Numerical Study of Oil Spilled Behavior under Ice–Covered Area in the East Siberian Sea

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ABSTRACT

The Recent demands of commercial shipping through the Arctic and exploit of natural resources increase the risk of an oil spill in the Arctic Ocean. State-of-the-art modeling techniques are necessary for prevention measures and oil response and determine the fate and effect of oil in the environments. So we developed a numerical simulation model for spilled oil forecasting under ice-covered areas. This simulation model can perform high-resolution computations at low computational cost. Numerical model results of oil spreading over open water, under fully ice-covered water, and under a broken ice field are agreed reasonably well with the previous experimental results. Results of oil spilled behavior under the ice-covered area in the East Siberian Sea have shown the possibility of establishing an accurate and practical forecast system for oil spreading under a marginal ice covers.

KEY WORDS: Oil spill; Ice cover; Numerical modeling of oil.

INTRODUCTION

The retreat of summer sea ice in the Arctic Ocean continues to attract interest in exploring Arctic areas in order to locate and exploit natural resources and to establish shorter commercial shipping routes. Increasing those activities in the Arctic have increased the risk of oil spill accidents in ice-covered areas. If oil spill accident happens in this area, it could impact the marine eco systems and regional economy of coastal areas.

Oil spill behavior is depending on two main processers. First process is weathering, the physical and chemical properties of the oil is changed due to the environmental conditions (eg. evaporation and emulsification)(Díez *et al.*, 2007; Boehm *et al.*, 2008). Second process is movement of oil in the environment (eg. Wind and ocean currents, sea ice conditions)(French-McCay, 2004). Weathering and movement process can also overlap on each other.

Many researchers have studied the spreading of oil spill in open water and many numerical models have been introduced to simulate the process(Fay, 1971; Fannelop and Waldman, 1972). In general, numerical prediction of oil spill spreading under the ice-covered water is more complex than the open water spreading. Therefore, research on oil spreading under ice-covered water has been very limited.

However, when oil spill accident happens in ice-covered area, the ability to predict oil spreading is important in assisting cleanup operation, evaluating the degree of environmental impact and spills prevention planning. Therefore, high accurate modeling technique is necessary for predict the oil spill behavior in order to spill preventions and spill responses.

Yapa and Chowdhury (1990) introduced the theoretical equations, based on Navier-Stokes equations, for spreading of oil under the ice. Izumiyama *et al.* (1998) improved the Yapa and Chowdhury (1990) oil spreading theory by introducing the net interfacial tension. Izumiyama *et al.* (2002) validated their previous results by conducting series of experiments. Those results are very important for numerical modeling.

In 2006, Engineering Advancement Association of Japan conducted the three-year research program to develop a prototype model for numerical prediction of spilled oil diffusion and advection in the Sea of Okhotsk (Terashima, 2003; Rheem and Yamaguchi, 2004; Hara, et al., 2008). In this study we used the same oil spill simulation model to predict the oil trajectories, weathering of oil spill and also simulate the variety of scenarios for the oil spill in the East Siberian Sea using different ensembles to create the hazards map. We also validated the numerical simulation under the ice-coved area comparing with the laboratory experiment data.

MODEL DESCRIPTION

Oil spill model used in this study is based on the model developed by Terashima (2003) and Rheem and Yamaguchi (2004). Vertical diffusion of oil on ice-covered area is defined on four stages as shown in Figure 1.

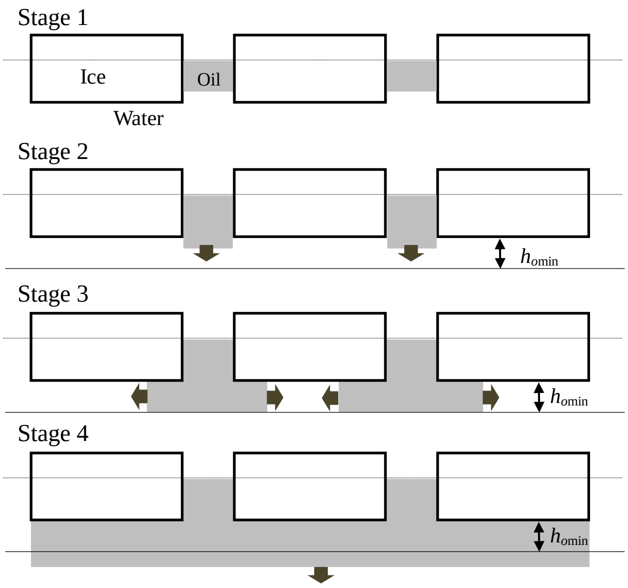

Figure 1. Schematic diagram of vertical spreading of oil under ice-covered water. h_{omin} is the minimum oil thickness for spreading under ice define in Eq.(1).

In the stage 1, spilled oil spreads horizontally through the gaps between ice floes. After stage 1, if oil contacts with land or surrounded by dense sea ice, spilled oil is thickened until the oil thickness below the ice bottom and until the minimum oil thickness (Mackay, Medir and Thornton, 1976)(Mackay et al., 1976) for spreading under ice (h_{omin}), which we call the stage

2. The minimum oil thickness for spreading under ice is defined by Eq.(1)

$$h_{o\min} = \sqrt{\frac{2\sigma_{o-i-w}}{g(\rho_w - \rho_o)}} \quad (1)$$

where, σ_{o-i-w} denote surface tension between ice, water and oil. g is a gravitational acceleration and ρ_w, ρ_o denotes the density of water and oil respectively. If oil further thickened and reaches the minimum oil thickness level, oil starts spreading horizontally under the ice in stage 3 while maintaining a constant thickness (h_{omin}). In stage 3 surface tension forces between ice, water and oil dominate the gravity force. In final stage (stage 4), when the oil spread whole sea ice bottom, then oil begins to further thickening due to the supply of oil.

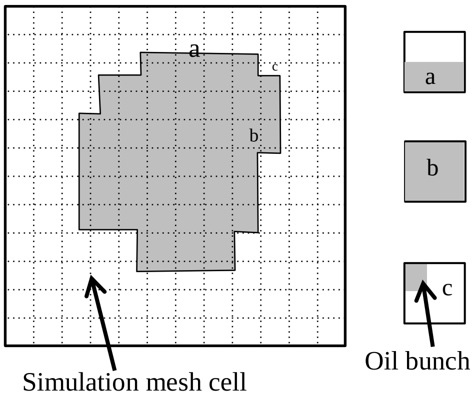

Figure 2. Simulation mesh and oil bunch locations

To improve the ability of the oil spill model to locate the oil edges accurately, we implemented the Eulerian–Lagrangian method for advection (Rheem et al., 1997) of the oil spill (the so-called subgrid-scale oil motion). First, we solve the momentum equation in a Eulerian grid, and then we solve the oil conservation laws in a Lagrangian grid. Spilled oil is simplified to one rectangular oil bunch at each simulation mesh as shown in Figure 2.

On the other hand, the ice field is represented by rectangular floe particles (side length D) with a given thickness and bundle to the rectangular bunches on top of the oil bunch as shown in Figure 3. We assumed ice floes are homogenously distributed among the cells and distance between two ice floes is l and number of ice floes in X direction is *nx* and Y direction *ny*. Sea ice concentration (*A*) can be written by the Eq.(2)

$$A = \frac{(Dnx)(Dny)}{bxdx \times bydy} \quad (2)$$

where, *bx* and *by* are oil bunch locations (varied from 0-1). *dx* and *dy* are cell size. Eq.(3) and 4 show the number of ice floes in X and Y directions.

$$nx = \frac{\sqrt{A}bxdx}{D} \quad (3)$$

$$ny = \frac{\sqrt{A}bydy}{D} \quad (4)$$

Eq.(5) shows the distance between two ice floes

$$l = \frac{\left(1 - \sqrt{A}\right)D}{\sqrt{A}} \quad (5)$$

In each Eulerian grid cell facers, the momentum equation (Eq.(6)) is solved for diffusion oil velocities.

$$m_o\left[\frac{\partial \overline{u}_o}{\partial t} + f\overline{k} \times \overline{u}_o\right] = \overline{F}_p + \overline{F}_f + \overline{F}_m + \overline{F}_{st} \quad (6)$$

where m_o is oil mass, u_o is oil velocity, f is Coriolis parameter, k unit vector in vertical direction and F_p, F_f, F_m, F_{st} are pressure force, frictional force, added mass force and surface tension force respectively. Over bar denotes the vectors.

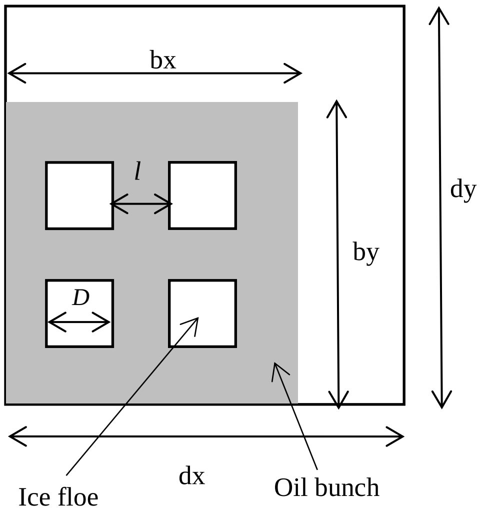

Figure 3. Simulation mesh, ice floe distribution and oil bunch location. Where dx, dy are cell size and bx, by are oil bunch size. D is length of rectangular ice floe size and l is distance between two ice floes

The external forces change in different sea surface conditions. When oil spills on sea surface where is no sea ice, forces acting on oil at the direction of diffusion are the surface tension, pressure force from gravity. The forces acting on oil at the direction of anti-diffusion are force of friction on sea current and forces by added mass as shown in Figure 4(a). On the other hand, when oil spills under sea ice, the force acting on oil at the direction of diffusion is only the pressure force from gravity, and the forces acting on oil at the direction of anti-diffusion are the surface tension, the forces by added mass, and the frictional force on sea ice and sea current as shown in Figure 4(b).

After calculating the cell each cell face velocities, each Eulerian cell oil bunch is advected in space creating new configurations. Finally, a new oil state is obtained for the Eulerian grid by summing and redistributing the advected configurations. More details about redistribution can be find in (Rheem et al., 1997).

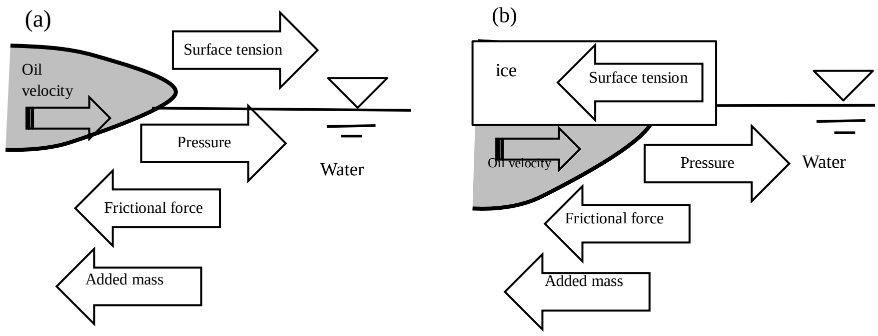

Figure 4. External forcers on oil (a) On water surface (b) under sea ice

ACCURACY VERIFICATION OF OIL SPILL DIFFUSION MODEL

In this section, oil spill experiments conducted in the past with different sea ice concentrations are compared with the oil spill numerical model. Three patterns of spilled oil diffusion radius were computed. First, spilled oil radius on open water this experiment is conducted by Yamaguchi, (2006). Second, spilled oil on fully ice covered (100% sea ice concentration) area experiment conducted by Izumiyama et al., (2002). Third, spilled oil under partially ice covered (sea ice concentration 65%) surface with the effect of ice floe motion experiment conducted by Gjosteen and Loset,(2002). In each experiment physical properties of the oil and experimental conditions are shown in Table 1.

Table 1. Experimental and calculation conditions of oil spill accuracy verifications

Experiment	Open water	Fully ice covered	Partially ice covered
Oil name	Idemitsu Dafny #32	Lubrication oil	IFO 30 bunker oil
Density [kg/m^3]	863	890	938.63
Water temperature [^{o}C]	12	-2	-2
Viscosity [Pa s]	1.1×10^{-1}	1.23×10^{-1}	6.87×10^{-1}
Oil-water surface tension [N/m]	1×10^{-2}	2.56×10^{-2}	2.32×10^{-2}
Spilled oil volume [m^3]	1.0725×10^{-3}	16.32×10^{-3}	9.8×10^{-3}
Oil spilled time [s]	205.6	600	57
Sea ice concentration	-	100%	65%
Sea ice thickness [m]	-	0.01	0.038
Ice bottom	-	Flat	Flat
Sea ice rotational velocity [rad/s]	-	-	0.003
Time step Δt [s]	0.1	0.1	0.1
Grid resolution [m]	0.03	0.03	0.04
The number of grids	100×100	100×100	100×100

Accuracy Verification of Oil Diffusion Model in Open Water Surface

The oil spill experiment on open water is carried out in the Institute of Industrial Science, University of Tokyo, tsunami and storm surge water tank by Yamaguchi,(2007). Physical properties of the oil and experimental conditions are shown in Table 1. Figure 5 shows the comparison of the diffusion radius of the oil obtained in the experiment (blue dots) and numerical model (black line). Present numerical model shows good agreement with experimental results.

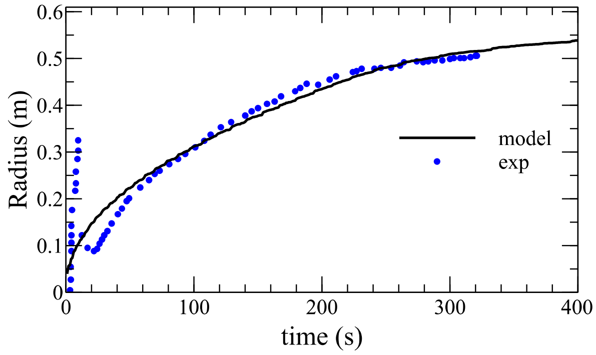

Figure 5. Accuracy verification of oil diffusion radius in open water. Blue dots denote the experimental results and black line denotes the numerical results.

Accuracy Verification of Oil Diffusion Model under Fully Ice Covered Surface

The oil spill experiment in the fully ice covered surface is carried out in the ice tank of National Maritime Research Institute, Japan by Izumiyama et al., (2002). The test was performed for level ice sheets with flat bottom and without the ice sheet movement. Physical properties of the oil and experimental conditions are shown in Table 1.

Figure 6 shows the comparison of diffusion oil slick radius of the experimental results and numerical model results. Distribution of oil radius with respect to the time shows the similar pattern compared with experiment and simulations. However, model over predict the radius about 0.05m.

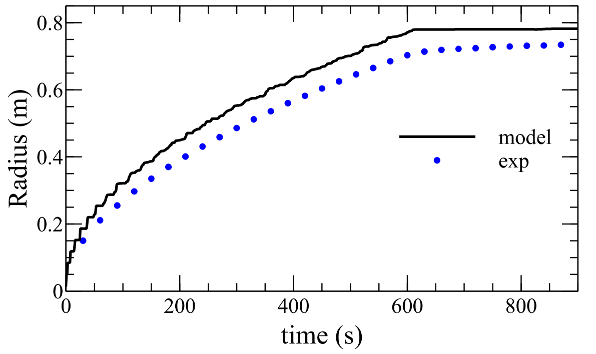

Figure 6. Accuracy verification of oil diffusion radius under the fully ice covered surface. Blue dots denote the experimental results and black line denotes the numerical results.

Accuracy Verification of Oil Diffusion Model under Partially Ice Covered Surface

Gjosteen and Loset,(2002) conducted the laboratory experiment of oil spill under the broken ice field at the Hamburgische Schiffbau Versuchsanstalt ice tank. Oil spreading and ice floe motion were monitored by video cameras. The results they have obtained are very useful for validate the oil spreading model under the influence of ice flow dynamics. Physical properties of the oil and experimental conditions are shown in Table 1.

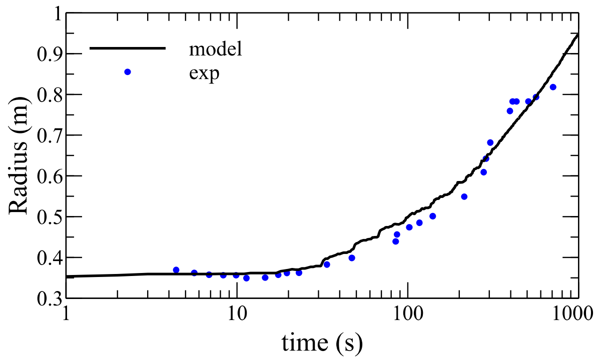

Figure 7. Accuracy verification of oil diffusion radius under partially ice-covered surface. Blue dots denote the experimental results and black line denotes the numerical results.

Figure 7 shows the comparison of oil diffusion radius between experimental results of (Gjosteen and Loset, 2002) and numerical model results. Numerical model has reproduced the experimental results reasonably. In this experiment ice floes had a clockwise, circular motion. These ice floe motions exert th e drag force on the oil and enhance the spreading further. In this experiment oil is place near the center of the domain and constantly spilled the oil for 57s.

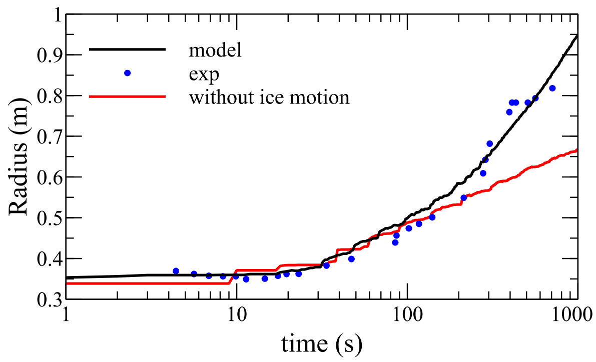

Figure 8. Accuracy verification of oil diffusion radius under partially ice-covered surface with and without ice motion. Blue dots denote the experimental results and black line denotes the numerical result with ice motion and read line denotes the numerical results without ice motion.

Short time after the injection was completed, ice cover was brought in to motion. At first oil is spread horizontally along the ice floes and very slowly spreading on vertical direction. After the oil thickness reach into the sea ice thickness oil begins to spread under the ice floes while receiving frictional force from ice bottom. Our model is able to reproduce those treads accurately. We also tried the effect of ice motion on oil spill simulation. Figure 8 shows the numerical results with and without ice rotational motion. Before the 200s both with and without rotational cases oil is spreading in similar radius. But after 200s with ice rotational experiment accelerate the oil spreading exponentially compared to the without rotational experiment.

COMPUTATION OF SPILLED OIL BEHAVIOR IN THE EAST SIBERIAN SEA

We carried out a numerical computation of sea ice and spilled oil behavior in the East Siberian Sea. Initial sea ice distribution and ocean conditions are given by high-resolution computation of ice-POM model (De Silva, Yamaguchi and Ono, 2015). It is assumed that the oil spilled at a rate of 2 m^3/s for 3000 seconds. Oil density is 890 kg/m^3 and viscosity 0.123 Pa s. Oil is spilled at the south of the Novaya Sibir island on 2015 July. Figure 9 shows the ice and oil distribution on initial 3,7 and 10 days later. It is demonstrated that the oil spilled near the East Siberian Sea can reach the coastal areas of the Novaya Sibir islands within few days.

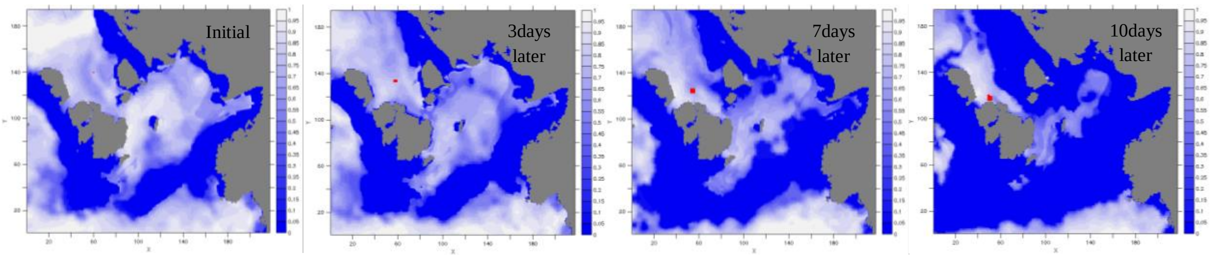

Figure 9. Sea ice distribution and oil spilled behavior in the first 10 days of computation in 2015 July. Red area shows the spilled oil in the computational grid

10-days and 15-days computations similar to the Figure 9 are made with the same oil spill conditions in July 2015.

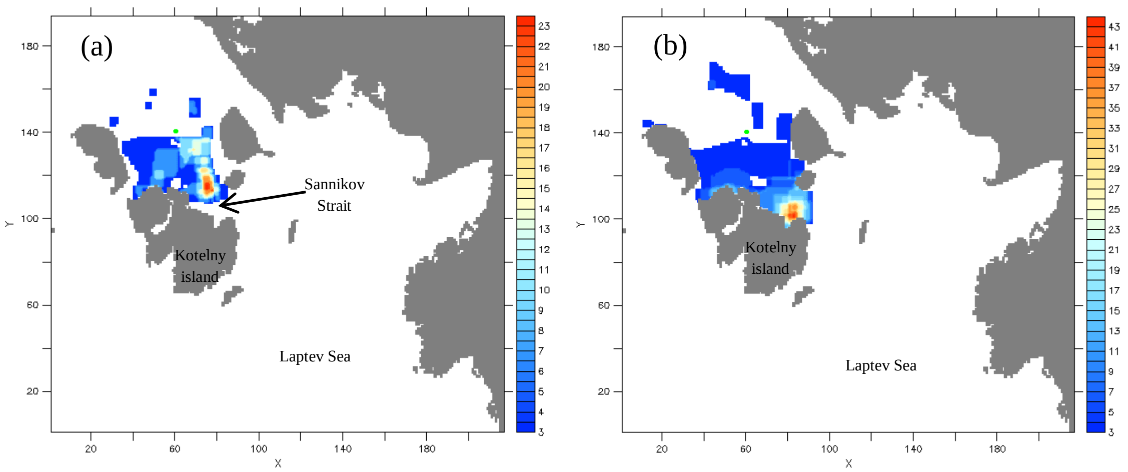

Figure 10. Probability distribution of oil presence (a) after 10days and (b) after 15 days later. Calculated by 30 ensembles from 1-30 July 2015. Note that color scales are not same.

30 ensemble computations are carried out; by changing initial oil spill dates. Figure 10 shows the probability distribution where spilled oil reaches within 10 days and 15days. Both figures shows widespread of probability distribution in the area and within 10 days 23% probability that oil may reach in the Sannikov Strait and after 15 days 43% probability that oil reach the east coast of Kotelny island.

CONCLUSIONS

Oil spill experiments conducted in the past with different sea ice concentrations are compared with the oil spill numerical model. Numerical model shows the good agreement with the laboratory experiments. Next, we have carried out a numerical computation of sea ice and spilled oil behavior in ice-covered East Siberian Sea. We have shown if oil spills in East Siberian Sea, the oil can reach coastal area of Kotelny Island in a few days. To accomplish the high accuracy spilled oil forecasting, we have to carry out high accuracy sea ice forecasting using ice-POM model.

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