Power Plant has been successfully predicted (Qiao et al., 2011a) and the macroalgae drift characteristics in the Yellow Sea has been clearly stated (Qiao et al.,

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2011b).

In this study, based on the OFS, we firstly simulate the 8 d trajectory of the drifted *Sanchi* after its collision to validate the prediction capability of OFS. Then we give an accumulative distribution of the virtual oil particles for 60 d. Finally, the risk probability distribution of the accumulative oil-contaminated water for years from 2009 to 2017 is presented.

2 Methodology

2.1 *Ocean model and particle tracking algorithm*

The regional (15°–41°N, 105°–135°E) and global operational real-time prediction systems (OFS) are used to provide the current field, which are developed by the First Instituted of Oceanography, SOA, China. The regional circulation model is based on the Princeton Ocean Model while the global model is based on MOM5 (Griffies et al., 2004). Previous operational validation has shown the accuracy and the advancement of the OFS (Wang et al., 2016; Xiao et al., 2016).

The condensate leaked from the sank *Sanchi* (115 m depth under water) will take about 20 min from the bottom to the sea surface. Due to the fast floating speed of condensate, we only consider the horizontal movement of oil particles both from the dissolved condensate and bunker oil at the surface layer as the first step. The Lagrangian particle tracking method is used to track the oil's displacement with a time step of 1 h. The OFS archived ocean current with interval of 3-h is linearly interpolated into 1-h interval for the prediction of oil particles.

2.2 *Accumulative Lagrangian probability-density functions*

Due to the complexity of the current system around the sink area (Guo et al., 2006), the final fate of the leaked oil may exhibit different patterns. It is hard to give accurate predictions of the atmospheric forcing for two months. Due to the annual variabilities in ocean currents, we used the monthly mean ocean currents from 2009 to 2017 in this study. For a robust risk assessment, we define the accumulative Lagrangian probability-density functions (APDFs) to evaluate the risk of the oil pollution. The APDFs indicates the accumulative probability that particles released from a certain site can arrive or pass through the area during a time span. It is developed based on the Lagrangian probability-density functions (Mitarai et al., 2009). The APDFs at position a and time T is determined as

$$\int_0^T f_X(\xi;\tau,a)d\tau \approx \frac{1}{\pi R^2}\int_0^T\int_0^R f'(\xi;\tau,a+r)\mathrm{d}r\mathrm{d}\tau, \qquad (1)$$

where T is the time duration from the sink time to the specified date, f_X is the PDF and f'_X is the discrete representation of Lagrangian PDFs:

$$f'_X(\xi;\tau,a)=\frac{1}{N}\sum\delta(X_n(\tau,a)-\xi), \qquad (2)$$

where N is the total number of particles released at the sink area of the *Sanchi*, δ is Dirac delta function and ξ is the sample space variable for X.

Three numerical experiments are designed for the fate of oil particles leaked from the *Sanchi*. In the first experiment, 8 d of *Sanchi*'s drift from the collision to the sank is simulated using the real-time forecast product. For the second one, we use the real-time forecast result from 6 to 21 January 2018 to predict trajectories of oil particles for the first half month to reach the accurate spread areas. After that, the current field from 22 January to 6 May 2017 was used for the prediction of the next 45 d. When the particles reach the boundary of the regional model, the outcomes of the global model was used subsequently. To assess the risk probability of the oil-polluted water at the surrounding seas, nine years (2009–2017) releasing experiment is simultaneously implemented.

3 Results and discussion

The previous oil-spill accidents usually occurred at regions with gentle current systems. The dispersion and advection of the oil-polluted water is slowly and the affected zones are relatively concentrated. Unfortunately, the current at the the *Sanchi*'s sank location is extremely complex, with the strong currents and eddies (Guo et al., 2006), so the spilled oil and contaminated water may be quickly transported in large distance. Figure 1 shows the mean ocean surface current field in January 2017 from the OFS. It is clear that the sink location of the *Sanchi* is very close to the western boundary of the Kuroshio, the strongest western boundary in the North Pacific with the maximum current speed larger than 1.0 m/s. Moreover, the Tsushima Current is also evident in this region, which may influence the final destination of the leaked oil.

3.1 *Simulation of the Sanchi's drifting route*

For an accurate prediction of the distribution of the oil particles spill from the drifted collided tanker, precise prediction of the tanker's drifting route can serve as a challenging validation. For the wrecked cargo, its motion is mainly forced by the ocean surface currents and wind. The wind exerts its impact on both speed and angle of movement, i.e., leeway drift and leeway angle (Allen, 2005). Based on the actual trace of the *Sanchi* in the first two days, we calibrated the value of leeway to be 5% of wind speed and leeway angle to be 26° to the right of the downwind direction. Both of the two parameters are in the reasonable value range for the drifted cargo (Ou, 2008). From 8 to 14 January, we predicted the drifting trajectory of the *Sanchi* using the same two parameters. It is obvious that the predicted drift path is almost consistent with the real drifting route, except that at the last day (Fig. 2).

3.2 *The long-term prediction of oil-polluted water after the Sanchi sank*

The 60 d's prediction (Fig. 3) shows that majority of the oil particles would be transported to northeast of the sink location, which is consistent with the real-time observations. Most of the virtual oil particles will be trapped by the Kuroshio. Except that, small portion of oil particles maintain in the East China Sea and may enter the Yellow Sea, of which the oil was mainly leaked from the ship before the sank. Fifty days later, the distribution of the oil will be extended due to the strong and massive eddies in the area of the Kuroshio extension. Both two routes are in coincidence with the important spawning grounds and the migration routes of the commercial fishes (Sassa and Hirota, 2013; Sassa and Konishi, 2015), such as the Japanese sardine and chub mackerel spawn ground from January to March. The oil pollution may have huge damage to the survival environment of the marine fisheries, and more research on this topic is highly needed.

3.3 *Risk probability analysis*

We tracked two months of the particles' trajectories from 14 January for each year from 2009 to 2017 with the virtual oil particles continuously released for two months from the sink location. The oil particles distribution of nine years can be classified

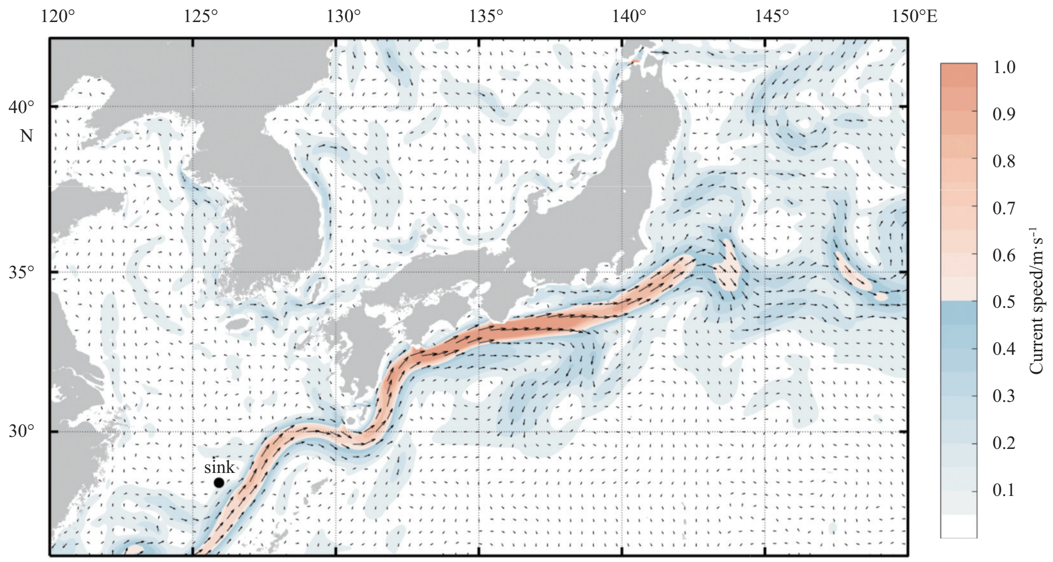

Fig. 1. Monthly averaged surface currents field in the northwest Pacific Ocean from 1 to 31 January 2017 from OFS. Color represents the magnitude of current speed, and arrows indicate the current direction.

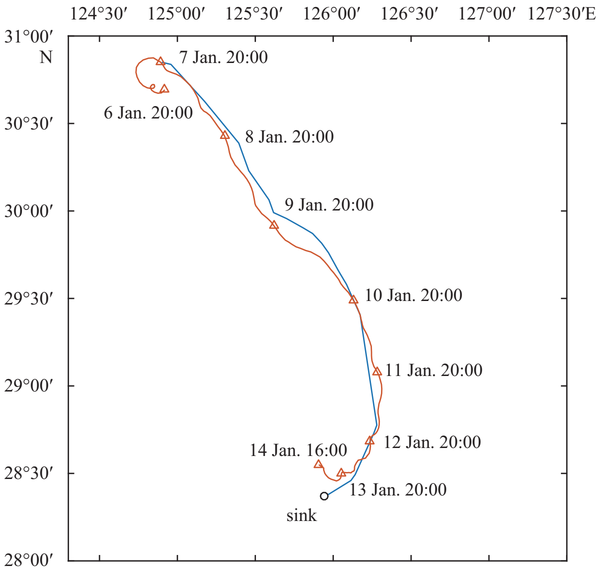

Fig. 2. The real (blue) and predicted (red) trajectories of the drifted *Sanchi* from the collision to sink.

into three classes: for years from 2009 to 2011, oil particles tended to enter the Tsushima Strait; while for years 2012 to 2014, the high risk affected area can even enter the Yellow Sea; for the third situation, majority of the spilled oil quickly entered into the northwest Pacific Ocean along with the Kuroshio for years 2015 to 2017. Based on above three classifications, APDFs for every three years are calculated (Fig. 4). High value in red means high risk probability of oil contamination in this region. From Fig. 4 we can conclude that particles go through the sink location are more likely to go to the open ocean along the Kuroshio in recent years (2015 to 2017). Although the the final destination of the oil particles is different at three classifications, the northeastern part of the sink location is always in high risk.

4 Summary

In this study, we predict the drifting path of the *Sanchi* after its collision based on the real-time forecast product of the OFS. The simulated drifting trajectory agrees well with the real drift route of the *Sanchi*, verifying the robust of the forecast system. The 60 d's prediction of accumulative distribution of the virtual oil particles shows that the leaked oil mainly trapped by the Kuroshio and the Kuroshio extension in two months, while small part of them go toward the Tsushima Strait. The nine-year statistical analysis indicates that the high risk area locates in the northeastern part of the sink location, although the final destination of the spilled oil is different at different years.

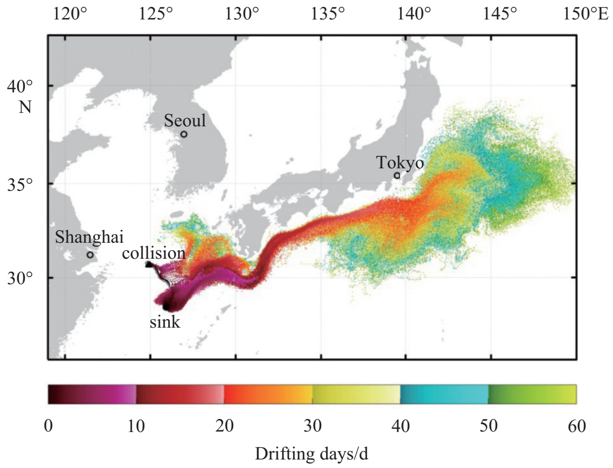

Fig. 3. Accumulative distributions of virtual oil particles leaking from the *Sanchi* 60 d after the collision. Oil was assumed to be leaking along with the drifting tanker continuously. Colors represent the drifting days of the virtual oil particles.

The leaked oil particles will be driven by physical processes (the wind, surface waves, ocean current, etc.) and chemical processes (the volatilization, decomposition, and emulsification, etc.), so the fate of the spilled oil will be quite uncertain. The ocean turbulence and the wind effects put uncertainties on long-term predictions and thus affect the trajectories of the oil particles. Besides, the prediction results reported here are de-

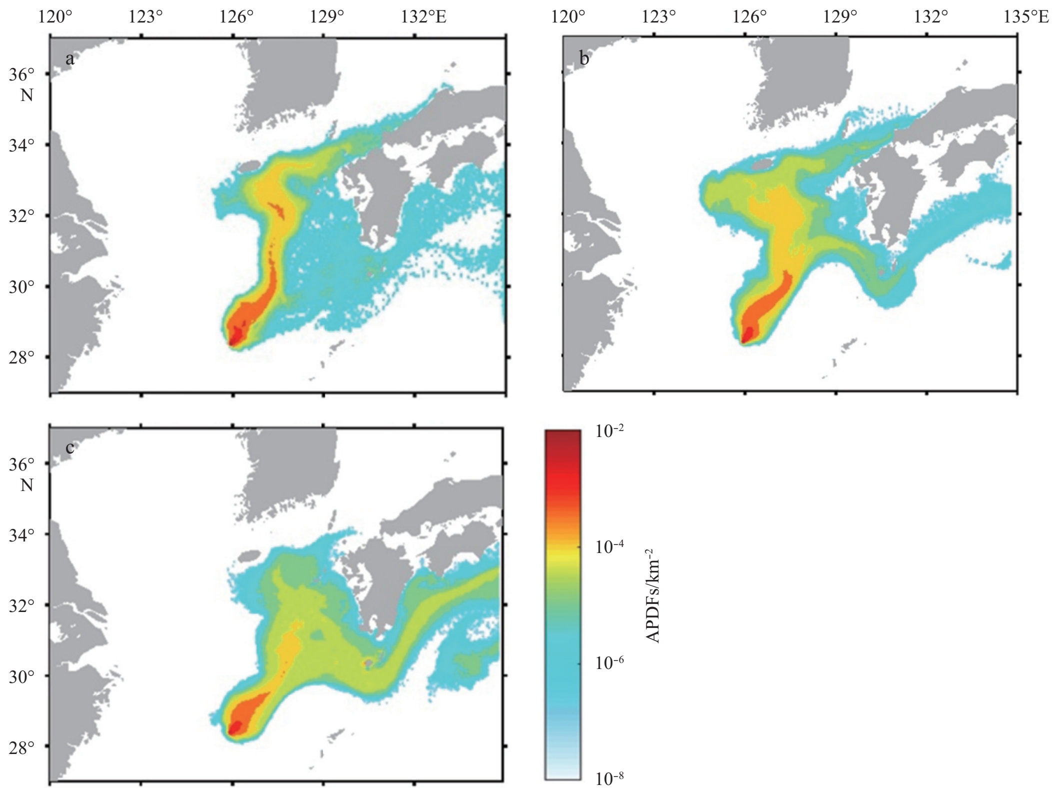

Fig. 4. Accumulative Lagrangian probability-density functions (APDFs) for three classifications: 2009 to 2011 (a), 2012 to 2014 (b), and 2015 to 2017 (c). Colors represent the APDFs of the sink location for integral time of 60 d from 14 January of each three years.

rived only from OFS. For operational uses, it would be better to develop ensemble forecasts using multiple models because of the randomness and uncertainty of marine-atmospheric boundary layer processes. In this research, we predict the probable dispersion area from a physical perspective as the first try. Further study including the chemical processes is needed for the precise prediction of the oil fate from the *Sanchi*.

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