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Numerical Prediction of Spilled Oil Behavior under Sea Ice Conditions: Modification of the 2011 Model

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Abstract
This report describes an updated version of the numerical prediction system for oil spilled under sea-ice conditions in the Sea of Okhotsk that was developed by the authors and presented at ATC 2011 (Paper Number: OTC 22123). Our previous version enabled the computation of high resolution predictions of the ice-spilled-oil behavior using only PCs; a one-week forecast of spilled oil behavior could be computed in a few hours. This previous method computed the behavior prediction serially: first step, computation of sea-ice behavior for the entire Okhotsk Sea (grid size of 16 km x 16 km); second, higher resolution computations (grid sizes of 4 km x 4 km or 2 km x 2 km) using the data resulting from the first step such as ice concentrations and velocities as boundary conditions; third, final computation of predicted sea-ice and spilled-oil behavior; and fourth, processing and displaying the results in a graphical interface. Since shorter computation times would be advantageous for oil-spill cleanup procedures, we modified the previous serial method to enable parallel computation not only to shorten the processing time but also to display spilled-oil/sea-ice images as the computation progressed. This paper includes an example of computed predictions that model the behavior of spilled oil under three conditions, namely, in open water, in water at the margins of ice-covered water, and in ice-covered water, all located near Soya Strait.

Introduction
In cold ocean environments with sea ice present, oil-spill cleanup is technologically difficult since spilled oil remains under as well as intermixed with the 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 for the predicted spread of the spilled oil 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 southward to the coastal area of Hokkaido, Japan's northernmost island. Within this environment, the Sakhalin Oil & Gas Project, undergoing continuing development offshore 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. The locations of the Sakhalin I and II project elements are shown in **Fig. 1**.

Fig. 1 Schematic of the Sakhalin I and II Project elements.

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. 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 (JASNAOE, 2010). In regard to the Sakhalin I and II projects, 220 oil and 340 LNG tanker shipments are estimated to occur offshore Sakhalin Island. Clearly, the expected growth in offshore production and shipping activities will increase greatly the transport of oil in the Okhotsk Sea. Thus, the rising risk of oil spill incidents increases markedly the necessity of implementing a system for anticipating, simulating, and monitoring oil spills.

Influence of Ocean Currents on Sea Ice in the Okhotsk Sea

The numerical method described in this paper is particularly applicable to the Okhotsk Sea, the southernmost sea with seasonal ice cover in the Northern Hemisphere, since ice appears annually for about 6 to 7 months. Sea ice formation, beginning over the northwestern shelf at the end of November, reaches maximum extent in late February or March, covering 50 to 90 % of the whole sea, with most of the ice disappearing by May. Every winter , the sea ice drifts southward along the east coast of Sakhalin Island as its extent grows and reaches the Hokkaido coastal area in February.

As the cause of this drift, ocean and tidal currents are the most significant factors in modeling sea ice behavior. In particular, the southward flowing East Sakhalin Current (ESC) and the southeastward Soya Warm Current (SWC) have a great impact on the probablity of spilled oil reaching the coast of Hokkaido. The ESC along the east coast of Sakhalin Island, becoming strong in October, continues to be influential until March (Ohshima et al., 2002, and Ohshima and Simizu, 2008). On the other hand, the SWC, coming in from the Japan Sea through Soya Strait 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; the northward component of this circulation is cancelled by the southward ESC in the region directly north of Hokkaido during the November to February period, when the ESC is strong. These ocean currents in the Okhotsk Sea are schematically shown in **Fig. 2**.

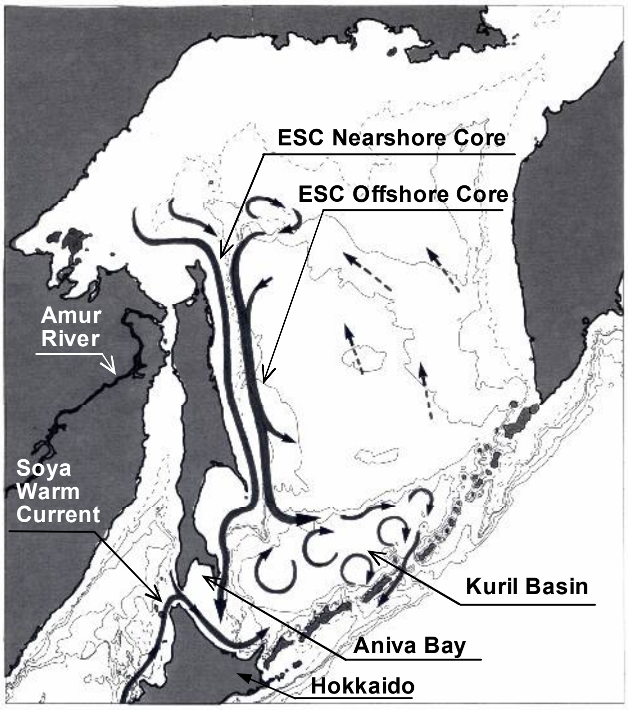


Fig. 2 Schematic of the East Sakhalin Current (ESC) flowing southward along the east coast of Sakhalin: nearshore core on the shelf and offshore core over the shelf slope. (modified from Ohshima et al., 2002).

Modified Computation Model: 2012

Data Sets Required

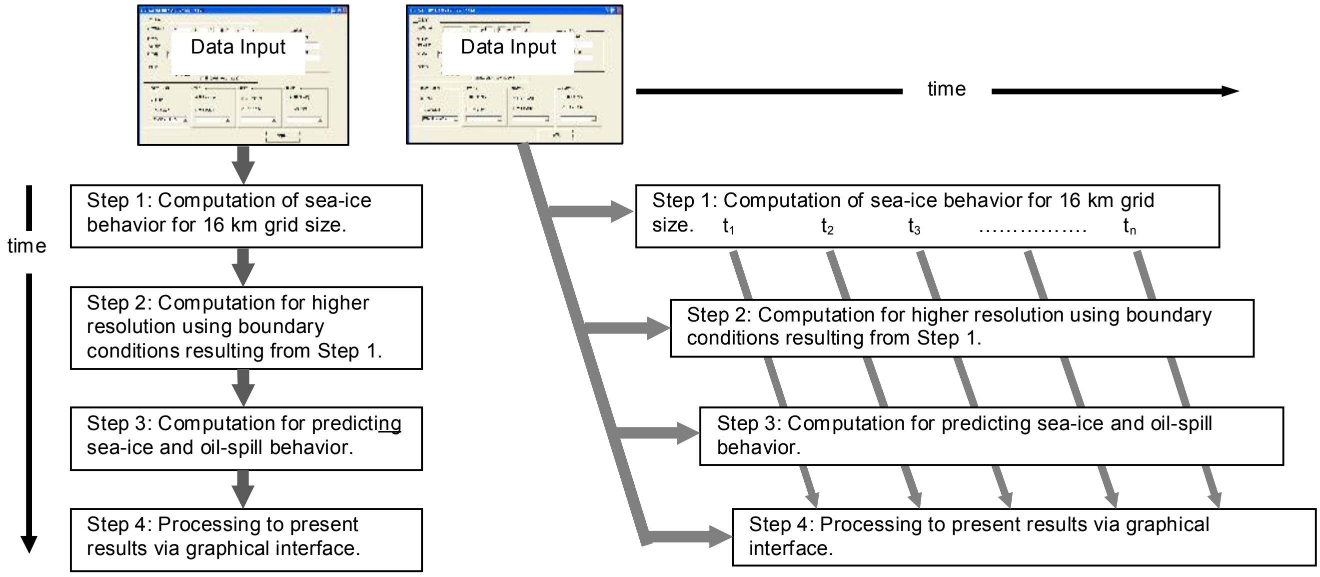
The computation of sea-ice behavior requires a number of sets of data, described in **Table 1**: ocean and tidal currents, initial sea ice concentrations, meteorological conditions, and sea surface temperatures. In addition to the data sets listed in Table 1, the computation of oil-spill behavior requires the following information: oil density, oil viscosity, duration of oil spill, oil spill rate, and computation grid size.

Table 1 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 (Ono et al., 2010, and Ono et al., 2012)
Initial sea ice concentrations	Advanced Microwave Scanning Radiometer-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-EOS (AMSR-E)	Japan Meteorological Agency (JMA)

Modification of the 2011 Model.

The 2011 computation model, introduced at ATC 2011 (Paper Number: OTC 22123, Yamaguchi et al., 2011), could produce a one-week forecast of spilled oil behavior in 2-3 hours using PCs. Our goal was to reduce this time since quicker computations would be advantageous for oil spill cleanup procedures. In addition, the installation of the necessary software onto PCs was simplified because this procedure involved six different software programs that previously had to be installed individually by someone with advanced computer skills. Now, a new installer unifies the installation of the six software programs and shortens the loading time by 70 %, resulting in a more versatile and user friendly system. Computations with the 2011 Model method involved four distinct steps processed in series. The first step computed sea-ice behavior for the entire Okhotsk Sea (area of 1,800 km x 2,400 km with grid size of 16 km x 16 km); the second applied appropriate results of the first step such as ice concentrations and velocities as boundary conditions for higher resolution computations in areas of interest: *i)* area of 480 km x 1,400 km with grid size of 4 km x 4 km for the case of an oil spill and *ii)* area of 400 km x 480 km with grid size of 2 km x 2 km for an oil spill; the third computed predictions of sea-ice and oil-spill behavior in the areas of special interest noted in step 2, but using grid sizes of 16 km and 4 km, respectively; and the fourth processed the results and presented them via a graphical interface. This serial processing method was improved by developing a parallel processing algorithm to compute the above four steps concurrently, resulting in a 20 % decrease in computation time. The serial and parallel processing methods for the computation of oil-spill behavior are illustrated in **Fig. 3**.



a) 2011 Model: Serial processing. **b) 2012 Model: Parallel processing.**

Fig. 3 Serial and parallel computation of oil-spill behavior.

In addition, an effort is being made to increase the ease of use and availability of the 2012 Model by creating a new interface for the data input procedure and by eventually making it available for introductory use via the Internet. For any practical use of the model to predict the behavior of spilled oil in the Okhotsk Sea using the Internet, however, web links to the required data sets shown in Table 1 have to be set up in coordination with the appropriate groups. The input data needed to calculate the spilled oil behavior are shown in **Fig. 4** (in Japanese) and listed in **Table 2**. In addition to the input data shown in Table 2, the required data sets shown in Table 1 have to be available.

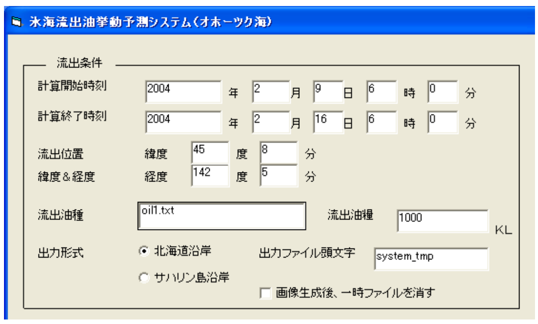


Fig. 4 Data input interface for oil-spill calculations (in Japanese).

Table 2 Input Data of Oil Spill Parameters for the Computation of Spilled Oil Behavior

Input data	Example
Computation start time	year_month_day_hour_minute
Computation end time	year_month_day_hour_minute
Oil spill location	latitude: degree_minute longitude: degree_minute
Oil type	chose from the database in the software
Spilled oil volume	kiloliter
Geographical location for graphical output	Japan Hokkaido coast or Sakhalin coast

Numerical Computation of Spilled Oil Behavior

Comparison of Spilled Oil Behavior in Ice-free, Sea-ice Edge, and Ice-covered Conditions.
An example of a short term, 7 days, prediction modeling that illustrates the effects of sea ice on the behavior of spilled oil near Soya Strait using the data sets for February 2005 is shown in **Figs. 5** and **6**; using the February data, a simulation of the monthly-averaged surface current velocities is shown in **Fig. 4**. The locations (a, b, c) in Fig. 5 denote three hypothetical sites of oil spill events: *a)* away from sea ice (in open water), *b)* at the perimeter of the sea ice, and *c)* surrounded by sea ice. The results of the modeling, see Fig. 6, show clearly that the presence of sea ice influenced markedly the behavior of spilled oil, in particular, its spread: after 7 days, the spread of spilled oil was largest in situation a) and smallest in situation c), with b) showing intermediate results. In detail, the oil spilled at the perimeter of the sea ice (b) spread westward from the initial oil spill point, i.e., toward ice-free water, away from the ice edge. Since any movement of the oil spilled in water surrounded by sea ice (c) is constrained by this ice, the oil moved with it. (Although computed using the 2011 Model, the 2012 Model would have produced the same results, but with shorter computation times.)

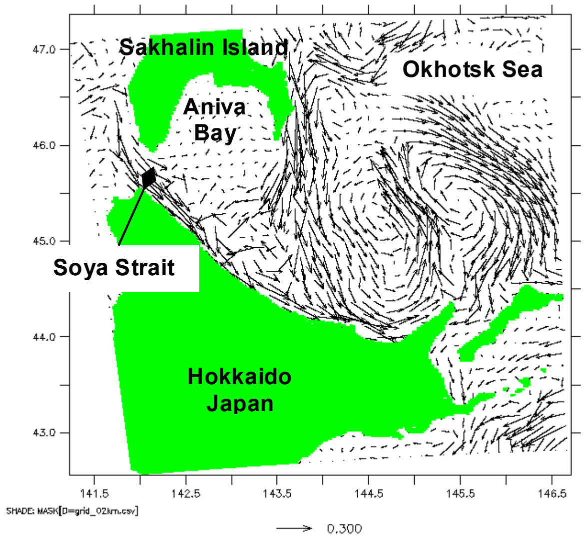


Fig. 4 Simulation of the monthly-averaged surface current velocities for February 2005: the southeastward Soya Current flows along the Hokkaido coast.

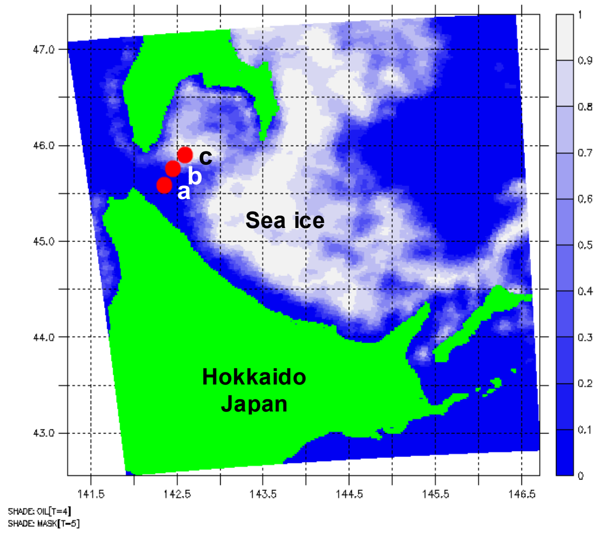
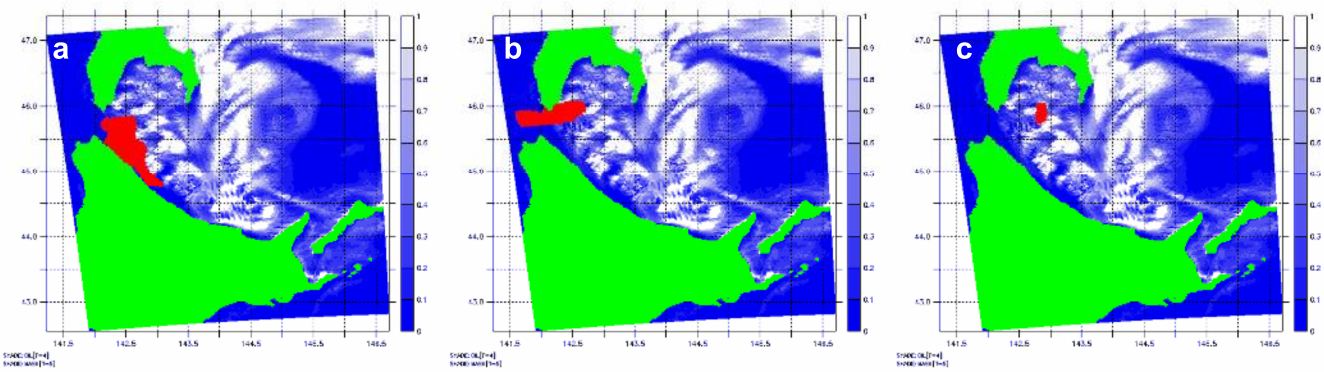


Fig. 5 Three hypothetical oil spill sites located near Soya Strait: *a)* away from sea ice (open water), *b)* at sea ice perimeter, and *c)* in water surrounded by sea ice.



a) Oil spilled in open water: spread over greatest area.

b) Oil spilled at sea ice perimeter: intermediate amount of spread in a direction toward ice-free water.

c) Oil spilled in water surrounded by sea ice: smallest spread and moved with sea ice.

Fig. 6 Predicted spread 7 days after a hypothetical oil spill at locations noted in Fig. 4 using data sets for February 2005: oil spilled a) away from sea ice (in open water), *b)* at sea ice perimeter, and *c)* in water surrounded by sea ice.

Summary and Conclusions

i) Rising risk of Oil Spill Incidents in the Okhotsk Sea

The expected growth in offshore production and shipping activity by the Sakhalin I and II projects will greatly increase the transport of oil in the Okhotsk Sea. Thus, the rising risk of oil spill incidents necessitates implementing a system for anticipating, simulating, and monitoring oil spills.

ii) New Software Installer for the 2012 Model

A new installer unified the installation of the six software programs and shortened the loading time by 70 %, resulting in a more versatile and user friendly system.

iii) Computation Performance

The processing method of the 2011 Model was improved by developing a parallel processing algorithm to compute concurrently what had previously been four steps computed serially, resulting in a 20 % decrease in computation time.

iv) Computation of Sea-Ice and Oil-Spill Behavior

A simulation of a possible oil spill event near Soya Strait was computed to compare the behavior of oil spilled in the sea in ice-free waters, at the perimeter of the sea ice, and in ice-covered waters. The largest spread of the spilled oil after 7 days occurred in ice-free waters, with lesser amounts of expansion found in waters along the sea-ice perimeter and in the midst of an ice-covered area, in descending order. The oil spilled at the perimeter of the sea ice spread away from the ice edge, toward the ice-free water. The oil spilled in water surrounded by sea ice was constrained by the surrounding ice and moved with it.

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 result 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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