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Numerical Prediction of Spilled Oil Behavior in the Sea of Okhotsk Under Sea Ice Conditions

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Abstract

A numerical prediction system for sea ice and spilled oil has been developed specifically for the Okhotsk Sea. Our method enables the prediction of the behavior of oil spilled in an ocean with sea ice present using PCs to obtain high resolution results; a one-week forecast of spilled oil behavior can be obtained in a few hours of computation. First, sea ice behavior is computed for the entire Okhotsk Sea (grid size: 16 km x 16 km). Second, appropriate results such as ice concentration and velocities are set as boundary conditions for high-resolution (grid size: 4 km x 4 km or 2 km x 2 km) computations of areas of interest. Third, predictions of sea-ice and spilled oil behavior are computed. We used a Distributed Mass/Discrete Floe (DMDF) model for sea ice computations that can predict the behavior of spilled oil on both open water and ice-covered seas. The DMDF model combines the advantages of both a continuum model and a discrete element model: the shorter computation times found in continuum models as well as being able to express the discrete nature of sea ice**.** In addition, this combined model can treat a larger number of floes in much shorter computation times than previously developed discrete element models.

Introduction

In cold ocean environments with sea ice present, oil-spill cleanup is technologically difficult since spilled oil remains under/between sea-ice cover. Up-to-date information of spilled oil drift is indispensable for the development and implementation of an effective response. In particular, shorter computation times would be advantageous for timely implementation of oil-spill cleanup procedures, e.g., deployment of oil-spill equipment, protection of fisheries, and rescue of wildlife.

Sea ice is generated every winter in the Okhotsk Sea and drifts to the coastal area of Hokkaido, Japan's northernmost island. Within this environment, the Sakhalin Oil & Gas Project, undergoing continuing development offshore of Sakhalin Island, has greatly increased oil transportation in the Okhotsk Sea. Any oil spilled in this area may drift to the coastal areas of Hokkaido and cause damage to the marine environment and economy of this area. The risk of oil spill incidents requires a system for anticipating, simulating, and monitoring oil spills. **Figure 1** shows the affected region, including Hokkaido, Japan, and Sakhalin Island.

The Engineering Advancement Association of Japan (ENAA) started a six-year program, "A Study to Predict Spilled Oil Behavior in the Okhotsk Sea Under Sea Ice Conditions," in 2003 that was sponsored by the Ministry of Economy, Trade, and Industry (METI) of Japan. The University of Tokyo (Prof. Hajime Yamaguchi) and Hokkaido University (Prof. Kay I. Ohshima) joined the project to work on the numerical modeling of the ice-spilled-oil rheology and the ocean circulation, respectively, of the Okhotsk Sea.

Fig. 1 Geography of Hokkaido, Japan, and Sakhalin Island in the Okhotsk Sea.

Morphology of the Okhotsk Sea

Sea Ice

The Okhotsk Sea is the southernmost sea with seasonal ice cover in the Northern Hemisphere; ice can be found in the area for 6 to 7 months per year on average. The temperature of the sea surface water ranges from -1.8 to +2.0 °C in winter and from 10 to 18 °C in summer. In winter, sea ice formation begins over the northwestern shelf at the end of November; ice extent reaches maximum in late February or March, covering 50 to 90 % of the whole sea. Most of the ice disappears by May. Sea ice drifts southward along the east coast of Sakhalin Island as its extent grows and reaches the Hokkaido coastal area in February every winter. The Okhotsk Sea sea ice conditions are shown in **Table 1** (ISO/CD 19906, 2007-11-15). The level-ice thickness of the floe off the east coast of Sakhalin Island is in the range from 0.7 to 1.3 m and 0.8 to 1.2 m for the northern and southern areas, respectively. First-year ridge ice is about 6 m in sail height and about 20 m in keel depth.

Table 1 Okhotsk Sea Sea-Ice Conditions

Sea Ice	Parameter	Sakhalin Island (North) – East Coast		Sakhalin Island (South) – East Coast	
		Average Annual Value	Range of Annual Values	Average Annual Value	Range of Annual Values
Occurrence	First ice	1 November	25 October to 10 November	30 October	25 October to 20 November
	Last ice	30 May	20 May to 25 June	30 April	20 April to 30 May
Level ice (first-year)	Landfast ice thickness (m)	1.13	1.06 to 1.21	0.6	0.45 to 0.85
	Floe thickness (m)	0.9	0.7 to 1.3	0.9	0.8 to 1.20
Rubble fields	Sail height (m)	5.1	4.4 to 6.0	5.0	4.5 to 6.0
Ridges (first-year)	Sail height (m)	6.2	5.4 to 8.1	5.5	4.5 to 7.0
	Keel depth (m)	20.7	19.8 to 23.2	17	16 to 20
Ice movement	Velocity nearshore (m/s)	1.79	1.60 to 2.01	1.1	0.9 to 1.4
	Velocity offshore (m/s)	1.60	1.5 to 1.8	1.0	0.9 to 1.4

Ocean Currents

The ocean current field in the Okhotsk Sea has been under observation from the 1990s; in particular, intensive current measurements were carried out in 1998-2001 under a joint Japanese-Russian-U.S. study of the Okhotsk Sea. Surface drifter observations conducted by Hokkaido University (Ohshima et al., 2002, and Ohshima and Simizu, 2008) revealed a southward current along the east coast of Sakhalin Island, the East Sakhalin Current (ESC). The ESC consists of two cores, a nearshore core on the shelf and an offshore core over the shelf slope, and characteristically exhibits a strong seasonal variation of its volume transport with a maximum in winter and a minimum in summer (Mizuta et al., 2003): schematically shown in **Fig. 2**.

Ono *et al.* (2010) carried out numerical particle-tracking experiments for the period from 1998 to 2005 to study intensively possible oil spills in the Okhotsk Sea. These oil spill simulations were conducted by releasing particles in both the Sakhalin II project area and the region off Prigorodnoye in Aniva Bay where oil export facilities exist. In the case of the Sakhalin II project area, particles released in September-January were transported southward by the ESC, finally arriving at the coast of Hokkaido after 90 days. In contrast, particles released in March-August were diffused offshore by the synoptic wind drift rather than captured by the mainstream of the ESC. In general, particles under the influence of the beaching effect tended to end up on the coast of Sakhalin, regardless of the deployment month. However, particles released in October-December, when the ESC is particularly strong, can reach the coast of Hokkaido, regardless of the beaching effect.

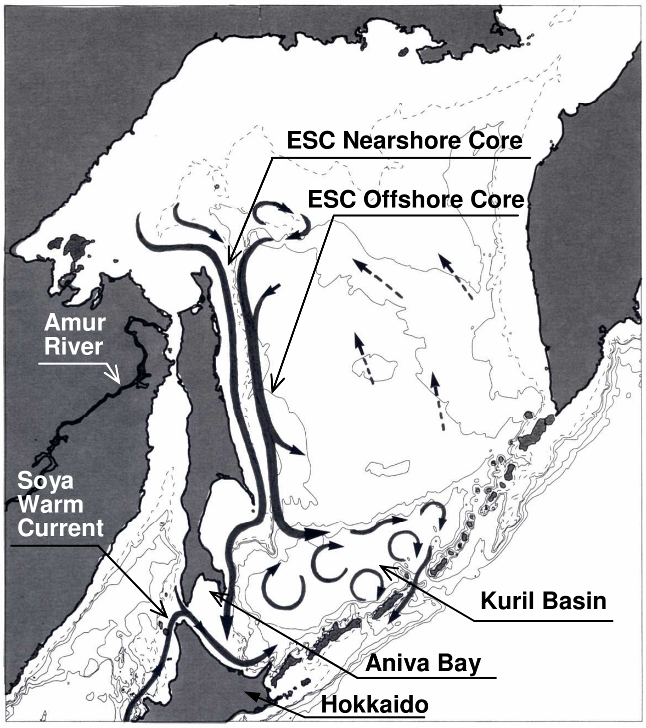


Fig. 2 Schematic of the East Sakhalin Current (ESC) flowing southward along the east coast of Sakhalin: nearshore core on the shelf and offshore core over the shelf slope. (modified from Ohshima et al., 2002)

Sakhalin Oil and Gas Project

The exploitation of gas and oil fields in areas offshore of Sakhalin Island, estimated to contain 45 billion barrels (TOE), has continued since the 1990s. Sakhalin I and II projects are already producing oil and gas commercially, while several other projects (Sakhalin III-VI) are at the stage of seismic surveys and test drillings. The locations of the Sakhalin I and II project elements are shown in **Fig. 3**.

The Sakhalin I project includes three oil and gas fields (Chayvo, Odoptu, and Arkutun Dagi) that are located off the northeast coast of Sakhalin Island: potential recoverable resources of 2.3 billion barrels of oil and 485 billion cubic meters of natural gas. A pipeline across the Tatar Strait transports oil and gas produced by onshore and offshore facilities to the export terminal in DeKastri.

The Sakhalin II project, estimated deposit of 4 billion barrels (TOE), involves the development of two fields off the northeastern coast of Sakhalin: Piltun-Astokhskoye (mostly oil) and Lunskoye (mostly gas). Three platforms have been installed offshore (10 km or more) to produce oil and gas; 300 km of offshore pipelines connect all three platforms to the shore. Onshore oil and gas pipelines (parallel to each other and 800 km long) run from the north of the island to Prigorodonoye, Aniva Bay, in the south, where a liquefied natural gas (LNG) plant and an oil export terminal are located. The peak production capacities of the Sakhalin II project are 150,000 barrels of oil per day and 9.6 million tons of LNG per year. Oil and LNG are now being delivered from the export terminal to Japan and South Korea.

Besides the Sakhalin I and II projects, which have already started commercial oil and gas production, there are other projects and areas with potential for further oil and gas exploitation in the Okhotsk Sea, as shown in **Table 2** (JASNAOE, 2010). The total number of oil and LNG tanker shipments necessary for transport is predicted to reach 8,200 per year, resulting in 16,400 transits. In regard to the Sakhalin I and II projects, 220 oil and 340 LNG tanker shipments are estimated to occur offshore of Sakhalin Island.

Fig. 3 Schematic of the Sakhalin I and II Project elements.

The expected increase in offshore production and shipping activities will greatly increase the transport of oil in the Okhotsk Sea. Thus, the rising risk of oil spill incidents necessitates a system for anticipating, simulating, and monitoring oil spills.

Table 2 Oil & Gas Potential and Predicted Shipping: Okhotsk Sea

Projects & Areas	Oil Equivalent (million ton)	Production 2)		Number of Shipments per Year	
		Oil (bpd)	LNG (TPA)	Oil Tanker 3)	LNG Tanker 4)
Sakhalin I	706	210,000	11,000,000	120	190
Sakhalin II	593	180,000	9,000,000	100	150
Sakhalin III to IX	5,122	1,550,000	78,000,000	900	1,330
Okhotsk and Kuril 1)	12,425	3,770,000	189,000,000	2,190	3,220
Number of Shipments per Year: Total				8,200	

1) Okhotsk and Kuril include fields in the North Okhotsk Sea (Khabarrovsk, Magadan, Koryak, and Kamchatka) and the Kuril Islands.
2) Production predictions are scaled from the Sakhalin II project.
3) Nominal oil tanker capacity is assumed to be 100,000 DWT.
4) Nominal LNC tanker capacity is assumed to be 125,000 m^3.
Symbols: bpd, Barrels per Day; TPA, Tons per Annum; and DWT, Dead Weight Ton.

Numerical Prediction of Spilled Oil Behavior

Computation Model for Sea Ice Behavior

Since shorter computation times would be advantageous for oil spill cleanup procedures, our goal was to complete a one-week forecast of spilled oil behavior in 2-3 hours with PCs using a Distributed Mass/Discrete Floe (DMDF) model developed by Rheem *et al.* (1997) of the University of Tokyo.

The DMDF model, which takes into account the discrete characteristics of sea ice using floe collision rheology, calculates the movement of ice floes that is induced by wind drag. The wind drag acting on an ice floe is divided into two components, ice-surface-friction drag and ice-floe-edge-separation drag, shown schematically in **Fig. 4**. The ice-surface-friction drag is a function of sea ice surface roughness, which is expressed as a function of ice thickness based on field measurements conducted by Fujisaki *et al.* (2009); thicker ice has higher surface roughness.

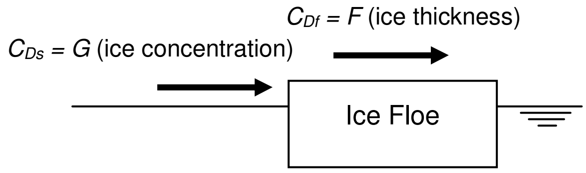


Fig. 4 Schematic of the DMDF model wind drag components acting on an ice floe: C_{Df} and C_{Ds} denote ice-surface-friction drag and ice-floe-edge-separation drag, respectively.

Computation Models for Ocean and Tidal Currents

Ocean and tidal currents are the most influential factors in modeling sea ice behavior. A three-dimensional (3-D) ocean current model for the Okhotsk Sea, based on a model devised by Uchimoto *et al.* (2007), has been developed that incorporates the effects of sea floor topography, water exchange between the Japan Sea and the North Pacific, wind stress, heat flux and fresh water from the Amur River. The Okhotsk Sea is a region of strong tidal currents. In particular, diurnal tidal currents induced by coastal-trapped waves are dominant over the shelves in the offshore area northeast of Sakhalin. In this study, we considered the diurnal tidal currents derived from harmonic constants calculated from a three-dimensional tidal simulation model (Ono and Ohshima, 2010). Simulated monthly-averaged surface current velocities are shown for January and September in **Fig. 5** and 12 months (January to December) in **Fig. 6**: monthly averages derived from 8 years of simulation (January 1998 to August 2006) (Ono *et al.,* 2010).

The southward ESC along the east coast of Sakhalin Island becomes strong in October and continues to be influential until March. On the other hand, the southeastward Soya Warm Current (SWC), coming in from the Japan Sea and moving along the Hokkaido coast, becomes strong in August, with an influence continuing until November. Another significant feature is anticyclonic circulation in the Kuril Basin. This circulation would exist throughout the year, but the northward component on the western side is cancelled by the southward ESC during the November to February period, when the ESC is strong.

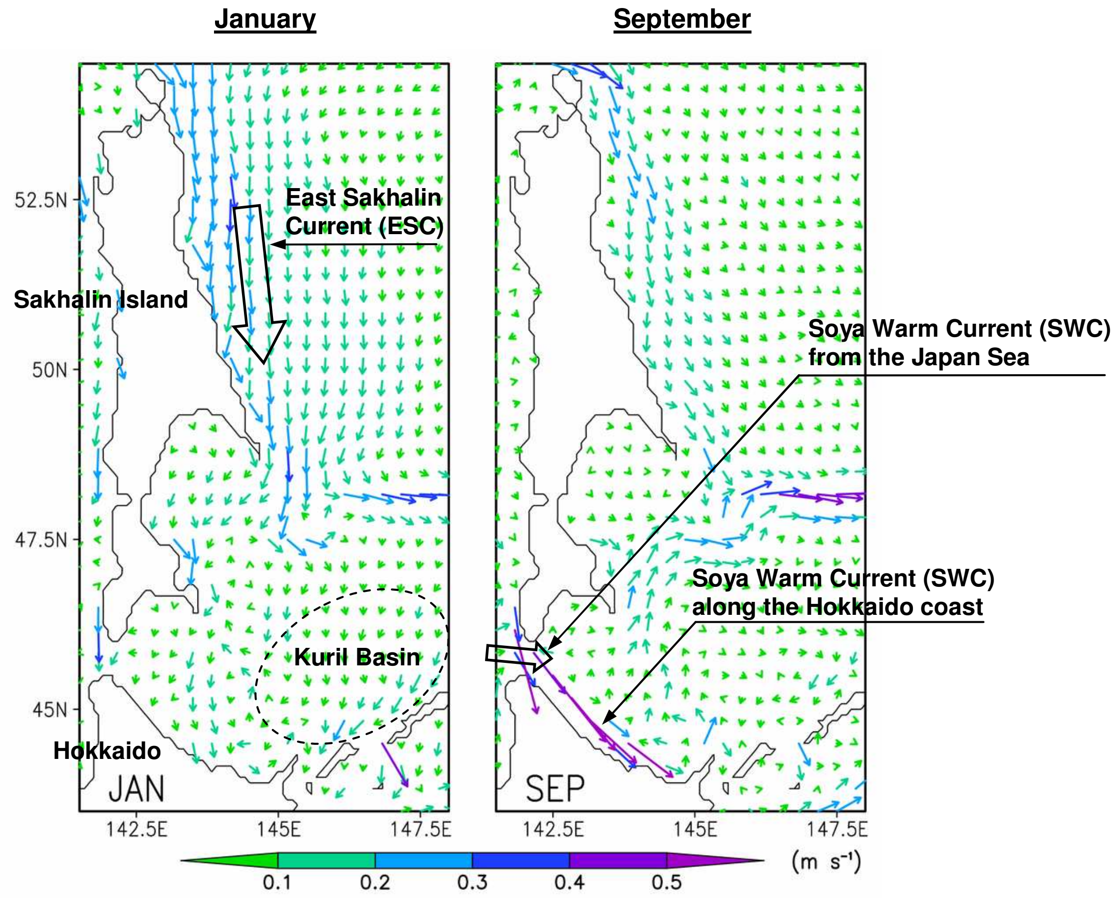


Fig. 5 Simulated monthly-averaged surface current velocities for January and September: the strong southward East Sakhalin Current along the east coast of Sakhalin Island in January and the southeastward Soya Warm Current along the Hokkaido coast in September.

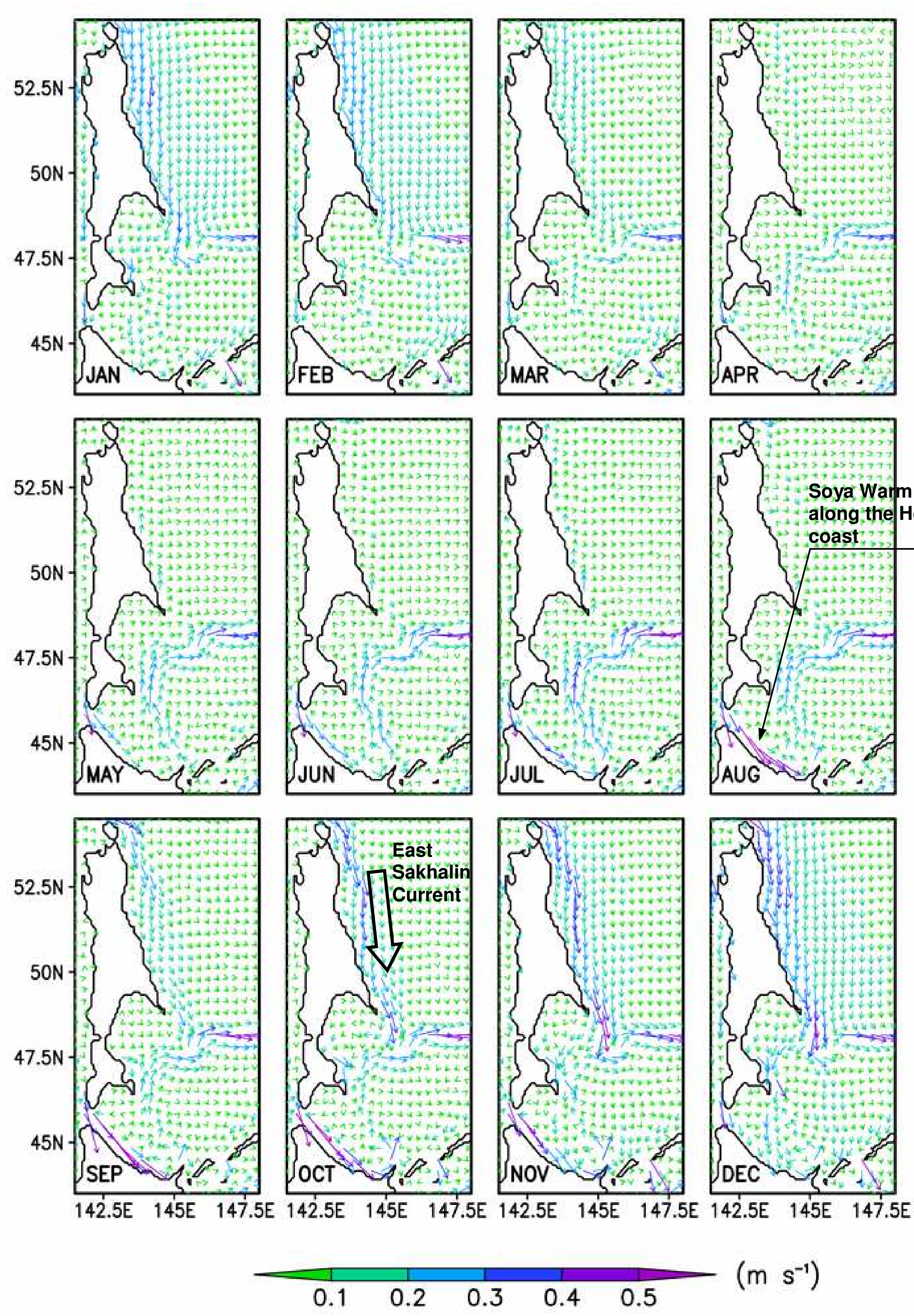


Fig. 6 Monthly-averaged surface current velocities (simulated) for 12 months derived from the simulated 8 years period of January 1998 to August 2006; the southward East Sakhalin Current (ESC) along the east coast of Sakhalin Island becomes strong from October until March, and the southeastward Soya Warm Current (SWC) along the Hokkaido coast becomes strong from August until November.

Data Sets Required

The computation of sea ice behavior requires a number of sets of data, described in **Table 3**: ocean and tidal currents, initial sea ice concentrations, meteorological conditions, and sea surface temperatures.

Table 3 Data Sets Required for the Computation of Sea Ice Behavior and Their Providers

Data Sets Required	Data Acquisition System/Generation Models	Data Providers
Ocean and tidal currents	Three Dimensional Ocean Circulation Model	Hokkaido University
Initial sea ice concentrations	Advanced Microwave Scanning Radiometer for EOS (AMSR-E)	Japan Aerospace Exploration Agency (JAXA)
Meteorological conditions	Regional Spectral Model (RSM)	Japan Meteorological Agency (JMA)
Sea surface temperatures	Advanced Microwave Scanning Radiometer for EOS (AMSR-E)	Japan Meteorological Agency (JMA)

Computation of Sea Ice and Oil Spill Behavior

The first of three steps in the simulation is to compute sea-ice behavior for the entire Okhotsk Sea (area: 1,800 km x 2,400 km, grid size: 16 km x 16 km). In the second step, appropriate results such as ice concentrations and velocities are set as boundary conditions for high resolution computations of areas of interest: *i)* area of 480 km x 1,400 km and grid size of 4 km x 4 km for the case of an oil spill in the northeast oil field and *ii)* area of 400 km x 480 km and grid size of 2 km x 2 km for an oil spill in Aniva Bay. Lastly, predictions of sea ice and oil spill behavior are computed. The computation areas with grid sizes are shown in **Fig. 7**.

In addition to the data sets listed in Table 3, the computation of oil spill behavior requires the following information: oil density, oil viscosity, duration of oil spill, oil spill rate, and computation grid size.

As an example, a 40 day prediction of oil spill behavior in Aniva Bay, using data sets for January and February 2003, is shown in **Fig. 8**. The spilled oil drifts out of Aniva Bay within 20 days of the initial spill and, within 40 days, approaches the northernmost Hokkaido coast, with a portion drifting into the Japan Sea.

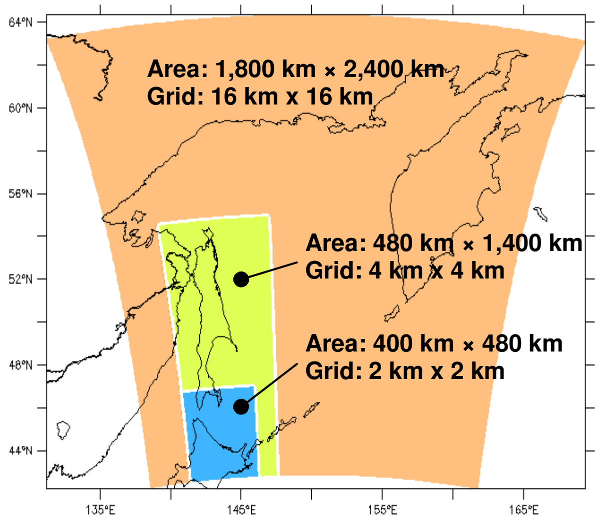


Fig.7 Computation areas and their computation grid sizes.

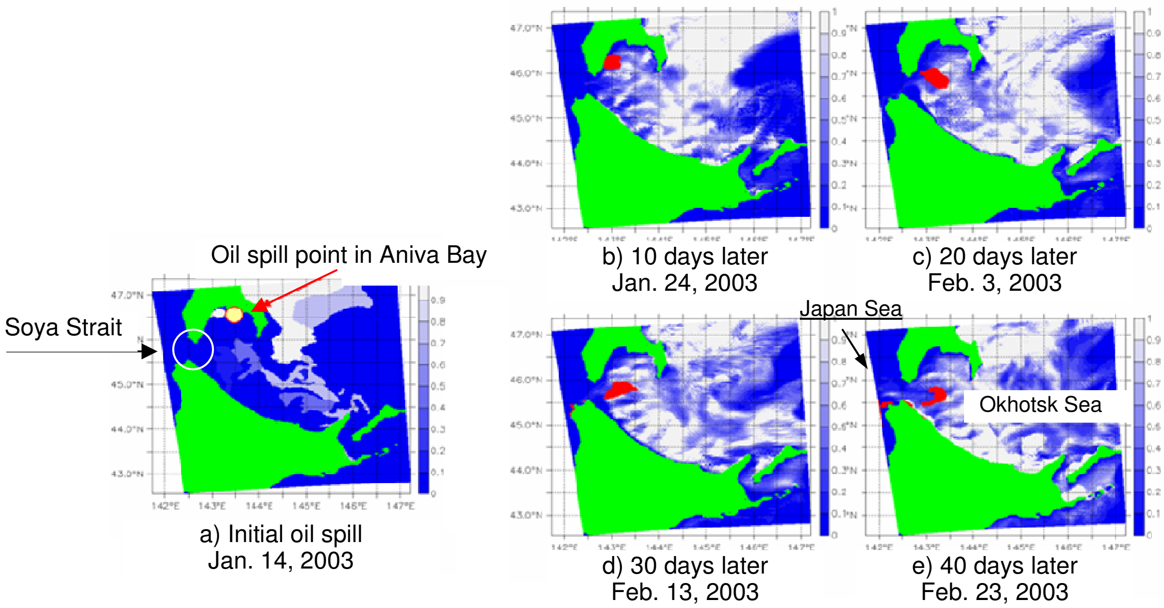
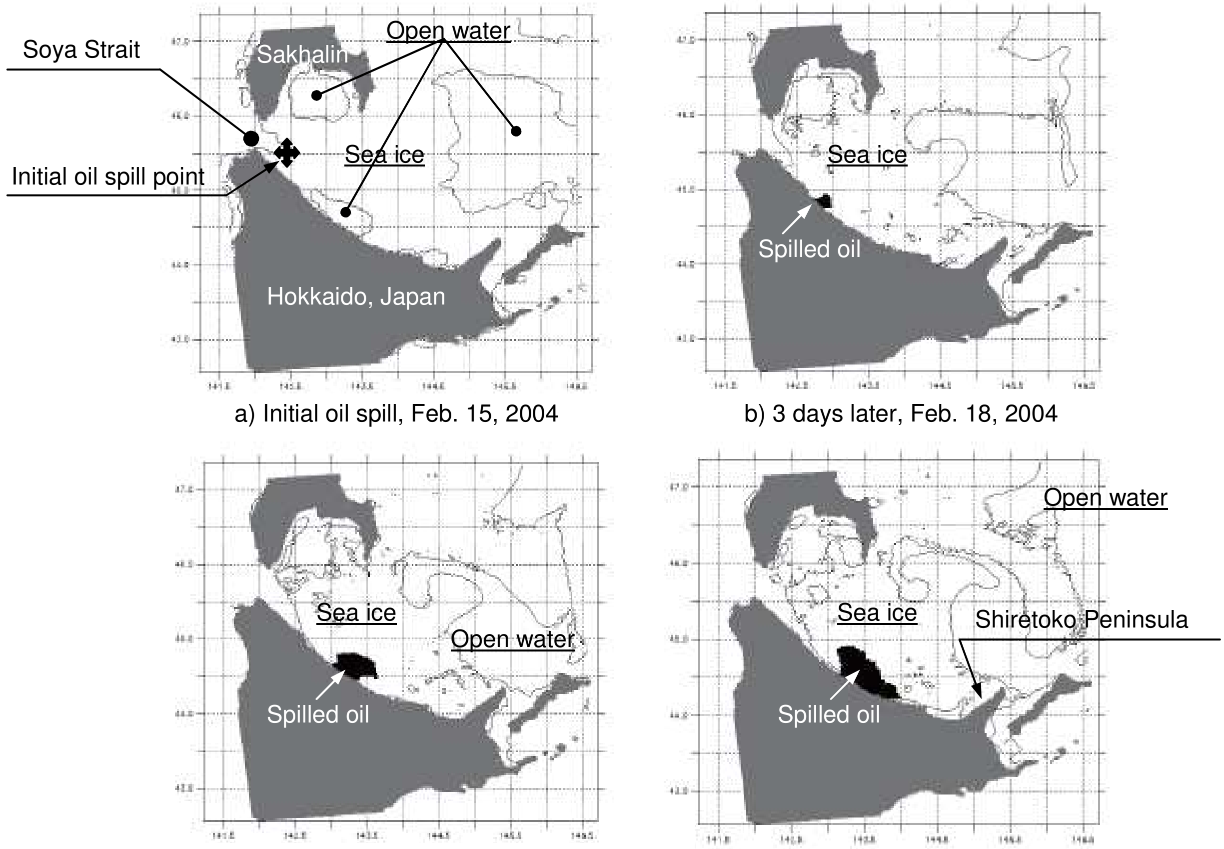


Fig. 8 Predicted behavior of oil spilled in Aniva Bay using data sets of January and February 2003; white and red colors denote sea ice and spilled oil, respectively.

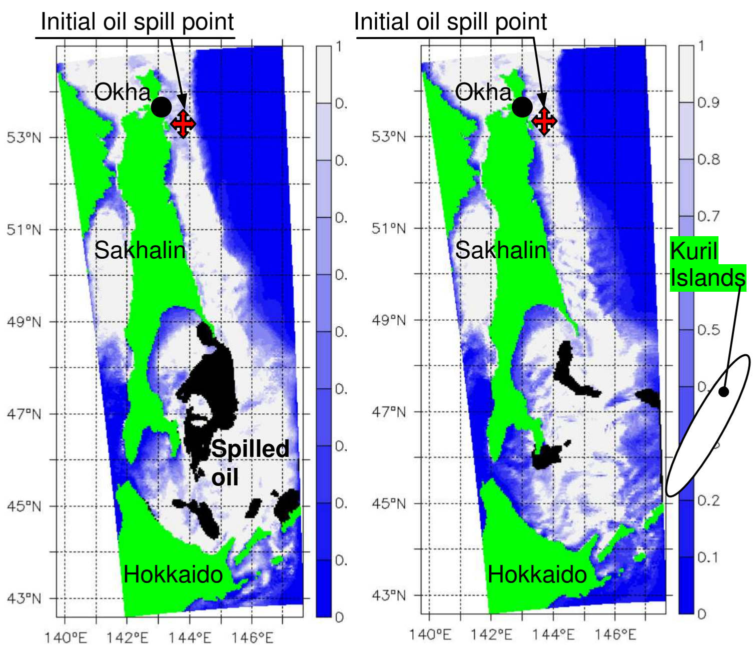


a) Initial oil spill, Feb. 15, 2004
b) 3 days later, Feb. 18, 2004
c) 5 days later, Feb. 20, 2004
d) 7 days later, Feb. 22, 2004

Fig. 9 Short term (7 days) prediction of the behavior of oil spilled in the Soya Strait, using data sets for February 2004.

A shorter term, 7 days, prediction example modeling the behavior of oil spilled in the Soya Strait, using data sets for February 2004, is shown in **Fig. 9**. The Soya Warm Current forces the oil to initially drift together with ice floes toward the coastline of Hokkaido, making landfall in three days. The spilled oil then continues to drift with the sea ice and expand along the coastline toward the Shiretoko Peninsula.

The third example clearly shows the effect of weather conditions on the behavior of oil spilled in the offshore oil production field northeast of Sakhalin Island. Predictions using data sets for 2003 and 2005 are shown in **Figs. 10 a)** and **b)**, respectively. Using the 2003 data, oil spilled offshore of Okha on January 3, 2003, would drift initially southward along the east coast of Sakhalin Island and approach Hokkaido in 60 days. In contrast, a strong westerly, i.e., eastward, wind condition that existed in January and February 2005 would drive the spilled oil toward the Kuril Islands, missing the Hokkaido coast.



a) 60 days after the initial oil spill on Jan. 3, 2003.
b) 60 days after the initial oil spill on Jan. 4, 2005.

Fig.10 Predictions of the behavior of oil spilled in the oil production field offshore northeast Sakhalin, using data sets for 2003 and 2005.

Summary and Conclusions

i) Computation Performance

Using the numerical prediction system described in this report, the behavior of oil spilled in the Okhotsk Sea with sea ice present can now be simulated using PCs to obtain high resolution results in a timely manner; for example, a one-week forecast of oil spill behavior can be obtained in 2-3 hours of computation.

ii) Distributed Mass/Discrete Floe (DMDF) model

The Distributed Mass/Discrete Floe (DMDF) model used for sea ice computations enables the behavior of spilled oil to be predicted relatively quickly for both open water and ice-covered sea conditions. This model, combining the advantage of shorter computation times found in continuum models with the ability to treat sea-ice as discrete elements, also enables the inclusion of a larger number of floes with much shorter computation times than possible using previous models.

iii) Computation of Sea Ice and Oil Spill Behavior

Simulations were computed for three possible oil spill events: in Aniva Bay, in the Soya Strait, and offshore of Okha. Using conditions for January and February 2003 in the first example, the spilled oil would drift out of Aniva Bay within 20 days and approach the northernmost Hokkaido coast within 40 days. In the Soya Strait spill example, the Soya Warm Current in February 2004 would force the spilled oil to first make landfall in three days on the coast of Hokkaido and then continue to drift with sea ice, expanding along the coastline toward the Shiretoko Peninsula. The oil spill example offshore of Okha illustrates the effect of weather conditions on simulations; using January 3, 2003, data, the spilled oil would drift southward along the east coast of Sakhalin Island and approach Hokkaido in 60 days, whereas the strong westerly winds during January and February 2005 would result in the spilled oil missing the Hokkaido coast.

iv) Applications of the Numerical Prediction Method

Although our numerical prediction method was originally developed using oceanographic and meteorological data for the Okhotsk Sea, this methodology can be applied to other Arctic sea areas. In addition to use in oil spill cleanup countermeasures, predictions of ice movement over time scales ranging from hours to days would be very useful in ice management for ship navigation and emergency evacuations. The graphic representations resulting from the computations can be particularly useful for understanding the ice movement predictions.

v) Future Work

Since accurate predictions of oil spill and/or sea ice behavior depend on knowing the state of ocean and tidal currents as well as the weather, these data have to be collected, kept up to date and made available in a timely manner. In addition, more accurate simulations of oil spill and/or sea ice movements would benefit from the incorporation of Geographic Information System (GIS) and Environmental Sensitivity Index (ESI) data to better predict and understand the consequences and plan for amelioration.

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