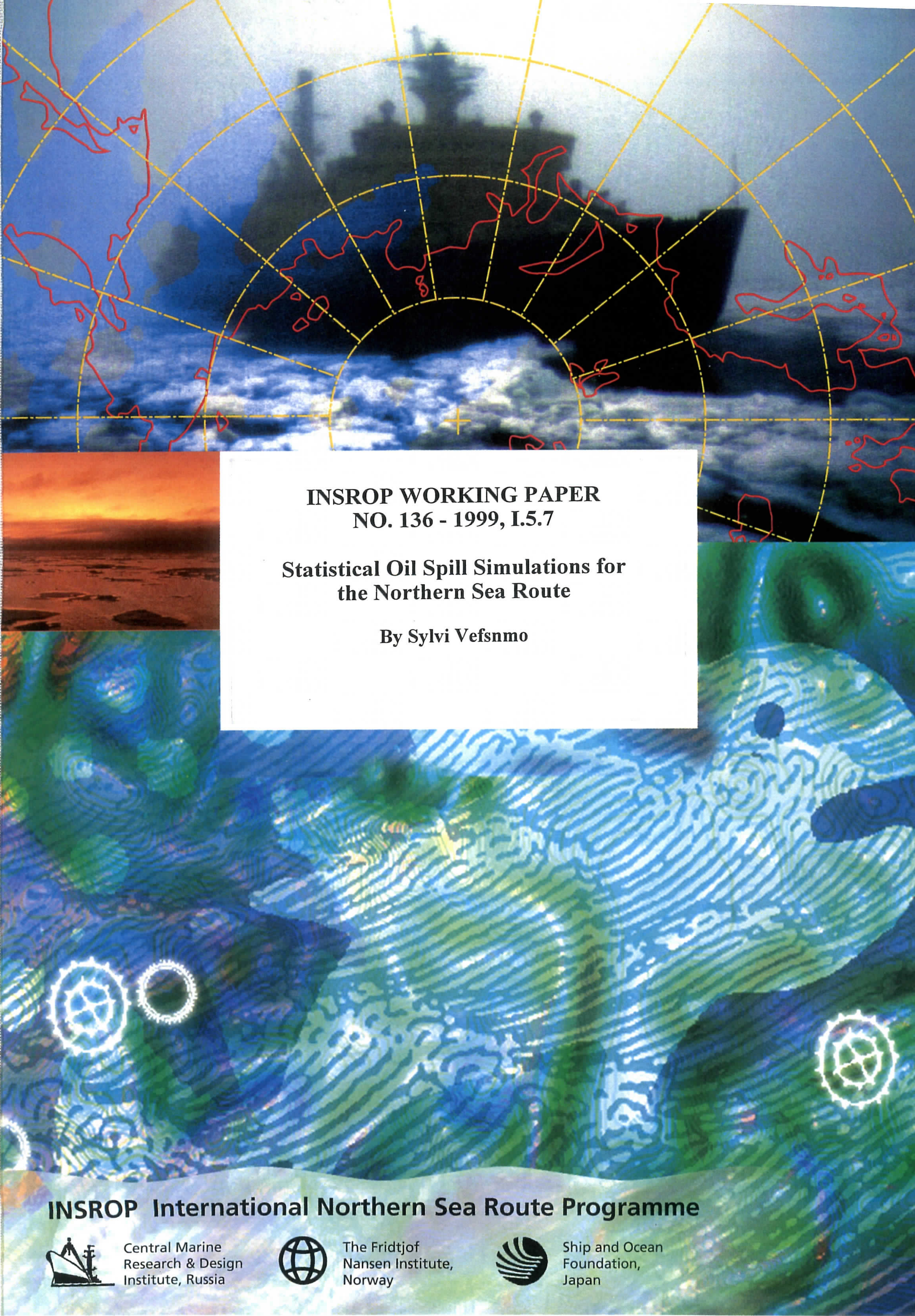

INSROP WORKING PAPER
NO. 136 - 1999, I.5.7

Statistical Oil Spill Simulations for the Northern Sea Route

By Sylvi Vefsnmo

INSROP International Northern Sea Route Programme

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International Northern Sea Route Programme (INSROP)

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Sub-Programme I: Natural Conditions and Ice Navigation

Project I.5.7: Statistical Oil Spill Simulations

Supervisor: Sylvi Vefsnmo, SINTEF

Title: **Statistical Oil Spill Simulations for the Northern Sea Route**

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What is an INSROP Working Paper and how to handle it:

FOREWORD - INSROP WORKING PAPER

INSROP is a five-year multidisciplinary and multilateral research programme, the main phase of which commenced in June 1993. The three principal cooperating partners are **Central Marine Research & Design Institute (CNIIMF)**, St. Petersburg, Russia; **Ship and Ocean Foundation (SOF)**, Tokyo, Japan; and **Fridtjof Nansen Institute (FNI)**, Lysaker, Norway. The INSROP Secretariat is shared between CNIIMF and FNI and is located at FNI.

INSROP is split into four main projects: 1) Natural Conditions and Ice Navigation; 2) Environmental Factors; 3) Trade and Commercial Shipping Aspects of the NSR; and 4) Political, Legal and Strategic Factors. The aim of INSROP is to build up a knowledge base adequate to provide a foundation for long-term planning and decision-making by state agencies as well as private companies etc., for purposes of promoting rational decisionmaking concerning the use of the Northern Sea Route for transit and regional development.

INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSROP as a third partner on an equal basis with CNIIMF and FNI.

The complete series of publications may be obtained from the Fridtjof Nansen Institute.

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TITLE

INSROP Natural Conditions and Ice Navigation

Project I.5.7 Statistical oil spill simulations

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ABSTRACT

The overall purpose of the project is to provide oil spill scenario information to the Environmental Impact Assessment process in Sub-programme II.

The statistical oil drift model *OILSPILL* is used to provide probabilities of oil contamination along the NSR. A total of 14 accidental oil spill scenarios have been considered. Advection and loss of oil due to evaporation and natural dispersion are the main physical processes accounted for in the model. The model also provides statistical distributions of arrival times to shore and stranded amounts of oil for each scenario. Stranding is defined when an oil drift trajectory enters into a coastal grid cell.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Environment	Miljø
GROUP 2	Arctic	Arktis
SELECTED BY AUTHOR	Oil spill	Oljesøl
	Modelling	Modellering
	Northern Sea Route	Nordlige sjørute

SUMMARY

The overall purpose of the project is to provide oil spill scenario information to the Environmental Impact Assessment process in Sub-programme II. This involves outlining a set of accidental scenarios for oil spills from ships and simulating the drift and fate of oil spills in the NSR area.

Historical data on oil spills on a worldwide basis has been evaluated. According to the IMO data, the average annual frequency for accidents involving tankers of more than 6000 registered tonnes is 0.31 for collisions with other ship and 0.41 for groundings. Oil spill from tankers mainly result from routine operations such as loading, discharging and bunkering which normally occur in ports or at oil terminals. Further, accidents involving collisions and groundings generally give rise to much larger spills, with a fifth involving quantities larger than 700 tonnes.

The worldwide statistics on tanker accidents are not directly applicable to the NSR. Most tankers used in the Arctic are equipped with double sides and double bottoms. Tankers transport oil products to consumers on the Arctic coast in the periods of summer and winter navigation. The largest volumes are observed in the summer season, from June to September. The most intensive navigation is in the Barents Sea and in the western part of the Arctic, where most oil transportation is carried out at the present time. However, the volume will increase significantly in the future, due to deliveries of crude oil from the drilling platforms of the Prirazlomnoye field and from the Ob'Bay. The amount of oil spilled during a tanker accident is uncertain, and an amount of 3 500 tonnes of oil has been chosen for the scenarios. A total of 14 oil spill scenarios along the NSR has been identified. According to Murmansk Shipping Company, most of the accidents occur at the end of the navigation period (August-September).

In order to assess how pollution from NSR shipping will impact the environment, a statistical oil drift model has been applied to provide drift tracks of the pollutants. The *OILSPILL* model is based on the trajectory concept which means that the model simulates the drift and the weathering of the oil as individual points of mass released at different times within the available historical time series of wind data. Advection and loss of oil due to evaporation and natural dispersion, as well as oil stranding, are the main physical processes accounted for in the model. The OILSPILL model is based on the assumption that the major contribution to the variability in the oil drift pattern comes from the wind induced current, while the residual current only depends on the season. The oil drift simulations for the NSR region are based on the following data:

- Monthly averaged surface current (EPOCA'95, AARI)
- Time series of surface wind (NCEP/NCAR Reanalysis Project)
- Monthly mean sea ice concentrations (AARI Global Sea Ice Database)
- Probability of landfast ice (AARI Global Sea Ice Database)

The *OILSPILL* model has been applied to provide probabilities of oil contamination. The probability for oil contamination is based on a count of the number of simulated spills where the cell has been visited by oil at least once. The simulated period for each trajectory is 30 days. The start time for each oil spill is drawn randomly within the time period July-September. The *OILSPILL* model also provides statistical distributions of arrival times to shore and stranded amounts of oil, as well as oil drift trajectories. Stranding is defined when an oil drift trajectory enters into a coastal grid cell. The study shows that 10 of 14 scenarios stranded within the simulated month.

TABLE OF CONTENTS

1. Introduction

Sailing the NSR represents a potential hazard to the environment, personal safety and damage on vessels. A major concern is the possible impact on the environment from accidental oil spills either from cargo or bunker fuel. Shallow waters and areas with heavy ice conditions are potential navigation risk areas.

Exploration for oil and gas resources in recent years has indicated that the Arctic may contain some of the world's largest oil and gas reserves. Major projects for development of oil and gas resources in the Barents and Kara Seas are currently underway or planned for the near future. Taking into account the vulnerability of the Arctic environment, these developments could increase the probability for large-scale releases of oil with accociated risks for the Arctic ecosystem.

The overall purpose of this project is to provide oil spill scenario information to the EIA process in INSROP's Sub-programme II. This involves outlining a set of accidental scenarios for oil spills from ships and simulating the drift and fate of oil spills in the NSR area. The oil spill scenarios are limited to tanker accidents, either collision, groundings or interaction with ice.

An oil spill has impacts both in the sea and on shore. The relative importance of these two impacts is handled in Sub-programme II. The environmental impact assessment tool developed in Sub-programme II for quantifying the risk of an oil spill will be useful in planning reponse to an actual oil spill.

Section 2 in this report gives information on historical oil spills and ship accidents in the Arctic. Physical environmental data influencing the oil drift, and available for the study, are described in Section 3. The statistical oil drift model is described in Section 4, while Section 5 presents the results from the simulations.

2. Accidental oil spill scenarios

2.1 Analyses of historical oil spills

According to the IMO data on a worldwide basis, the average annual frequency for accidents involving tankers of 6000 register tonnes or more is:

- 0.31 for collision with other ship or ice
- 0.41 for groundings

Since 1974, the federation ITOPF has maintained a database of oil spills from tankers, combined carriers and barges. This covers all accidental spillages except those resulting from acts of war. The database contains information on both the spill itself (amount and type of oil spilt, cause and location) and the vessel involved. Spills are categorised by size (<7 tonnes, 7-700 tonnes and >700 tonnes).

Figure 2.1 shows the number of oil spills in the period 1970-96. On average the number of oil spills is higher in the period 1970-79 than in 1980-89. From the database, it is notable that a few very large spills are responsible for a high percentage of the oil spilt. For example, in the ten-year period 1988-1997 there were 360 spills over 7 tonnes, totalling 1439 thousand tonnes, but 1003 thousand tonnes (70%) were spilt in just 10 incidents (less than 3%). The figures for a particular year may therefore be severely distorted by a single large incident. Figure 2.2 shows the quantities of spilled oil in the period 1970-96. This is clearly illustrated by 1979 (Atlantic Empress - 287,000 tonnes), 1983 (Castillo de Bellver - 252,000 tonnes) and 1991 (ABT Summer - 260,000 tonnes).

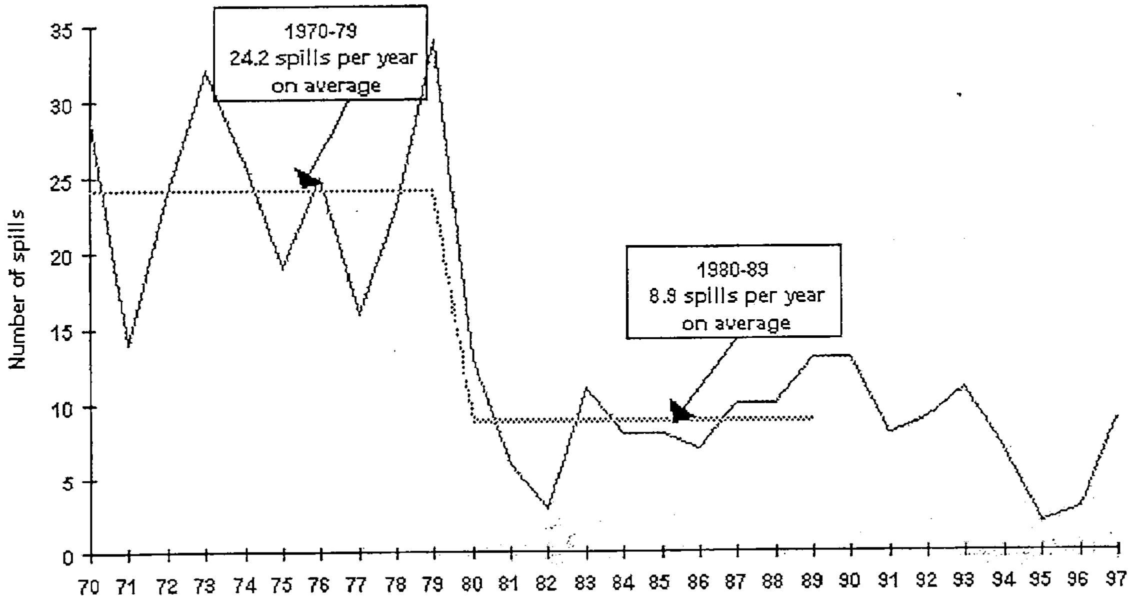


Figure 2.1 Number of spills over 700 tonnes (ITOPF).

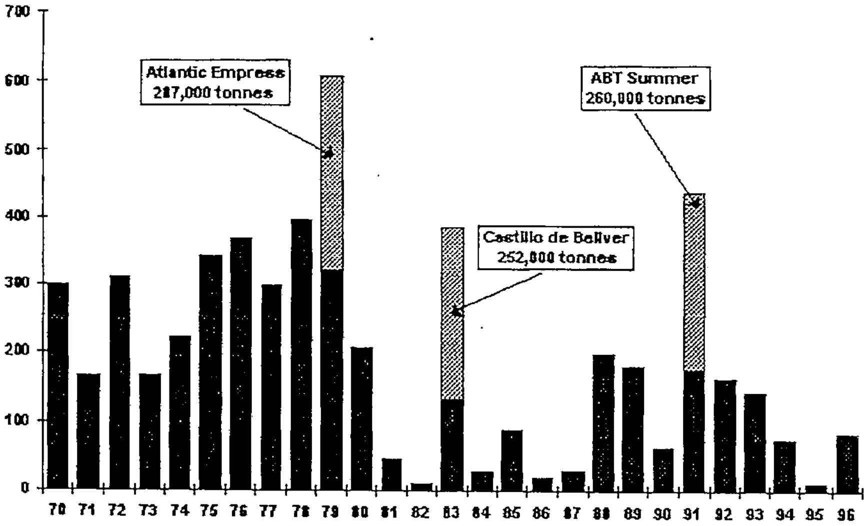


Figure 2.2 Quantities of spilled oil (ITOPF)

Table 2.1 shows that most spills from tankers result from routine operations such as loading, discharging and bunkering which normally occur in ports or at oil terminals. Further, the majority of these operational spills are small, with some 92% involving quantities of less than 7 tonnes. The table also shows that accidents involving collisions and groundings generally give rise to much larger spills, with a fifth involving quantities larger than 700 tonnes.

Table 2.1: Incidences of spills listed by cause, 1974-1997 (ITOPF)

	< 7 tonnes	7-700 tonnes	> 700 tonnes	Total
OPERATION				
Loading/discharging	2757	288	15	3060
Bunkering	541	24	0	565
Other operations	1162	47	0	1209
ACCIDENTS				
Collisions	144	225	85	454
Groundings	217	186	101	504
Hull failures	547	67	39	653
Fires and explosions	149	16	20	185
OTHER	2213	157	34	2404
Total	7730	1010	294	9034

The worldwide statistics on tanker accidents are not directly applicable to the NSR. Most tankers used in the Arctic are equipped with double sides and double bottoms. Tankers transport oil products to consumers on the Arctic coast in the periods of summer and winter navigation. The largest volumes are observed in the summer season, from June to September. The *most intensive* navigation is in the Barents Sea and in the western part of the Arctic, where most oil transportation is carried out at the present time. However, the volume will increase significantly in the future due to deliveries of crude oil from the drilling platforms of the Prirazlomnoye field and from the Ob'Bay.

PAME (1996) estimated the legal discharges of oil from ships using the NSR to be about 1.4 tonnes/year, most of this from ordinary carriers. With significant prospects from offshore oil and gas in the Kara and the Barents Sea, future expansion of ship and tanker traffic through the NSR is likely, thus increasing legal discharges, but also the probability of major tanker or other shipping-related spills.

Blowouts, spills, and leakage during development and transportation of petroleum reserves and products pose the largest oil pollution threat to terrestrial and aquatic ecosystems in the Arctic. So far, few oil spills have occurred in the Arctic. Pipeline ruptures and leakages, such as experienced at Usinsk in 1994-95 with 100 000 tonnes of crude oil flooding the rivers and lakes; and tanker accidents, like that of Exxon Valdez in Alaska in 1989 with about 35 000 tonnes spilled, are examples of oil contamination over large areas. Oil blowouts at production sites have not been experienced in the Arctic.

In 1997, four oil spills were registered in Russia (Oil Spill Intelligence Report, 1997):

- Nagayevo Bay, fish factory
- Nizhnevartovsk, pipeline
- Novorssiysk, pipeline
- Saratov, pipeline (Samara-Tikhoretskaya)

2.2 Ship accidents in the Arctic

Murmansk Shipping Company (MSC) has performed an analysis of ship accident data for the time period 1954-90. More than 800 accident cases were considered and the analysis was grouped according to the ships ice class and to their icebreakers assistance. In some cases ice damages of transport ships and icebreakers result from several reasons simultaneously.

The MSC analysis of the 1954-1990 period identified the 1983 summer Arctic navigation as the heaviest and the 1990 summer Arctic navigation as the lightest. During the summer period June-October 1983 a total of 104 ships were damaged in accidents and the majority of the incidents happened in the eastern part of the route. In 1990 and 1993 only 15 and 7 accidents were registered and the accidents happened mainly in the western part. The total number of ship sailings is not available and the accident data cannot be used to quantify accident risk for sailings. The database shows an increase in damages in 1983 during periods with favourable ice conditions. The main reasons may be the high number of ships with low ice class, high number of ships sailing alone, or reduced attention of the navigators. A statistical analysis of the AARI Sea

Ice Charts shows a high fraction of open water simultaneously with the presence of old ice in this period, and may explain the high accident numbers.

2.3 High risk regions

The MSC report shows that the eastern part of the NSR has a greater accident risk than the western part, when comparing average number of accidents with the total number of navigating ships. During the 1965 navigation season in the eastern Arctic, about 72 ships suffered ice damages and accidents. This represents more than 40 % of the total number of navigating ships. Most ship damages occur during heavy ice conditions and with ships of ULA and L1 classes. The majority of ice damages on ships of L1 class occurs during assistance from icebreakers. The ships of ULA class are most frequently damaged when sailing alone. In the Arctic seas about 40 % of the damages occur in the Kara Sea where the intensity of sailing is highest. About 20 % of the accidents occur in the Laptev Sea and the East Siberian Sea while only about 14 % occur in the Chukchi Sea.

Baskin et al. (1997) pointed out the Kara Strait, the segment from Bely Island to Yenisey Bay, Boris Vil'kitsky strait and the segment from East-Siberian Island to the Longa Strait as regions with high occurrence of ice accidents (see Figure 2.3). The accidents are located in regions of the ice massifs Novaya Zemlya, Severnaya Zemlya, Ayon and Wrangel with high concentrations of multi-year ice both in winter and summer seasons.

The MSC analyses also show that most of the accidents occur at the end of the navigation period (August-September). The analysis shows an increase in damages during periods with favourable ice conditions. The main reasons for that may be the high number of ships with low ice class, high number of ships sailing alone and reduced attention of the navigators.

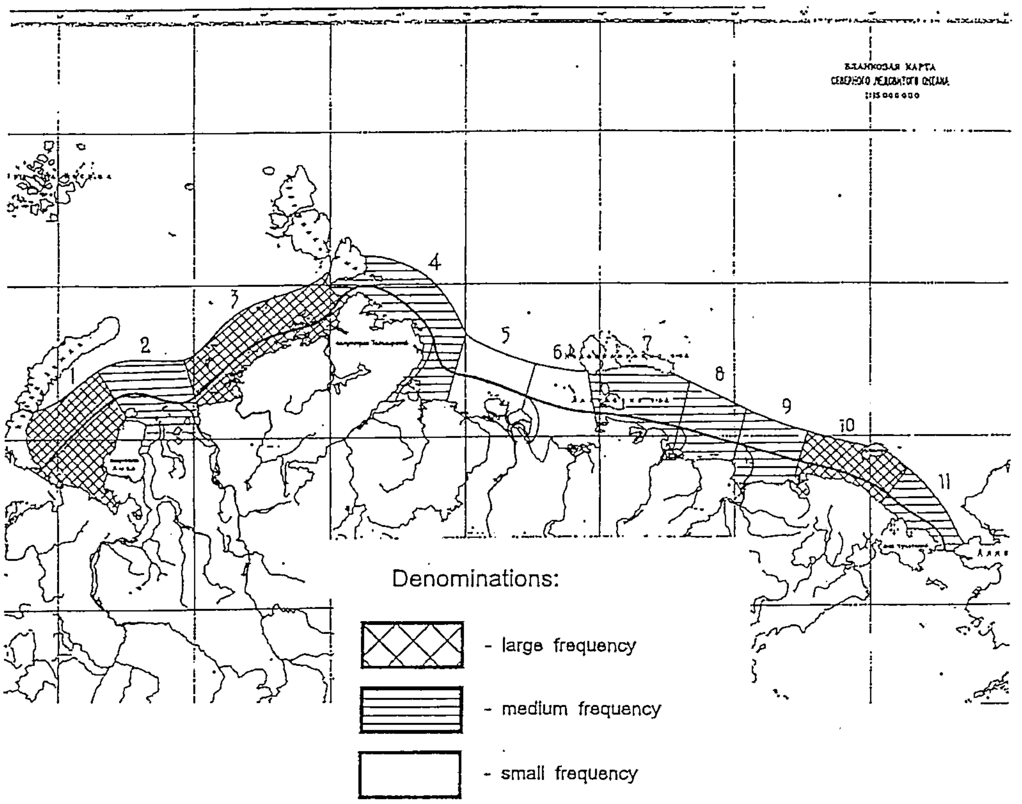


Figure 2.3 Frequency of ship accidents along the NSR (Baskin et al., 1997)

2.4 Amount of spilled oil

In 1994, 500 000 tonnes oil were delivered from Murmansk, of which 350 000 tonnes were exported to Europe and the remaining amount was delivered to consumers in the Russian Arctic. The largest volumes are shipped in the summer season, from late June to September.

The report by Tsoy et al. (1996) indicates that if double hulled tankers are used, and if these are ice strengthened, properly maintained and operated only in conditions for which they were designed, the risk of pollution due to ice damage or ship collision is very small. Table 2.2 shows the expected amount of oil spill for different events. The expected oil spilled from Samotlor due to groundings is estimated to be about 400 m^3.

Table 2.2 Expected amount of oil spill for different events (Tsoy et al., 1996)

Vessel type	Vessel dwt	Ship collision (m^3)	Grounding (m^3)	Ice interaction (m^3)
Samotlor	16800	0	400	0
Ventspils	6300	130	90	200
Partizansk	2900	60	50	40

Grachova et al. (1998) reported that the size of an average oil spill might be 1/48 of the transported volume by use of the *Helcom method.* Based on this assumption, the probable oil spill from the "Samotlor" type tanker is 374 tonnes and from a large–capacity tanker 2800 tonnes. Table 2.3 shows expected oil spill for the vessels Samotlor and Ventspils. The oil spill due to groundings is estimated to be about 1100 m^3 for Samotlor. This figure is about three times higher than the estimate in Table 2.2.

Table 2.3 Expected amount of oil spill for different events

Vessel type	Vessel dwt	Ship collision Oil spill (m^3)	Grounding Oil spill (m^3)
Samotlor	16800	428	1107
Ventspils	6300	41	116

On 2 January 1997, the Russian tanker *Nakhodka* that was heading from Shanghai (China) to Petropavlovsk Kamchatskiy (Russia) with 19 220 tonnes of C grade heavy cargo oil in her tanks, broke in two in the Sea of Japan. One part of the ship sunk and the other part drifted ashore at the beach and contaminated the shore. Spilled oil drifted ashore and fouled more than 200 km of shoreline. The total amount of spilled oil was estimated to 8 663 m^3 (Arita et al., 1998).

2.5 Accidental oil spill scenarios

According to the MSC report, most of the accidents occur at the end of the navigation period (August-September). Therefore, the time period July-September has been chosen for the oil spill scenarios. The amount of oil spilled during a tanker accident is uncertain, and an amount of 3 500 tonnes has been chosen for the scenarios.

The coastal route S and the high latitude route N, as described in the Working Package 1 (Baskin et al., 1998), are used when selecting positions for the scenarios. A total of 14 positions along the routes (see Figure 2.4) are identified and used in the specification of the accidental oil spill scenarios in Table 2.4.

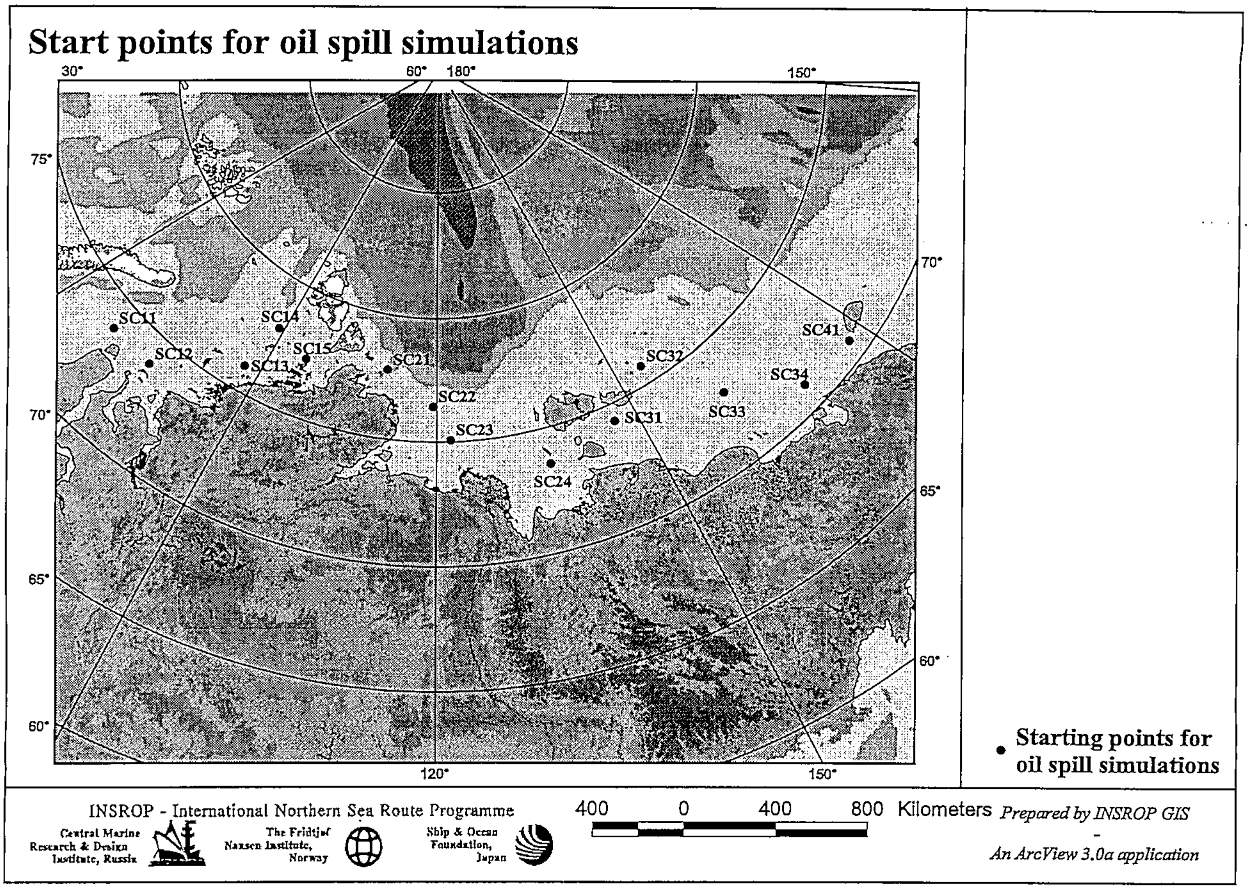


Figure 2.4 Location of the oil spill scenarios

Table 2.4 Accidental oil spill scenarios along NSR

Scenario	Position	Work Package 1 id.	Time of year	Amount (tonnes)
SC 11	73° 50' N, 68° 30' E	S-01	Jul-Sept	3 500
SC 12	73° 50' N, 75° 41' E		Jul-Sept	3 500
SC 13	76° 00' N, 87° 20' E	S-03	Jul-Sept	3 500
SC 14	77° 58' N, 89° 00' E	N-02	Jul-Sept	3 500
SC 15	77° 20' N, 96° 00' E	S-04	Jul-Sept	3 500
SC 21	77° 47' N, 110° 48' E	N-05	Jul-Sept	3 500
SC 22	76° 26' N, 119° 20' E	N-07	Jul-Sept	3 500
SC 23	75° 04' N, 122° 06' E		Jul-Sept	3 500
SC 24	73° 32' N, 136° 00' E	S-09	Jul-Sept	3500
SC 31	74° 18' N, 146° 38' E	S-11	Jul-Sept	3 500
SC 32	75° 44' N, 154° 20' E	N-09	Jul-Sept	3 500
SC 33	72° 58' N, 161° 45' E	N-10	Jul-Sept	3 500
SC 34	71° 00' N, 170° 00' E	N-11	Jul-Sept	3 500
SC 41	70° 45' N, 177° 39' E	N-13	Jul-Sept	3 500

3. Physical environment data

The physical data required for the oil spill model are time series of wind data, surface ocean current and sea ice concentration. Time series of wind data have been derived from NCAR for the period 1968-97. Gridded ocean current data for the Kara Sea are derived from the field experiment EPOCA-95 (King et al., 1996) and the Coriolis laboratory at SINTEF (Mc Climans et al., 1997). Gridded ocean current data for the entire NSR region has been derived from AARI. The Global Sea Ice Database (from AARI) covering the period 1967-90 is used to provide data on sea ice concentrations and fast ice for the oil spill model.

3.1 Wind data

The wind data has been derived from the NCEP/NCAR Reanalysis Project, which has been an effort to reanalyze historical data using state-of-the-art models. The data are part of the *ds090.0* reanalysis archive. The 10 m U and V wind data cover the time period 1968 Jan 01 to 1997 Aug 31 with a temporal resolution of 6 hours. The spatial grid is gaussian with dimension of 192 (zonal) by 94 (meridional). The grid starts at 88.542 °N and goes to 88.542 °S with increments of 1.904 degrees, and at 0 °E and goes eastward by increments of 1.875 degrees. Figures 3.1-3.4 show monthly mean wind data from selected seasons of the year 1980. In winter, high pressures over the continents and low pressures over the northern Pacific and Atlantic oceans dominate the lower tropospheric circulation of the northern polar region. In summer, the continental high pressure cells disappear, and the oceanic low pressure cells weaken, particularly in the north Pacific. Northward transport from mid-latitudes decreases accordingly. The climate is on the whole characterised by moderate winds with a mean speed of 3-8 m/s in the summer season. Wind speeds higher than 15 m/s are relatively seldom observed in the Kara Sea. Winds in the Laptev Sea and the East-Siberian Sea are normally weaker than in the Kara Sea.

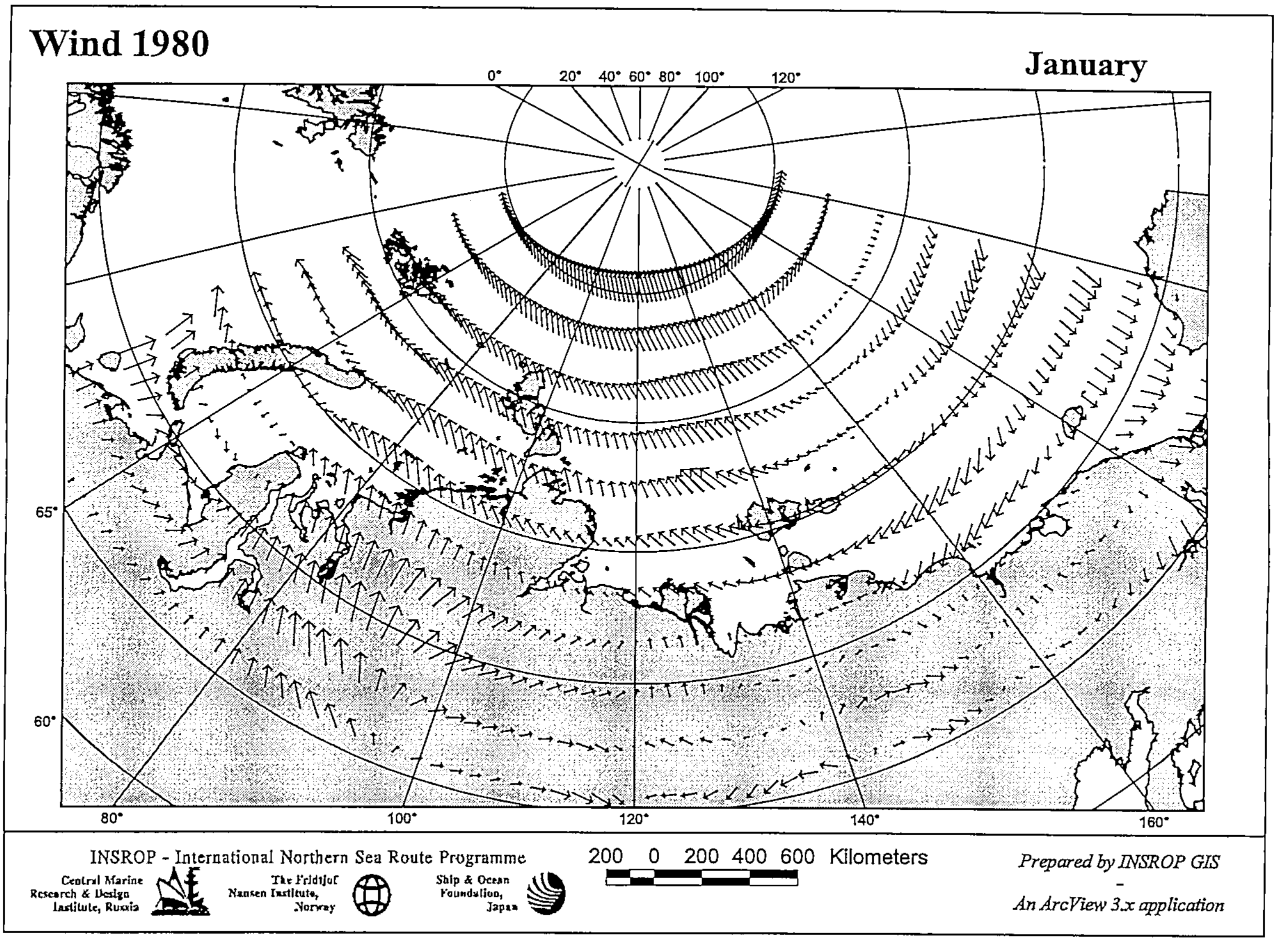


Figure 3.1 Monthly mean wind velocity, January 1980.

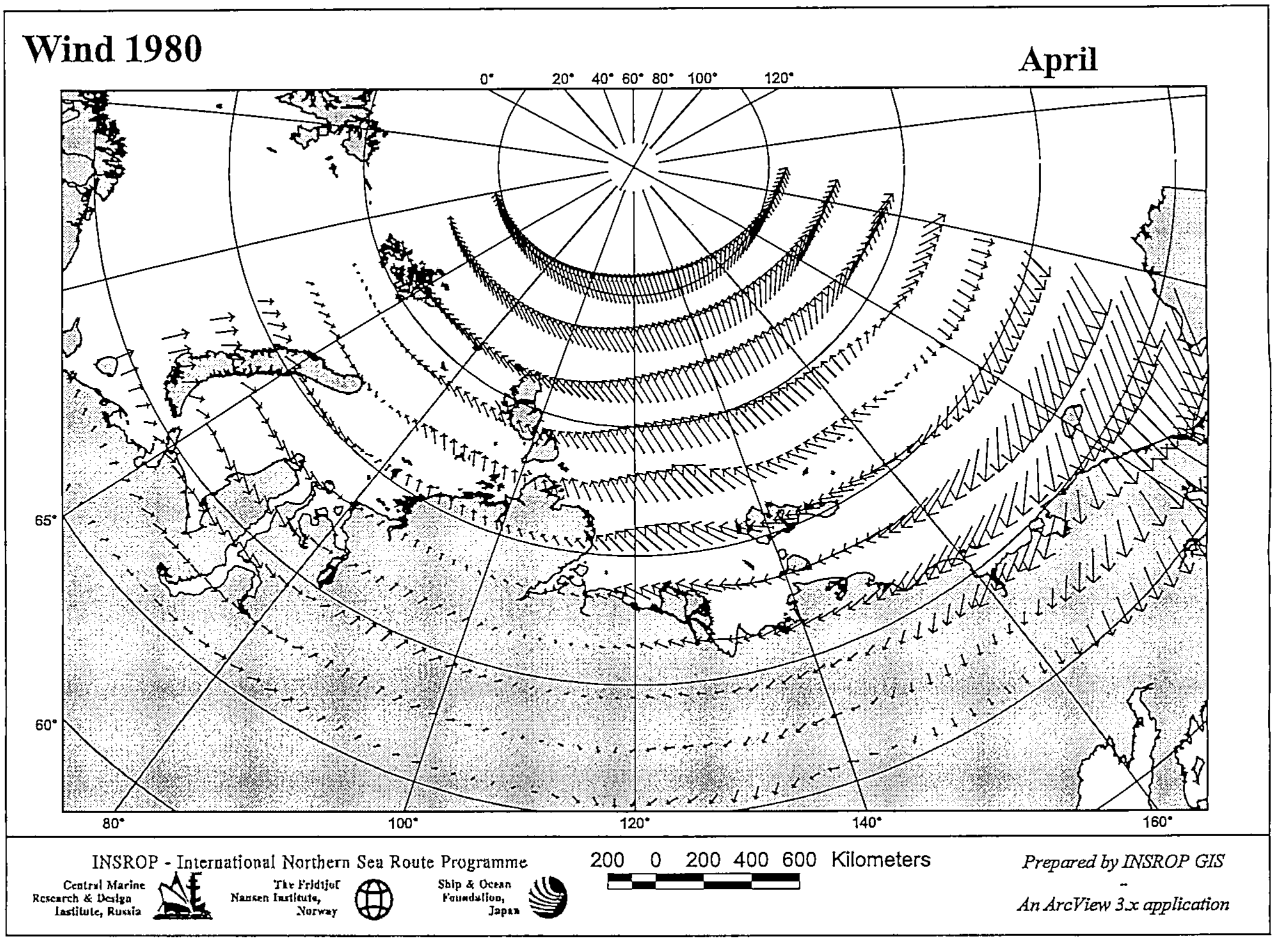


Figure 3.2 Monthly mean wind velocity, April 1980.

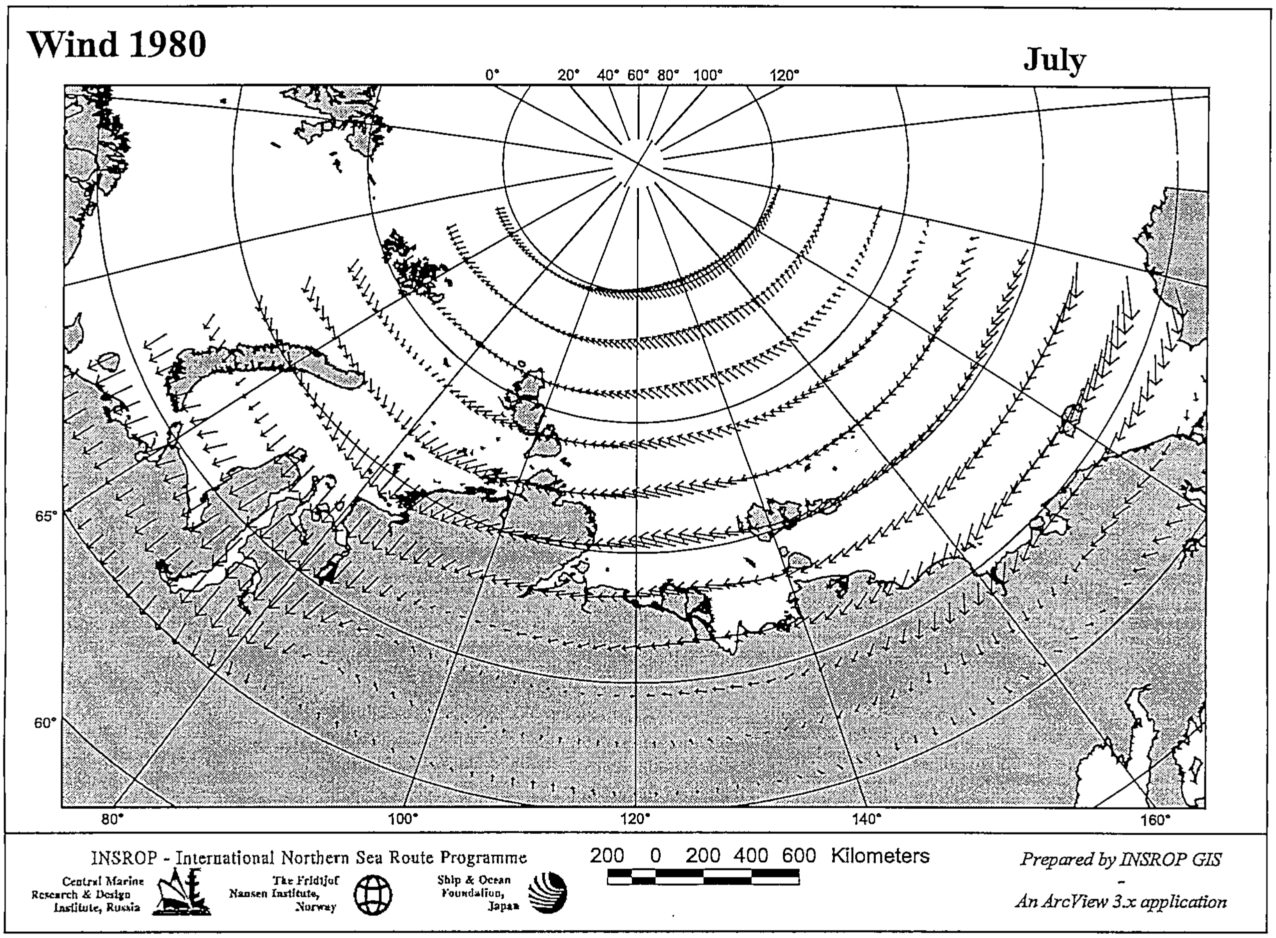


Figure 3.3 Monthly mean wind velocity, July 1980.

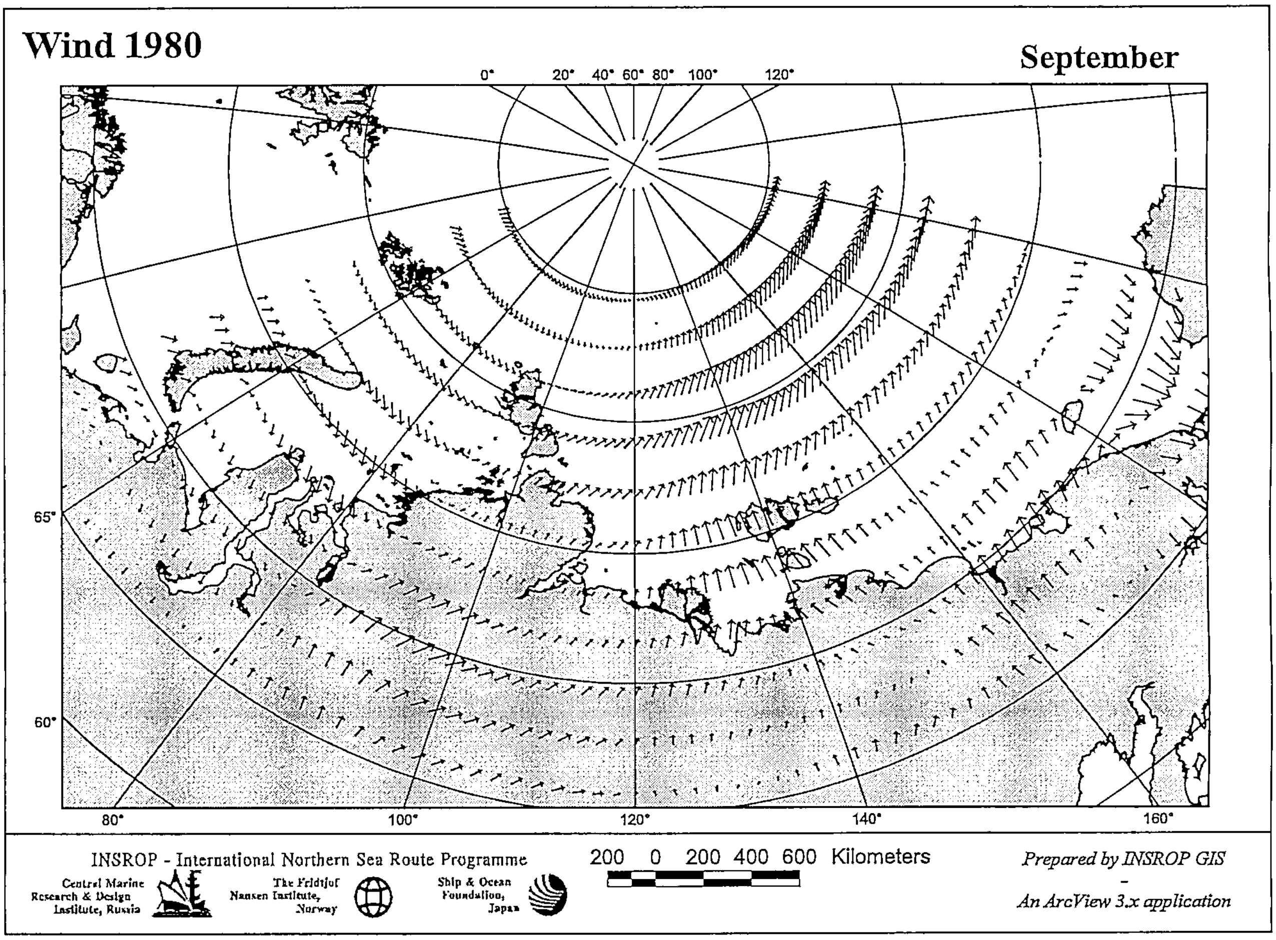


Figure 3.4 Monthly mean wind velocity, September 1980.

3.2 Ocean current data

Several sources of ocean current data have been derived for this study. The first phase of the project concentrates on the Kara Sea and several data sets for the Kara Sea were collected. Gridded ocean current data for the Kara Sea were derived both from EPOCA-95 (King et al., 1996) and the Coriolis laboratory at SINTEF (Mc Climans et al., 1997).

Available field data from the Kara Sea is sparce, both in time and space. Field data from R/V H.U. Sverdrup during the late summer cruise of 1995 (King et al., 1996) have been made available for the study. During the cruises, a bottom tracking ADCP mounted on the ship provided detailed description of the current fields. The surface current data has been interpolated to a grid with an e-folding distance of 100 km and is shown in Figure 3.5. The spatial resolution of the interpolated data is 0.27 °N x 1.03 °E.

A laboratory model of the eastern Barents and Kara Seas, which rotates to produce the effects of the earth's rotation, has been used to simulate the transport routes for various water masses in these shelf seas (McClimans et al., 1997). The model domain, together with the sources and sinks that are used to force the flow, is shown in Figure 3.6. The model results show a good validation to the field observations of Loeng et al. (1994) in the northern region and of Maximov (1936) in the Kara Strait. The general character of the ocean circulation, based on surface particle trajectories, is shown in Figure 3.7.

The laboratory results, without wind, show that the circulation pattern is much more complicated than the existing maps indicate, with both fine scale geographical and temporal variability. From particle paths, the tidal residuals over the rugged topography cause many regions of recirculation, like the anticyclonic circulation around Sverdrup Island, to the north of Dikson. Tides over topography and winds steer the river plumes over the shallow delta in the Kara Sea. Only a small portion of the Yenisey plume is steered along the coast to the east, in agreement with available field observations. Most of the river discharge flows northwest toward the delta edge (50 m isobath), subsequently following the delta slope northeast to the Voronin Trough.

Surface ocean current data have also been derived from AARI. The data are based on direct measurements of current speed and direction in the subsurface sea layer (5-10 m) at buoy moorings during the period 1956 to 1995 in the summer hydrological season (August-September). Totally 107 buoy stations are included in the database with durations from two weeks to one month. The time interval of observations was one hour. The data are interpolated to a grid with resolution of 100 km. The seasonal current was interpolated to the grid points by use of the weighted means. If no data exist within the square, climatic fields of water density are used to compute geostrophic velocities. Figure 3.8 shows the ocean current data derived from AARI.

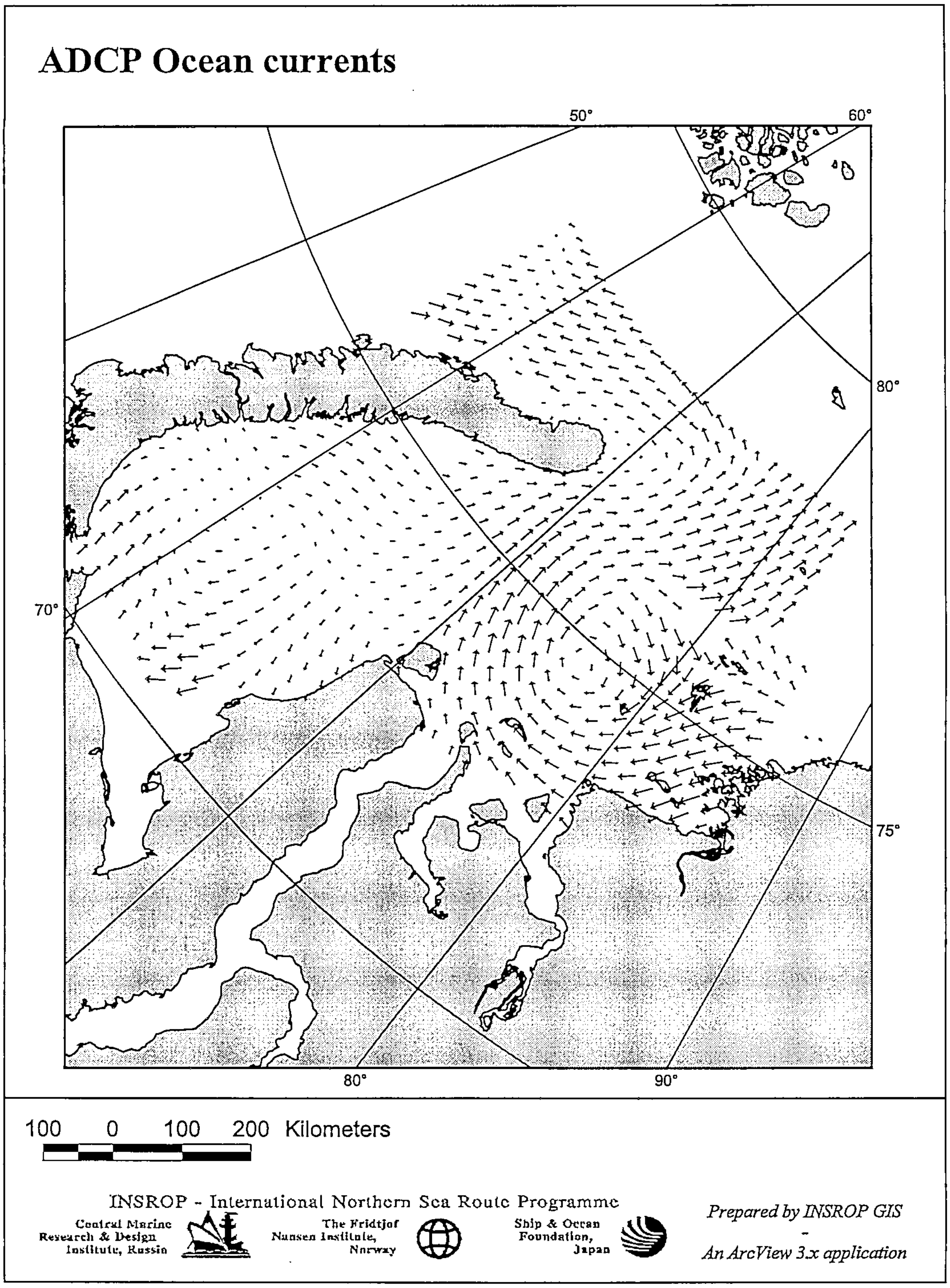


Figure 3.5 Surface ocean currents from ADCP measurements (EPOCA, 1995)

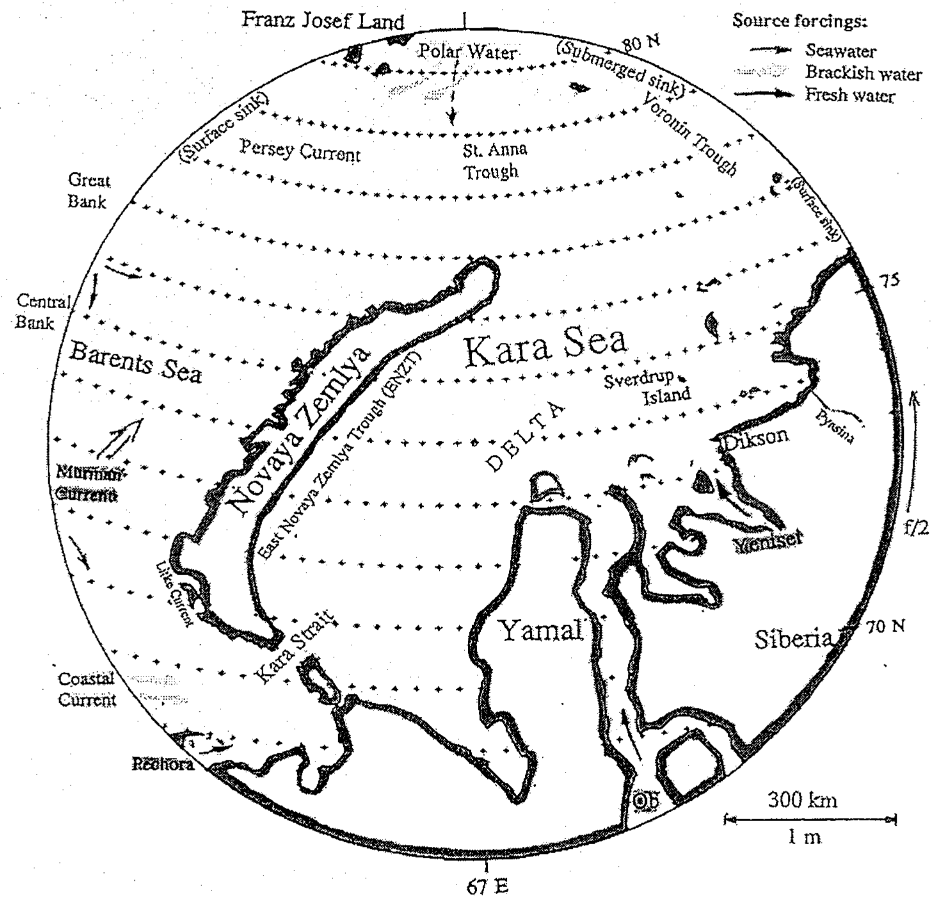


Figure 3.6 Map of region modelled in the laboratory (Mc Climans et al., 1997)

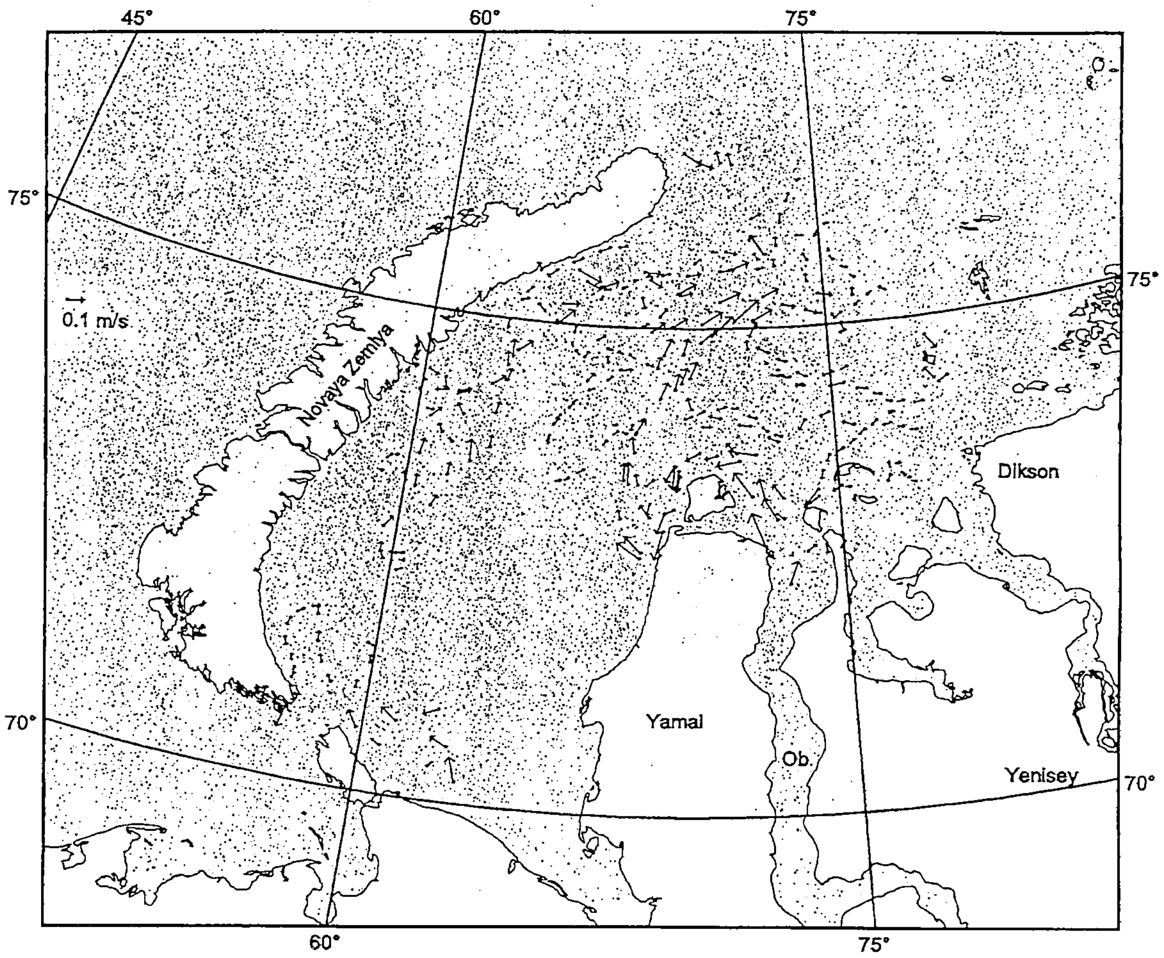


Figure 3.7 General character of the surface ocean circulation in September-October (McClimans et al., 1997)

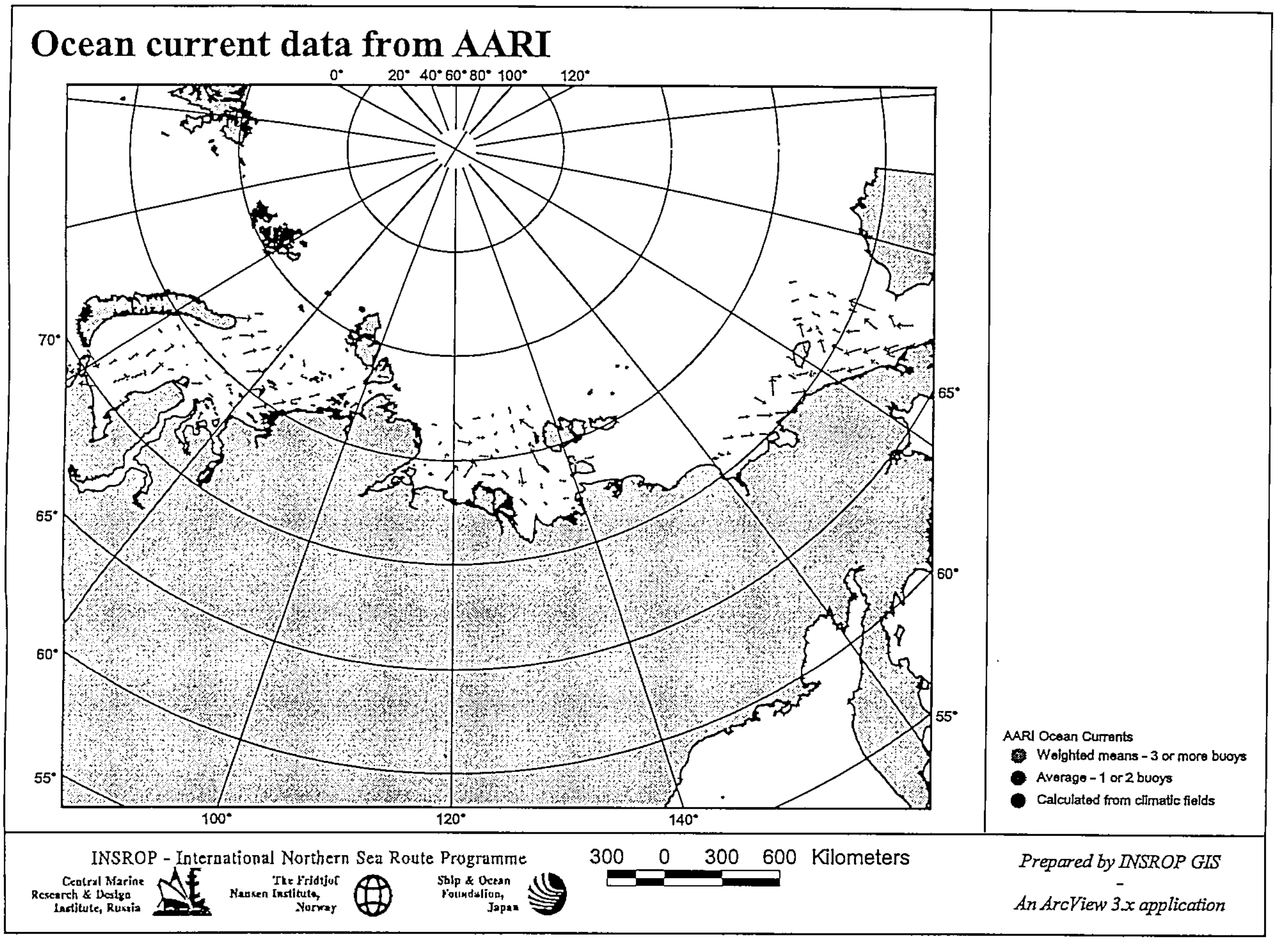


Figure 3.8 Surface ocean currents (AARI)

3.3 Sea ice data

The sea ice data applied in the oil drift simulations are derived from the AARI Sea Ice Charts database covering the period 1967-90. The data have been statistically analyzed on a monthly basis in the INSROP report by Vefsnmo and Løvås (1996). Variability analyses are carried out for parameters such as total ice concentration, ice thickness, fraction of old ice and presence of fast ice on a monthly basis.

The ice conditions along the NSR are extremely dynamic, leading to large annual, seasonal and regional variations. Large ice fields are observed in the same regions each summer and are obstacles to ship traffic along the NSR, since the massifs contain significant concentrations of multi-year ice and frequently heavily hummocked ice is present.

During the winter period the coastal zone is occupied by fast ice which is non-uniformely developed. The fast ice extent is generally narrow except in the eastern Kara Sea where it may extend up to 150-200 km seaward. The Laptev Sea has the largest expanse of fast ice from January to June. Fast ice begins to form in mid-October in the fresher water of the river estuaries and expands to cover most of the continental shelf up to 500 km from the mainland. The thickness of the fast ice commonly reaches 200 cm and may grow up to 250 cm in severe years. The fast ice in the East-Siberian Sea extends 250-500 km from the mainland and may reach a thickness of 150-170 cm in late winter. Only a narrow band of fast ice (about 10-15 km) forms along the mainland coast and around Wrangel Island. Fast ice is very seldom observed in September and when fast ice has been observed the extension has been very limited.

Seasonal freeze-up of the sea begins in September at the northern ice edge and along the rapidly cooling mainland coast. Freeze-up is complete by mid-October. Figure 3.9 shows the average ice concentrations in August. On average, the total ice concentration is high in October due to a high fraction of new ice. East of Dikson the concentration is about 90-100 % for the whole region. During mild years no ice is registered in the southern part of the sea except for the Severnaya Zemlya massif.

In some years, no old ice is observed in the region except in the Severnaya Zemlya massif. On average, the main old ice is found in the ice massif, with Severnaya Zemlya and the Ayon massif showing the highest concentrations (up to 70 %). On average, no old ice is found in the western part of the Kara Sea and the southern part of the Laptev Sea. In extreme years, the fraction of old ice is very high, up to 90-100 %, being observed both in the Kara Sea and the Laptev Sea.

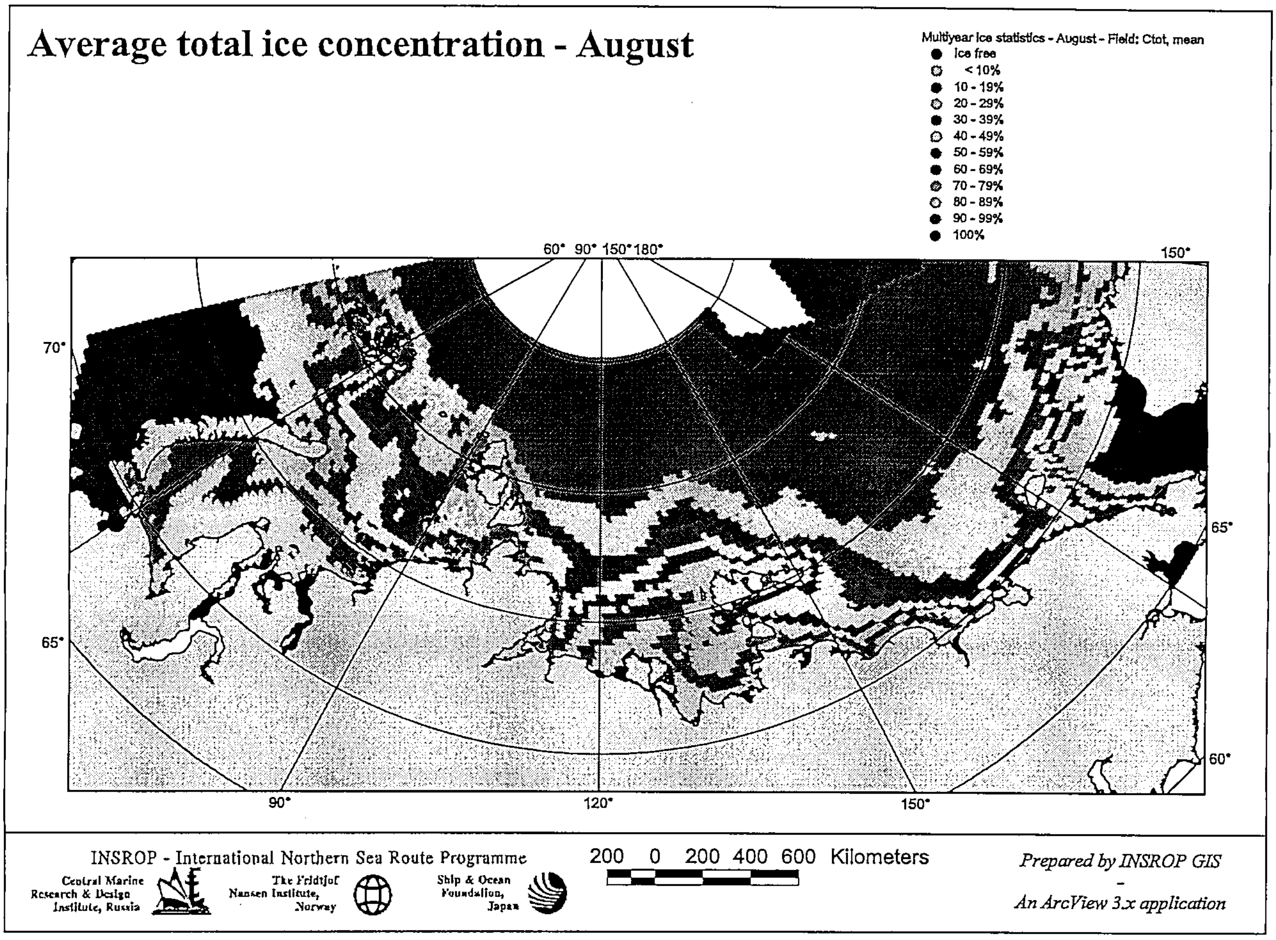


Figure 3.9 Monthly mean sea ice concentration in August

4. Statistical oil drift model

In order to assess how pollution from NSR shipping will impact the environment, it is necessary with a statistical model to provide drift tracks of the pollutants. In order to quantify the assessment of possible conflict between pollutants and vulnerable resources, statistical oil drift data are needed to give a measure of the potential impacted area.

The statistical oil drift model *OILSPILL* is based on the trajectory concept which means that the model simulates the drift and the weathering of the oil as individual points of mass released at different times within the available historical time series of wind data. Advection and loss of oil due to evaporation and natural dispersion as well as oil stranding are the main physical processes accounted for in the model.

The oil drift statistics are obtained by repeating the simulations of oil drift from chosen spill sites for a large number of spill scenarios, each based on monthly mean climatological surface currents and historical records of ice coverage and wind speeds. The oil drift mapping is performed for different seasons of the year in order to reflect the seasonal variations in wind climate and ice conditions.

4.1 Oil drift model

The major factors to be taken into account for oil drift and spread in broken ice are the ice coverage and the quality of the oil. Behaviour and fate of oil in broken ice is schematically shown in Figure 4.1. Oil in regions with low ice coverage will behave practically unaffected by the ice, i.e. drift and spreading will proceed as under open water conditions. In moderate to dense ice coverage, oil drift will be governed by the movement of the ice field. Spreading rates will be reduced, compared to open water conditions, due to restrictions imposed by narrow channels between broken ice.

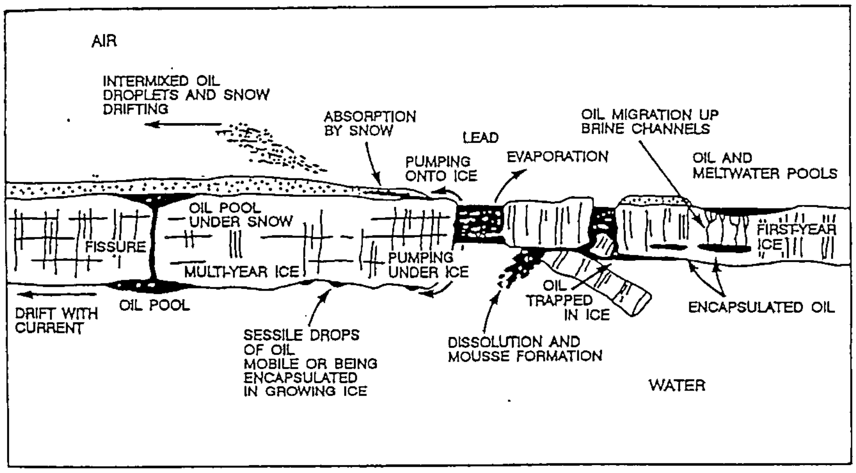


Figure 4.1 Behaviour and fate of oil in broken ice (from Bobra and Fingas, 1986).

When weathering effects are considered, the major factors to be taken into account, in addition to the factors known to be active under temperate conditions, are:

- Cold sea temperatures and subcooling of oil due to cold ambient temperatures will cause reduced evaporation rates and increased viscosity.
- Water in oil emulsions may be more stable once formed, due to increased oil viscosity in cold temperatures.
- Broken ice reduces the exposed oil surface by limiting the lateral spreading of the oil - thus reducing the rate of evaporation.
- Moderate to dense ice cover may shelter the oiled surface from the wind - reducing the evaporative loss rate.
- Reduced turbulence due to the wave damping effects of moderate to dense drifting ice causes reduced loss of oil to the water column - as well as reduced rate of emulsification.

The spreading of oil in the presence of ice may be quite different from that on open water. Initial spreading is dominated by gravity forces. Ice floes will normally have a freeboard larger than the initial oil thickness and hence reduce the spreading of oil both as a barrier for oil spreading perpendicular to the ice floe edges and due to interfacial tension at the ice/oil interface for oil spreading parallel to the ice floe edges. The interfacial tension is small in the initial spreading phase where gravity forces dominate, but as the oil slick gets thinner the effect of interfacial tension increases. Oil spilled in slush, grease ice or brash ice will have a higher equilibrium thickness than oil spilled on open water between ice floes.

4.1.1 Oil drift in ice

The presence of ice will influence the oil drift. Oil drifting in dense ice will follow the ice drift. Ice drift velocities are not available, so the ice drift is estimated from wind-induced drift and a seasonal averaged background current.

$$\mathbf{U}_{\text{oil}} = \mathbf{U}_{\text{current}} + \mathbf{k}\,\mathbf{U}_{\text{wind}}$$

The wind-induced drift is derived from the local surface wind by a wind-drift factor. It is assumed that the wind-drift factor depends on the ice concentrations, decreasing from the value of 3.5 % normally used for oil drift in open water, to 2 % in dense pack ice. The wind-induced drift is in general found to deviate from the wind direction by a certain angle θ. In open water, the angular deviation is normally assumed to be in the order of 15°, while the deviation may be larger for ice drift in dense ice, about 30°.

During the oil spill experiment in the Barents Sea (Sørstrøm et al., 1994), the wind drift factor was found to be about 2.5 % of the wind speed in a height of 10 m. The deviation between ice drift and the wind direction was on average 24°. The ice concentration was relatively high, about 60-90 %, during the experiment. Both the wind drift factor and the angular deviation depend on the ice concentration.

The follwing asumptions are made in the model:

Wind drift factor: $k = (1\text{-}c)\, k_o + c\, k_i$ where $k_o = 0.035$ and $k_i = 0.02$

Angular deviation: $\theta = (1\text{-}c)\, \theta_o + c\, \theta_i$ where $\theta_o = 15$ and $\theta_i = 30$

The contributions from tidal variations are neglected in the model. It is assumed that the tidal current will have minimal influence on the long time transport of the oil far from shore, unless it is pressed through narrow passages like the Kara Strait.

The start time for each oil spill is drawn randomly within the time span of the wind data or limited to a specific season of the year. Oil entering a cell with fast ice will be stopped until the wind eventually turns at a later stage.

4.1.2 Weathering of oil

The weathering processes, taken into account in the model, include loss of oil due to evaporation and natural dispersion. Both natural dispersion and evaporation rates will be influenced by the presence of sea ice. Natural evaporation depends mainly on the wave conditions, which in the open sea may be related to the wind speed. Waves propagating into the ice field will be damped by the presence of ice floes. The evaporation rate will also be influenced by the presence of sea ice.

Based on the experimental oil spill carried out in the Barents Sea (Sørstrøm et al., 1994) the evaporation was only about 20 % after 5 days. Oil spilled in ice will spread more slowly than in open water and the spreading depends strongly on the ice conditions. Since spreading processes will not be explicitly represented in the model, the local ice concentration is used to parametrize this difference in evaporation rates.

In open water, the dispersion rate is normally assumed to be in the order of 10 % per day in 8 m/s wind and increasing proportionally with U^2. In the model, natural dispersion is accounted for by a first order decay process, i.e. $dQ_{dis}/dt = -\ \beta\ Q_{dis}$ where β is the wind-dependent dissipation rate. For oil in ice-infested waters, the dispersion rate will be reduced due to wave damping in the ice field. In the model, it is assumed a dispersion rate of the type $\beta \propto (1\text{-}c)^2$.

4.1.3 Oil stranding

Stranding of oil is determined by a check of the ocean/land matrix. If the matrix value is 1, it is a land point and the particle is assumed to be stranded. In regions of the ice field where fast ice is prescribed by the ice database, oil will not be allowed to enter. In the winter season fast ice is present along the NSR coast and the thickness may reach 200 cm. The fast ice boundary will be an important barrier for the oil transport and important limitation of the oil spreading.

4.2 Geophysical data input

The statistical oil drift model is based on the assumption that the major contribution to the variability in the oil drift pattern comes from the wind induced current, while the residual current depends only on the season. The statistical oil drift model simulations for the NSR region are based on the following data:

- Monthly averaged surface current (EPOCA'95, AARI)
- Time series of surface wind (NCEP/NCAR Reanalysis Project)
- Monthly mean sea ice concentrations (AARI Global Sea Ice Database)
- Probability of landfast ice (AARI Global Sea Ice Database)

All the data are described in Section 3. Two data sets for ocean currents are used. The ADCP measurements from EPOCA'95 is used west of 85 °E, otherwise the AARI current is used. The ocean current is kept constant in time during one simulation. The resolution of the AARI ocean current data is sparse and limited to a narrow region along the NSR. When applying the data in the simulations, the nearest gridpoint within a radius of 100 km to the oil drift trajectory is used.

The wind data are interpolated both in time and space. The temporal resolution is 6 hours and a linear interpolation in time is applied. Each component of the wind is interpolated in space by using a weighted average method.

The monthly mean sea ice concentrations are linearly interpolated in time. Since the ice concentration value is representative for the whole grid cell, no interpolation in space is applied. When the probability for fast ice is greater than 90 % in a month and the total ice concentration is 100 %, the grid cell is assumed to be fast ice.

4.3 Oil type and spill conditions

Both the weathering properties of the oil and the initial film thickness will influence the amounts of remaining oil. The evaporation and the dispersion rate will depend on type of oil. The winter diesel fuel and arctic fuel are the largest part of the oil transportation along the NSR. For the oil spill simulations, a medium light crude oil with density 835 kg/m^3 is used.

During the simulations it is assumed that 3 500 tonnes of oil is released during one day. By using the Fay spreading formula for continuous leakage (Fay, 1991), the initial oil film thickness has been simulated to be 3.3 mm for open water conditions. Each oil drift trajectory has a duration of 30 days.

4.4 Output data

The oil drift model is run in a grid with spatial resolution of 15 km x 15 km and all the results are presented in this grid. The output from the model concentrates on the probability of oil contamination. However, the model also provides statistical distributions of arrival times to shore and stranded amounts of oil, as well as oil drift trajectories. For each scenario, a total of 600 oil drift trajectories are simulated.

The probability for oil contamination is based on a count of the number of simulated spills, where the cell has encountered oil at least once. The probability of contamination is given as the ratio between this number and the total number of simulated spills in the chosen season. The quantity of oil within a grid cell has no influence on the probability.

5. Statistical oil spill data

This section presents the results obtained from the statistical oil drift simulations for the 14 scenarios presented in Table 2.4. The presentation is divided into three groups:

- Probability of oil contamination
- Oil drift trajectories
- Statistical distribution of arrival times to shore and stranded amounts of oil

5.1 Oil drift trajectories

A total of 600 oil trajectories have been simulated for each scenario. One release from each scenario is presented in Figures 5.1 - 5.3. The simulated period for each trajectory is 30 days. The start time for each oil spill is drawn randomly within the time period July-September between 1968 and 1997. Once a simulation starts, it uses actual historical time series of wind data and monthly mean data of ice concentration and ocean current.

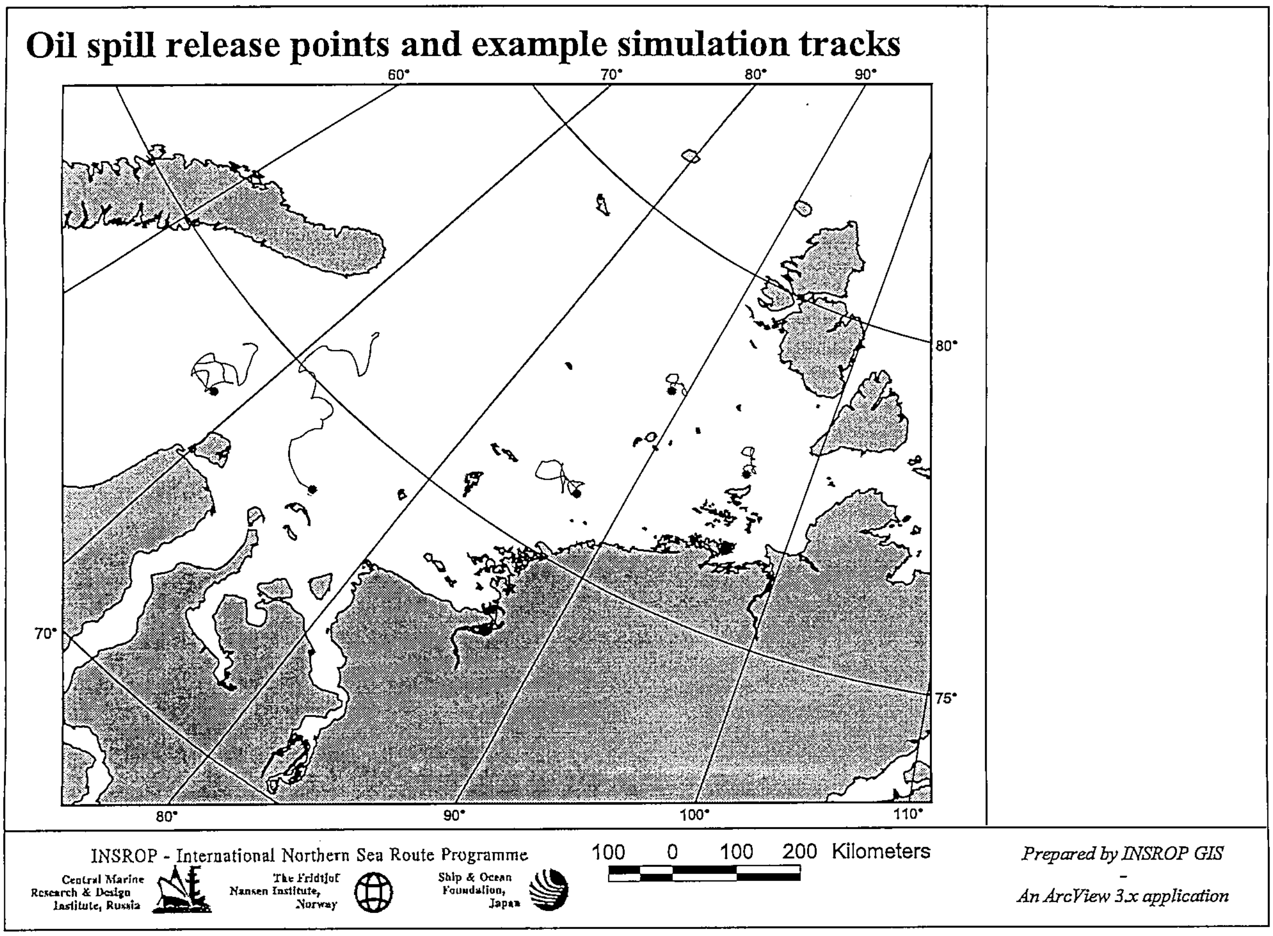


Figure 5.1 Oil drift trajectories in the Kara Sea

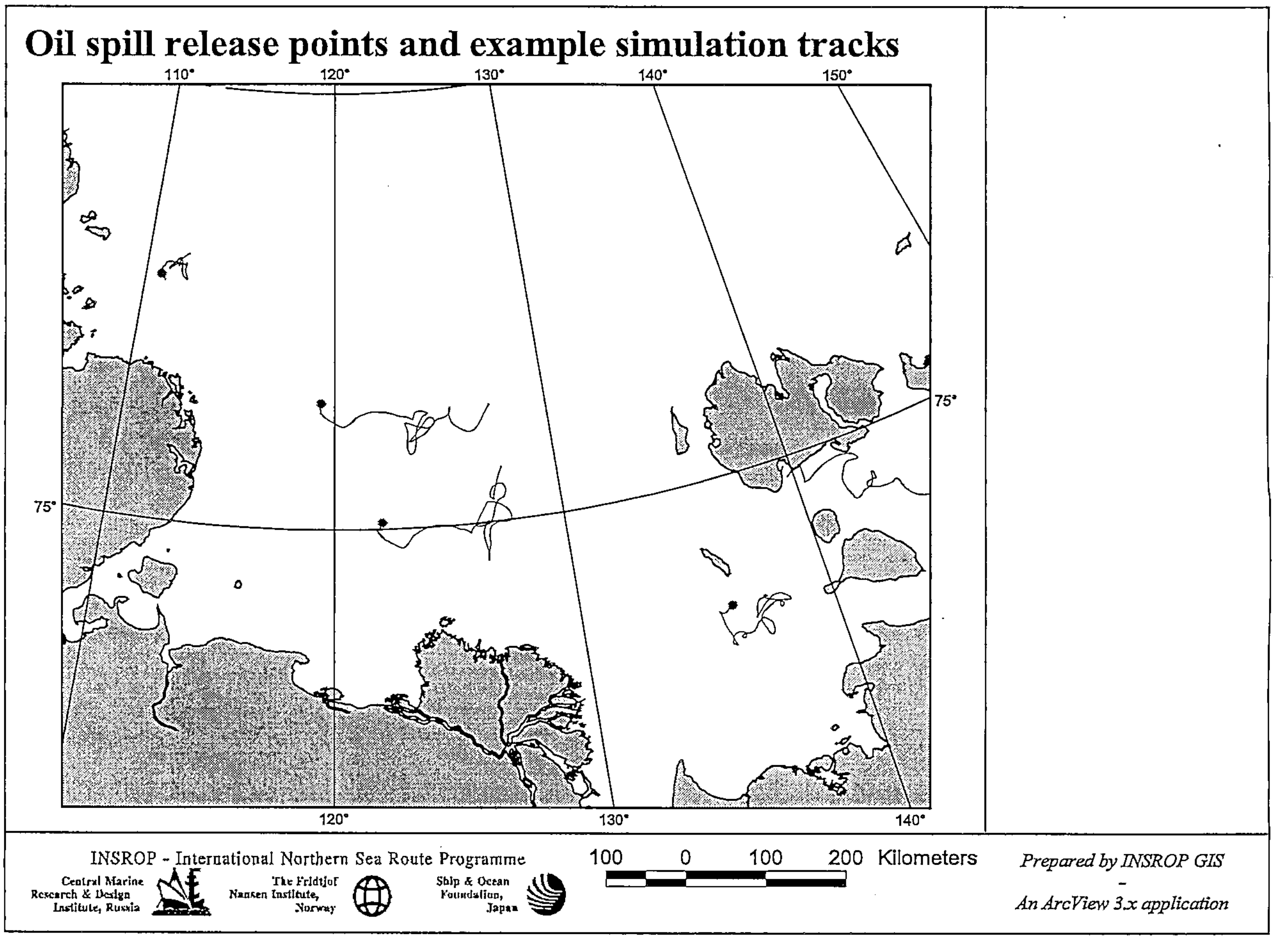


Figure 5.2 Oil drift trajectories in the Laptev Sea

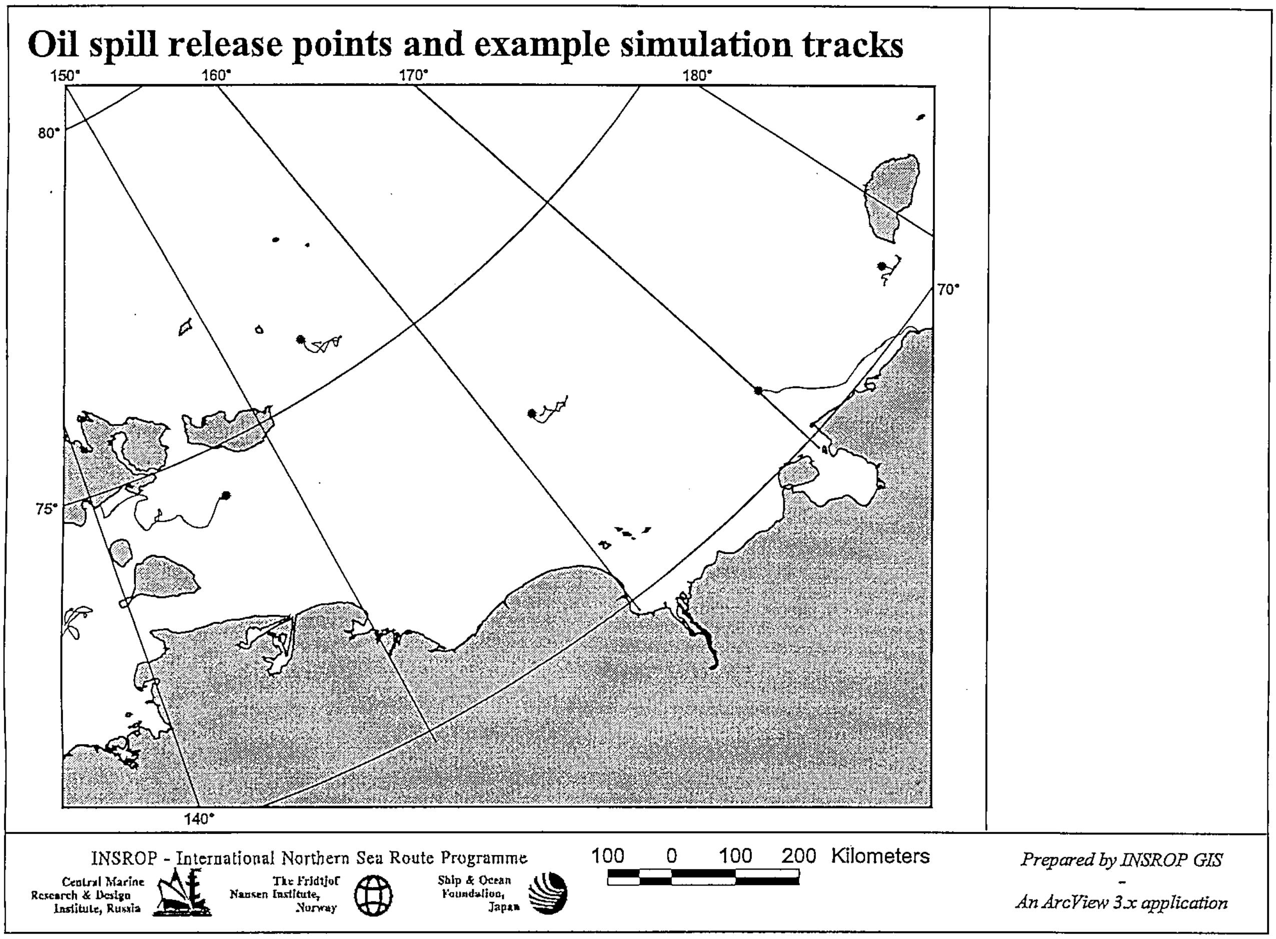


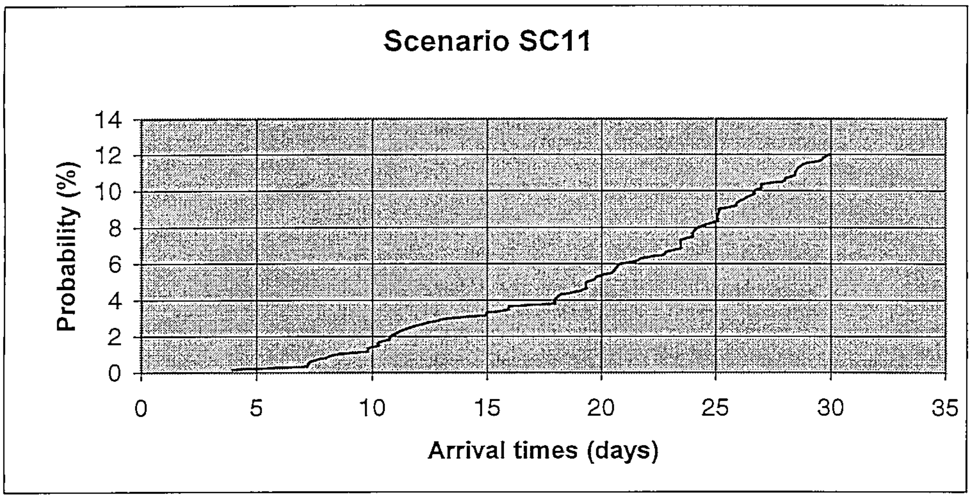
Figure 5.3 Oil drift trajectories in the East Siberian Sea

5.2 Stranding of oil

Stranding is defined when an oil drift trajectory enters into a coastal grid cell. Figures 5.4-5.13 show the statistical distribution of drift time to the coast and stranded amount of oil for the 10 scenarios that stranded within a month. Scenario SC 15 shows that the probability for stranding within 5 days is 10 %. Further, the probability for stranded amount of oil to be more than 2000 tonnes is 25 %. For the other scenarios the probability for stranding within 5 days is less than 1 %. Table 5.1 shows a summary of stranding properties for the selected scenarios. Scenario SC 15 shows that the oil may reach coastal areas within 1 day. Further, the table shows that no oil drift trajectories stranded (within 30 days) in Scenario SC 14, SC 22, SC 32 and SC 33.

Table 5.1 Probability for stranding

Scenario	Stranding within 5 days (%)	Stranding within 10 days (%)	Stranding within 20 days (%)	Shortest drift time to shore (days)
SC 11	0.2	1.3	5.3	4
SC 12	0.7	7.7	16.7	2
SC 13	0	1.7	14.3	6.2
SC 14	0	0	0	
SC 15	10.2	17.3	24.2	0.7
SC 21	0	1.2	8.7	8.4
SC 22	0	0	0	
SC 23	0	0	2.2	13.7
SC 24	0.2	1	7.2	4
SC 31	0	8	28	5.1
SC 32	0	0	0	
SC 33	0	0	0	
SC 34	1.2	27.2	70.5	4.7
SC 41	0	2	11.2	7.7



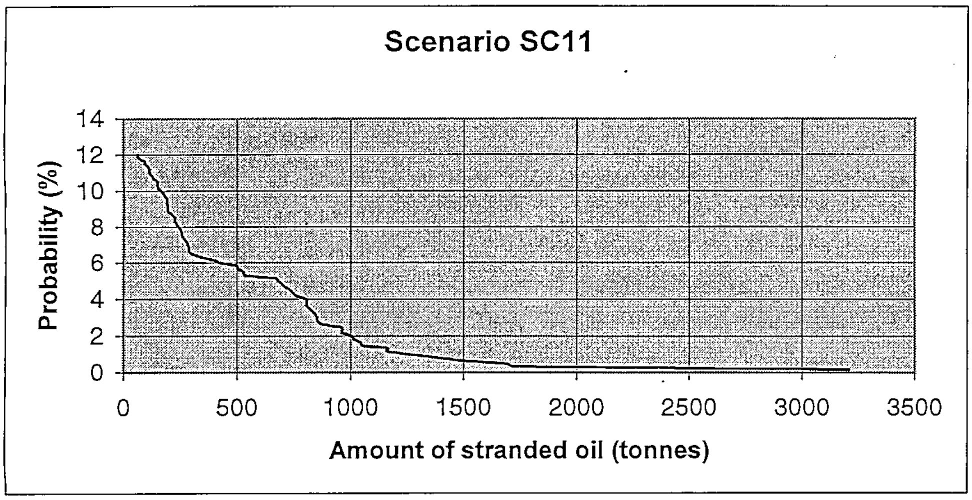
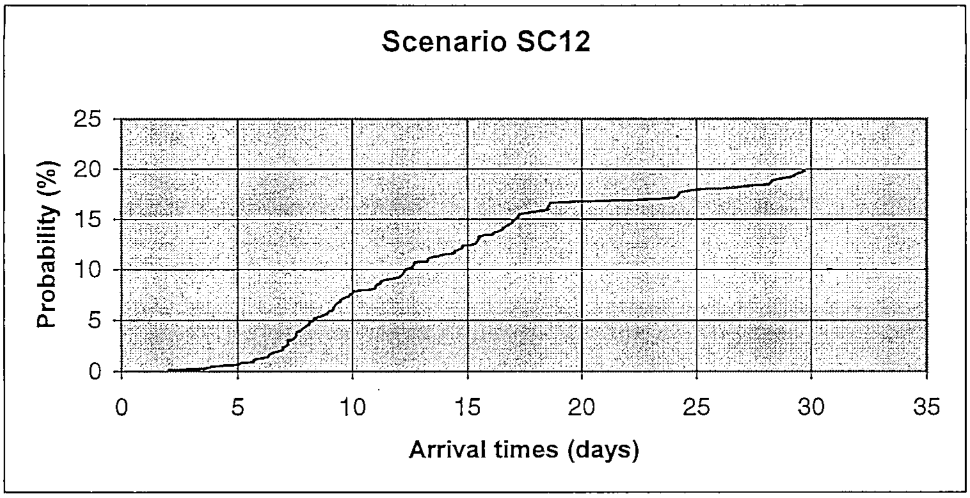


Figure 5.4 Statistical distribution of arrival times to shore and corresponding stranded amounts of oil for Scenario SC 11



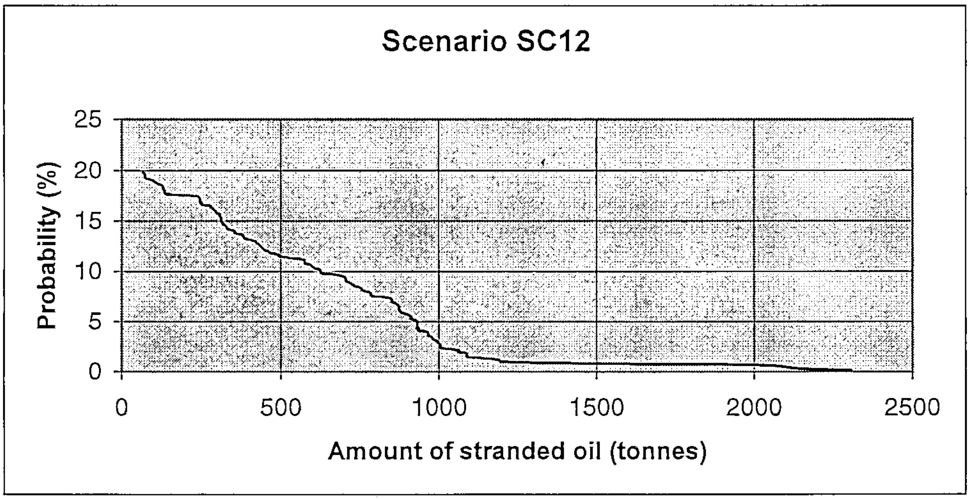
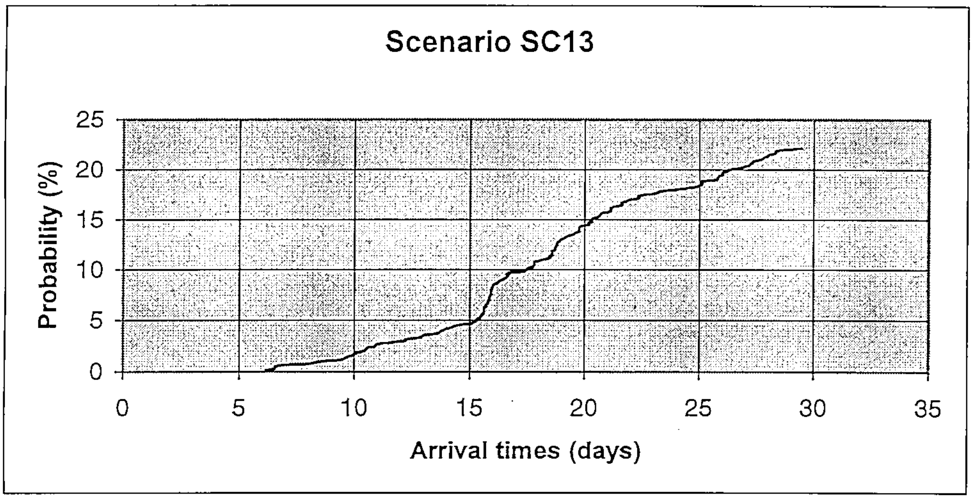


Figure 5.5 Statistical distribution of arrival times to shore and corresponding stranded amounts of oil for Scenario SC 12.



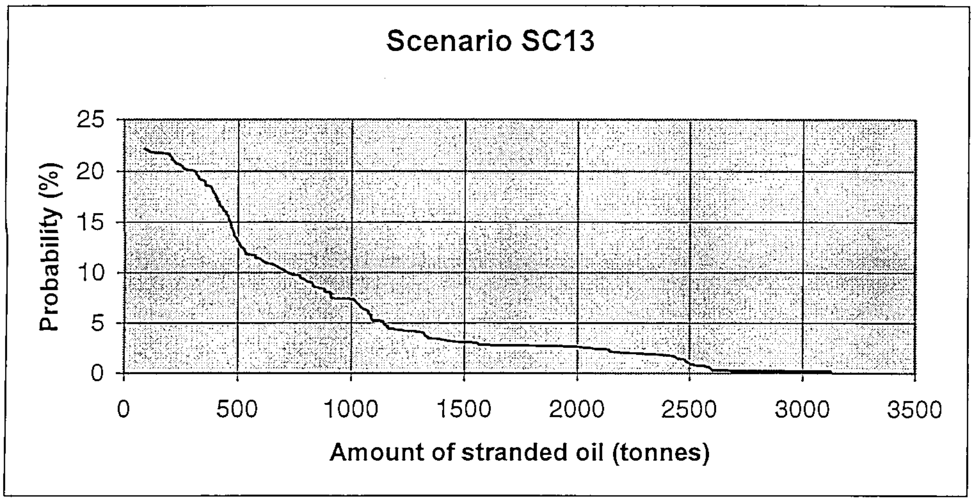
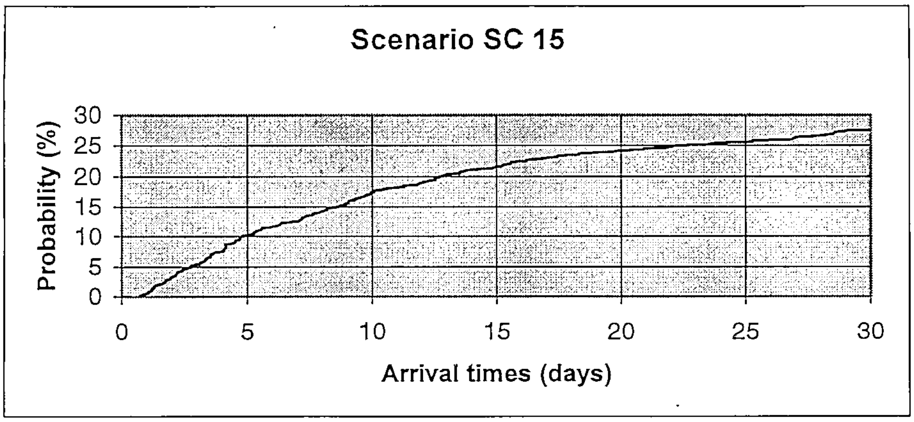


Figure 5.6 Statistical distribution of arrival times to shore and corresponding stranded amounts of oil for Scenario SC 13.



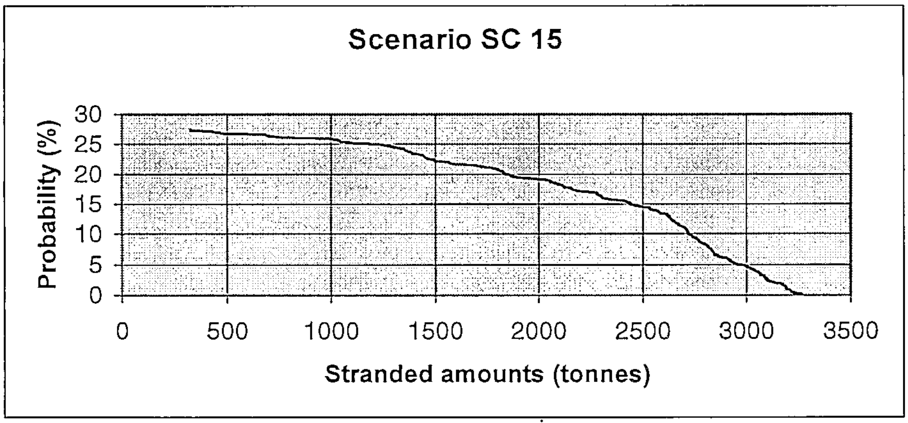
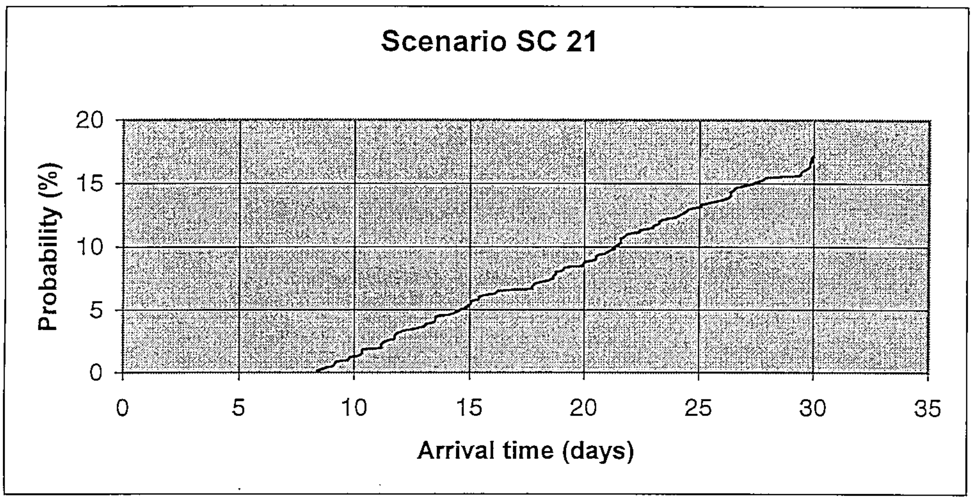


Figure 5.7 Statistical distribution of arrival times to shore and corresponding stranded amounts of oil for Scenario SC 15.



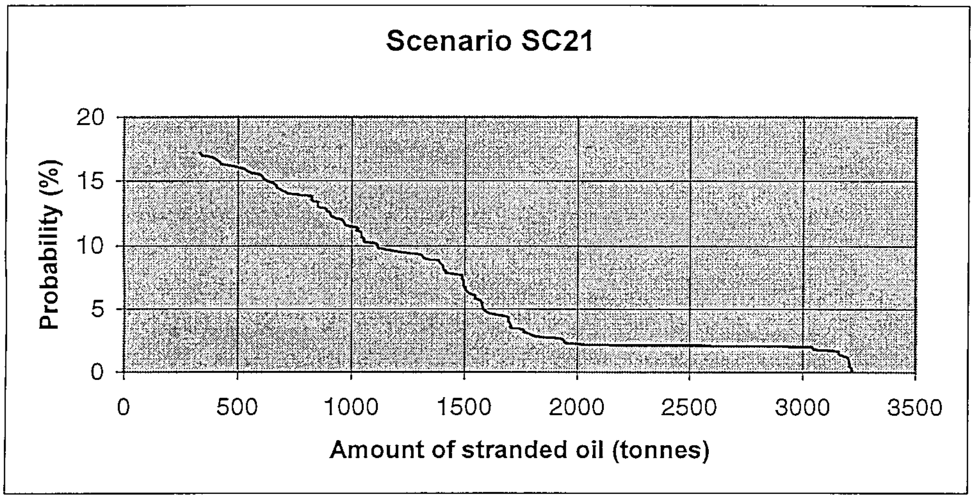
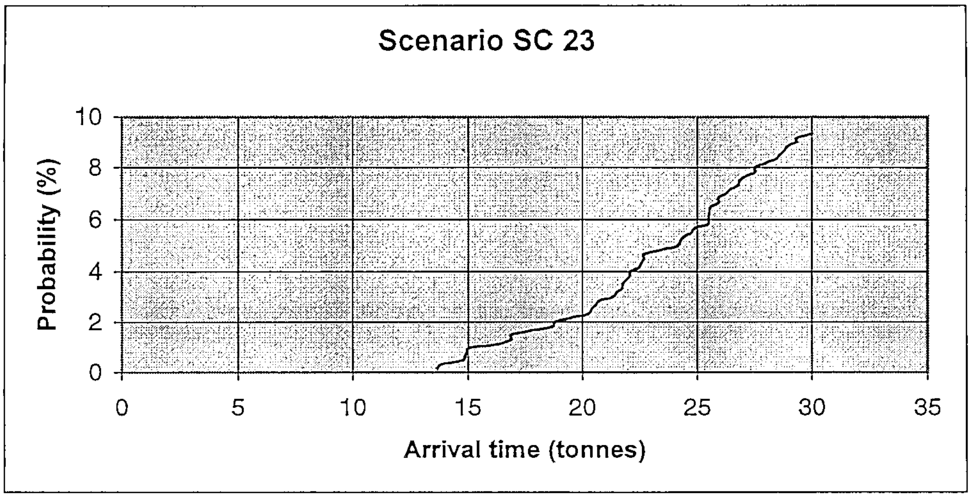


Figure 5.8 Statistical distribution of arrival times to shore and corresponding stranded amounts of oil for Scenario SC 21.



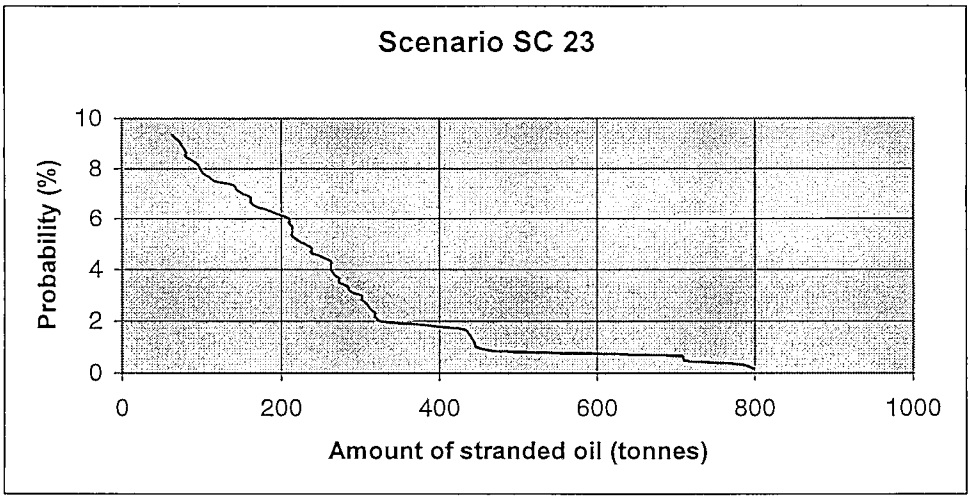
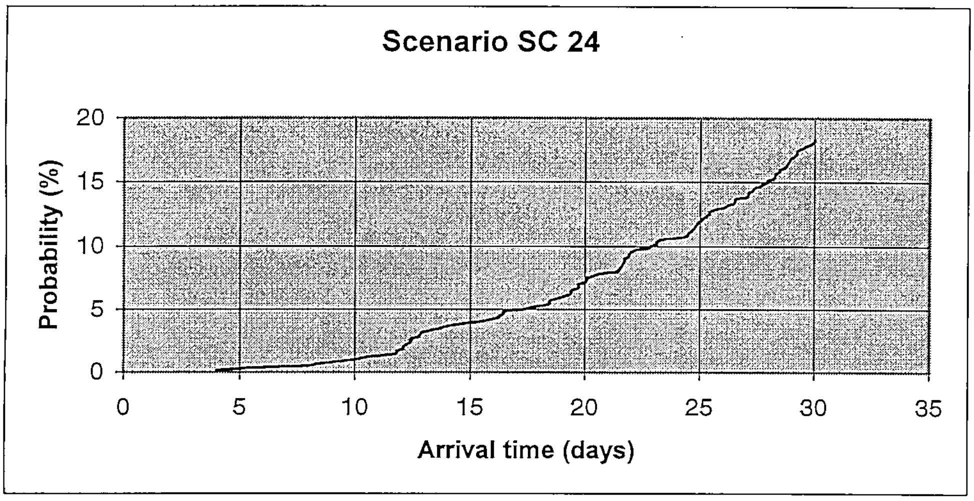


Figure 5.9 Statistical distribution of arrival times to shore and corresponding stranded amounts of oil for Scenario SC 23.



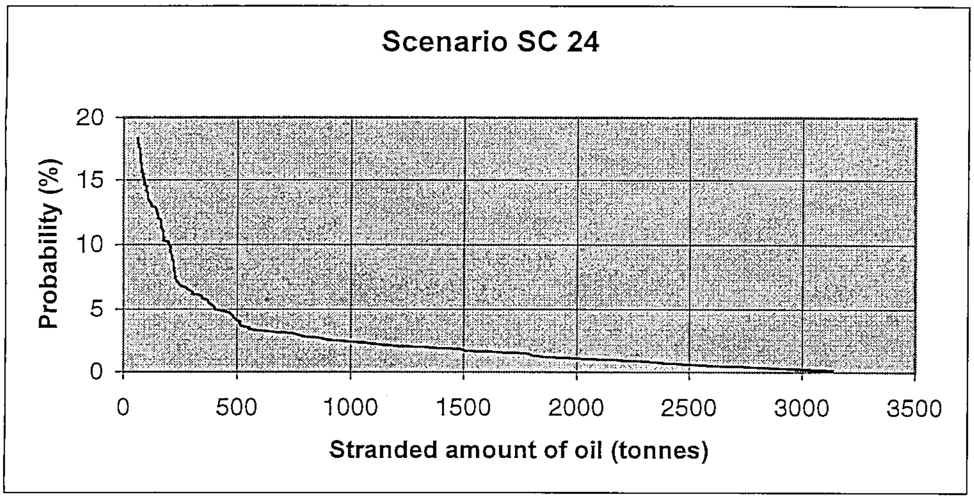
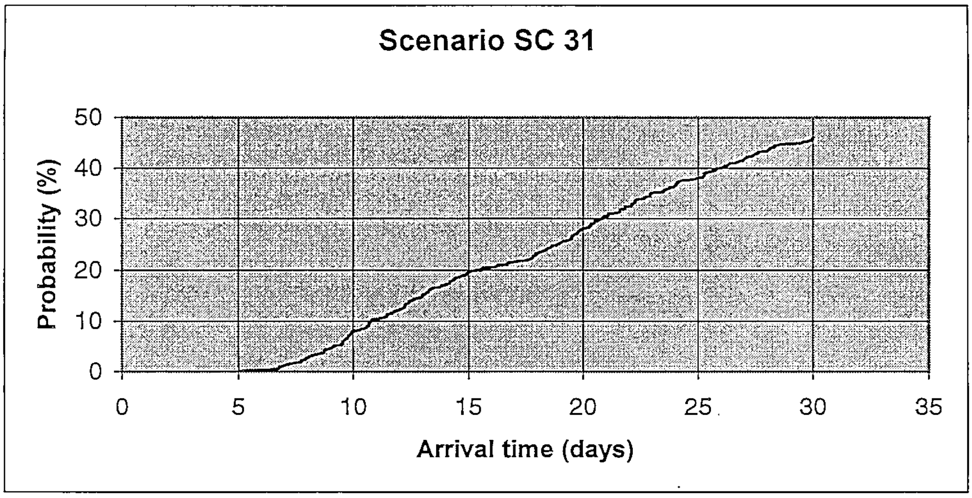


Figure 5.10 Statistical distribution of arrival times to shore and corresponding stranded amounts of oil for Scenario SC 24.



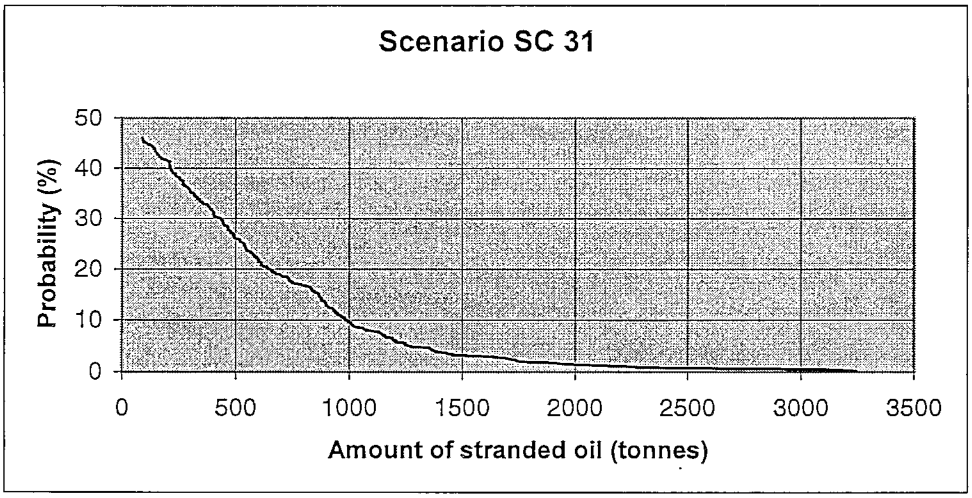
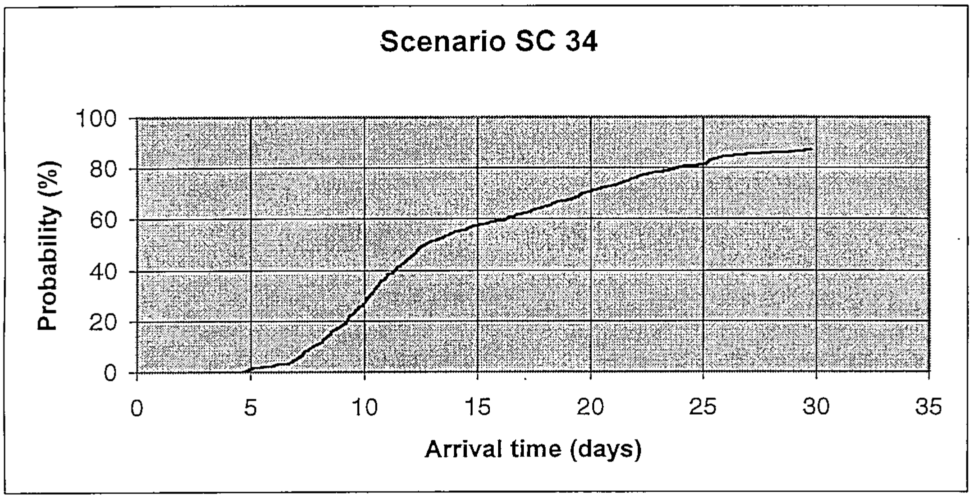


Figure 5.11 Statistical distribution of arrival times to shore and corresponding stranded amounts of oil for Scenario SC 31.



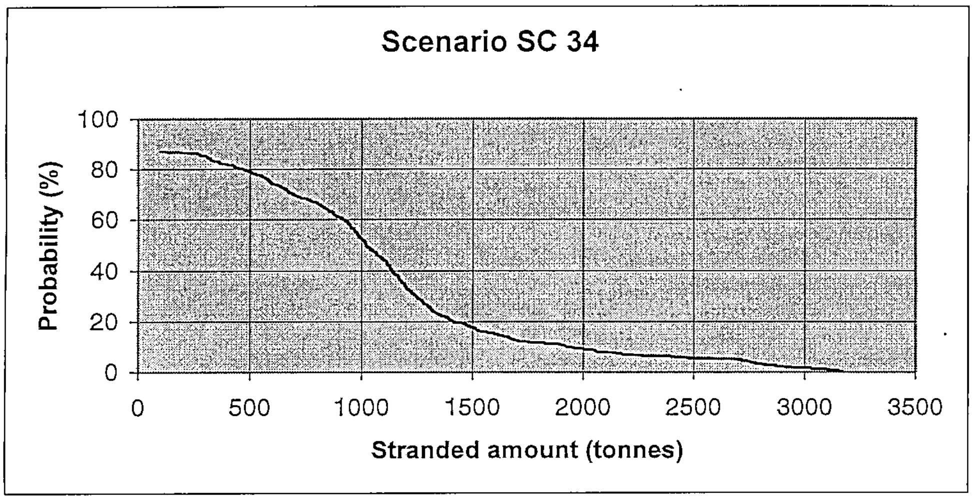
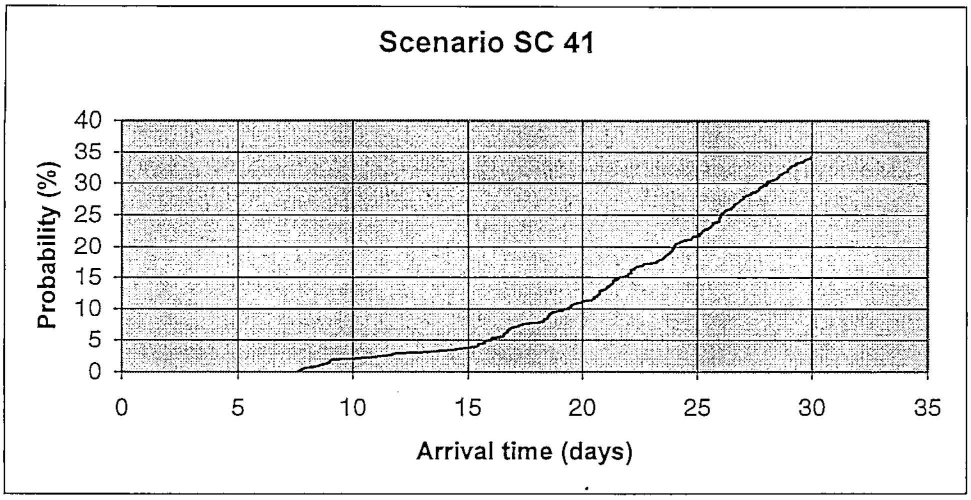


Figure 5.12 Statistical distribution of arrival times to shore and corresponding stranded amounts of oil for Scenario SC 34.



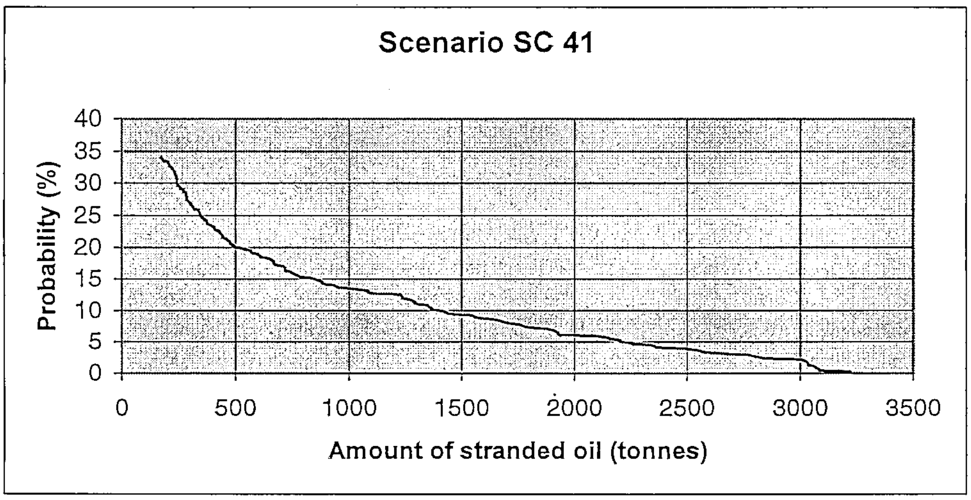


Figure 5.13 Statistical distribution of arrival times to shore and corresponding stranded amounts of oil for Scenario SC 41.

5.3 Areas of influence

Figures 5.14-5.16 show the probability for oil contamination. For each scenario the statistics are based on 600 oil drift trajectories. Regions with probability less than 5 % for oil contamination are not included in the figures.

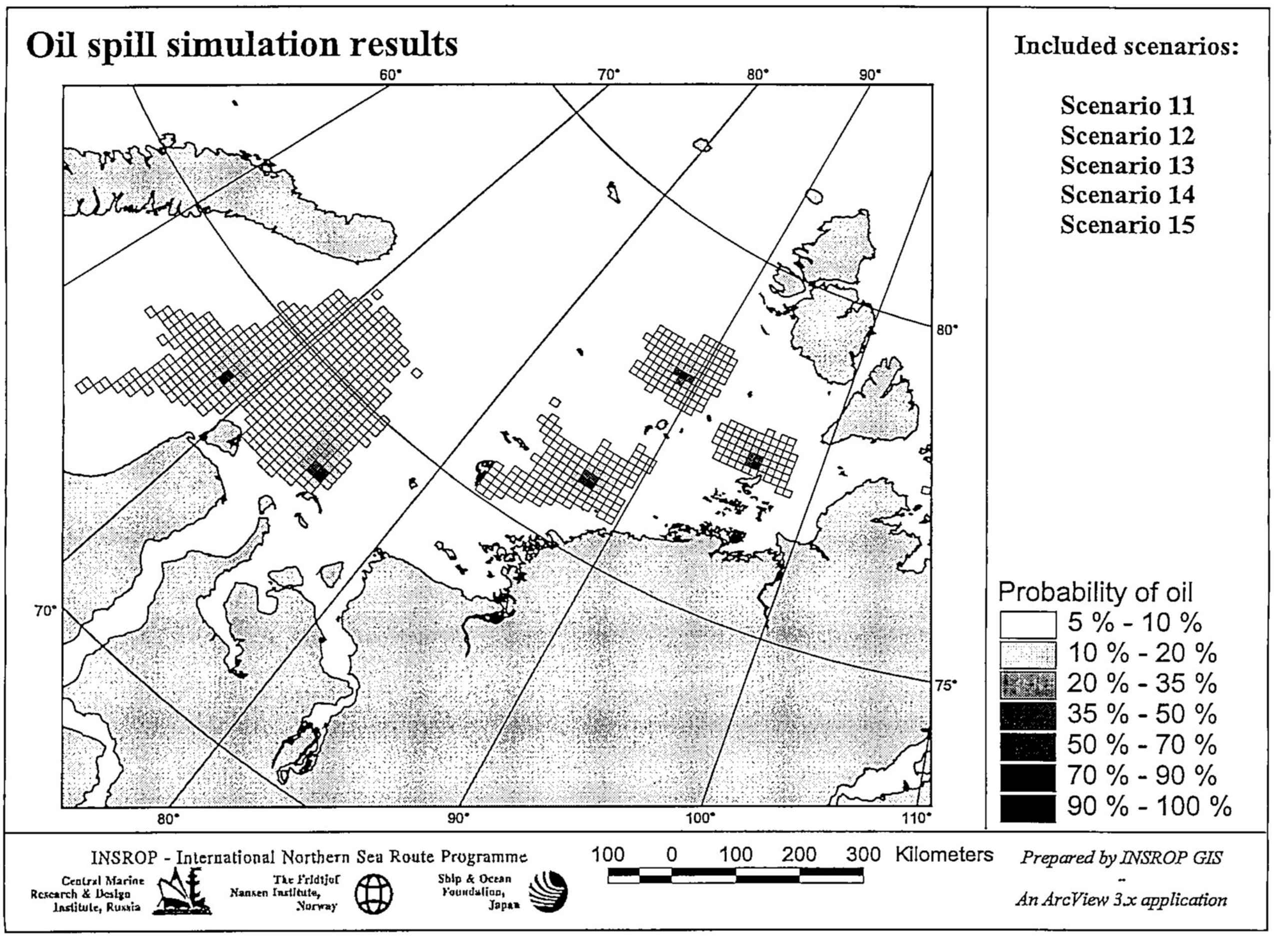


Figure 5.14 Probability for oil contamination in the Kara Sea

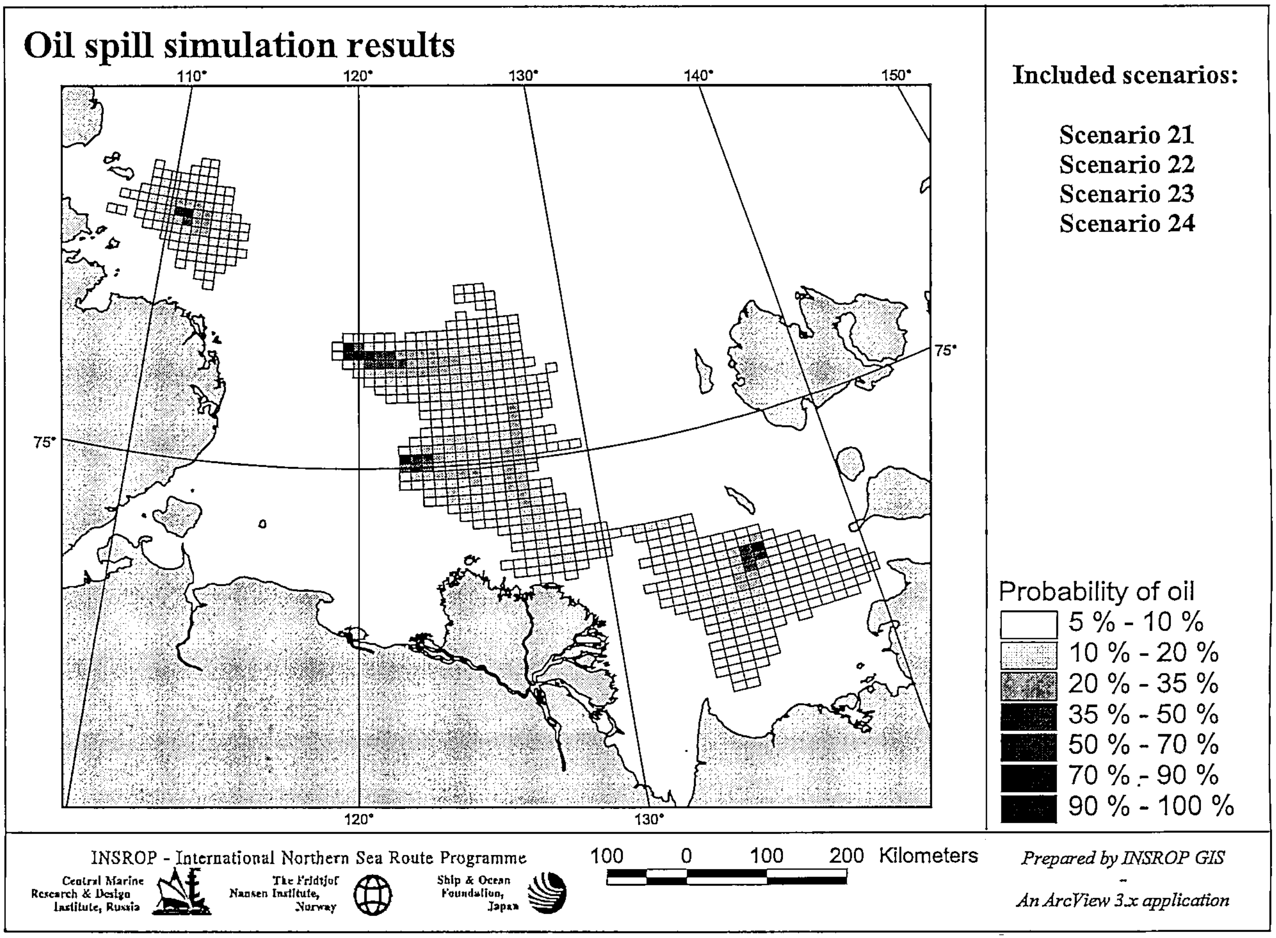


Figure 5.15 Probability for oil contamination in the Laptev Sea

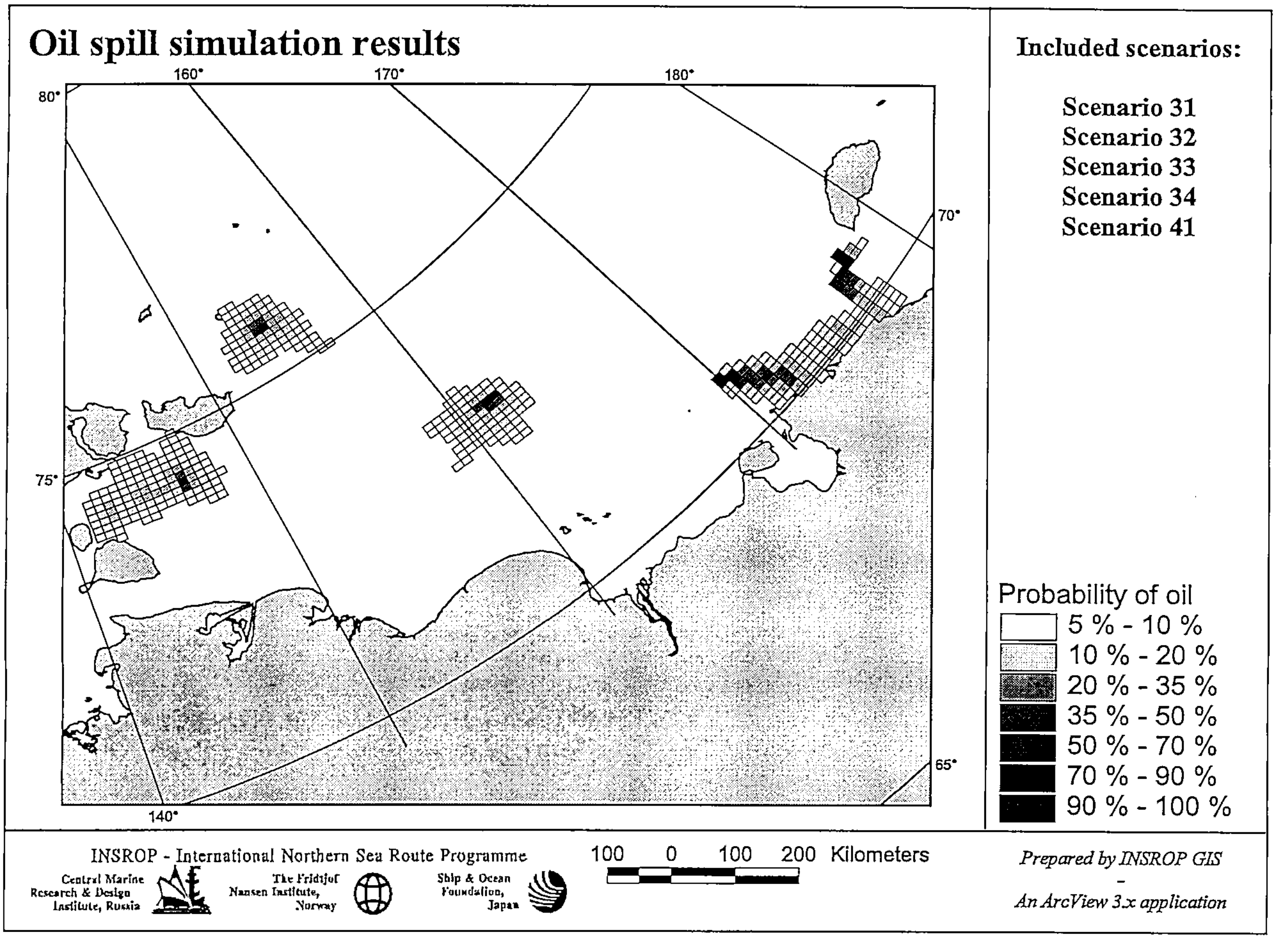


Figure 5.16 Probability for oil contamination in the East Siberian Sea

6. Conclusions and recommendations

According to the IMO data, on a worldwide basis, the average annual frequency for accidents, involving tankers of more than 6000 registered tonnes, is 0.31 for collision with other ship and 0.41 for groundings. Since 1974, the federation ITOPF has maintained a database of oil spills from tankers, combined carriers and barges. This covers all accidental spillages except those resulting from acts of war. The database contains information on both the spill itself and the vessel involved. Spills are categorised by size (<7 tonnes, 7-700 tonnes and >700 tonnes). On average the number of oil spills is higher in the period 1970-79 than in 1980-89. From the database, it is notable that a few very large spills are responsible for a high percentage of the oil spilt. For example, in the ten-year period 1988-1997 there were 360 spills over 7 tonnes, totalling 1439 thousand tonnes, but 1003 thousand tonnes (70%) were spilt in just 10 incidents (less than 3 %). The figures for a particular year may therefore be severely distorted by a single large incident. Few tanker accidents are registered in the Arctic. Most tankers used in the Arctic are equipped with double sides and double bottoms. Therefore, the worldwide statistics on tanker accidents are not directly applicable to the NSR.

Murmansk Shipping Company (MSC) has performed an analysis of ship accident data for the time period 1954-90. More than 800 accident cases were considered and the analysis was grouped according to the ships ice class and to their ice breakers assistance. The MSC analysis identified the 1983 summer Arctic navigation as the heaviest and the 1990 summer Arctic navigation as the lightest. During the summer period June-October 1983 a total of 104 ships were damaged in accidents and the majority of the incidents happened in the eastern part of the route. In 1990 only 15 accidents were registered and the accidents happened mainly in the western part. Generally, the eastern part of the NSR has a greater accident risk than the western part, when comparing average number of accidents with the total number of navigating ships. The accidents are located in regions of the ice massifs Novaya Zemlya, Severnaya Zemlya, Ayon and Wrangel with high concentrations of multi-year ice both in winter and summer seasons. The MSC analysis also shows that most of the accidents occur at the end of the navigation period (August-September).

The physical data required for the oil spill model are time series of wind data, surface ocean current and sea ice concentration. Several sources of data have been ordered for the study. Time series of wind data have been derived from NCAR for the period 1968-97. Gridded ocean current data for the Kara Sea are derived from the field experiment EPOCA-95 (King et al., 1996) and the Coriolis laboratory at SINTEF (McClimans et al., 1997). Gridded ocean current data for the entire NSR region have been derived from AARI. The Global Sea Ice Database (from AARI) covering the period 1967-90 is used to provide data on sea ice concentrations and fast ice for the oil spill model. The resolution of wind and sea ice concentration data is satisfactory, as is the ocean current data for the Kara Sea. The resolution and coverage of ocean current data east of 85 °E should be improved. The amount of ship traffic and the frequency of accidents are highest in the summer season. Available field data of ocean current is sparse both in time and space. The ocean data cover only the summer season. It is therefore recommended to use a numerical model to produce climatological seasonal variability of the ocean currents.

In order to assess how pollution from NSR shipping will impact the environment, a statistical oil drift model has been applied to provide drift tracks of the pollutants. The *OILSPILL* model is based on the trajectory concept, which means that the model simulates the drift and the weathering of the oil as individual points of mass released at different times, within the available historical time series of wind data. Advection and loss of oil due to evaporation and natural dispersion, as well as oil stranding, are the main physical processes accounted for in the model. The oil drift statistics are obtained by repeating the simulations of oil drift from chosen spill sites for a large number of oil spills.

A total of 14 scenarios along the coastal and the high latitude route have been identified. For each scenario, a total of 600 oil trajectories have been simulated. The simulated period for each trajectory is 30 days and the start time for each oil spill is drawn randomly, within the time period July-September. In all the scenarios, an amount of 3 500 tonnes is assumed. Stranding is defined when an oil drift trajectory enters into a coastal grid cell.

The oil drift model is run in a grid with spatial resolution of 15 km x 15 km and all the results are presented in this grid. The output from the model concentrates on the probability of oil contamination. The probability for oil contamination is based on a count of the number of simulated spills, where the cell has encountered oil at least once. The probability of contamination is given as the ratio between this number and the total number of simulated spills in the chosen season. The model also provides statistical distributions of arrival times to shore and stranded amounts of oil, as well as oil drift trajectories. The simulations show that 10 of the 14 scenarios stranded within one month. Scenario SC 15 shows that the probability for stranding within 5 days is 10 %. For the other scenarios, the probability for stranding within 5 days is less than 1 %. Scenario SC 15 shows that the oil may reach coastal areas within 1 day.

Due to restrictions of the ocean current data, the oil drift model is only run for the period July-September. It is assumed that this period represents the largest spreading of the oil due to the low ice concentration. High ice concentration will reduce the oil spreading as well as the weathering of the oil.

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Review of INSROP Report I.5.7 "Statistical Oil Spill Simulations" by Sylvi Vefsnmo, SINTEF

The objective of the work is to provide oil spill scenario information to the Environmental Impact Assessment initiative of INSROP Sub-programme II. The report is well written and a useful contribution to the objectives of INSROP. It contains a good analysis of the historical record of oil spills world-wide. There is a further analysis of ship accident data from the Russian Arctic provided by the Murmansk Shipping Company. This information was used to identify regions and time of year of high accident occurrence along the Northern Sea Route. An interesting observation was that most damage seemed to occur during period of most favourable ice conditions (August-September). This situation was attributed to the operation of more low ice class ships at this time of year. Oil spill scenarios were identified as occurring at 14 locations along the tracks of Northern Sea Routes identified by Baskin et al 1998. These locations were in three general areas, the Kara Sea, Laptev Sea and the East Siberian Sea.

The oil drift model requires time series physical data on wind, surface ocean currents and ice concentration. Gridded wind speed data at 6-hour intervals for the period 1968 to 1997 were obtained by reanalysis of archived data. Several sources were accessed to generate monthly averaged gridded ocean current data. Gridded monthly sea ice concentration data and probability of landfast ice were used to describe ice conditions.

The statistical oil drift model requires a drift path prediction model. The oil drift model simulates drift and weathering including advection, evaporation, dispersion and stranding of the oil. The simulation is assumed to start at some random time in the interval July-September. It assumes a spill of 3500 tonnes in a one-day period and then runs for 30 days. An averaged monthly surface current, time-series surface wind and interpolated ice conditions (concentration and land fast ice edge) are used to drive the drift model. Simulations are run for 600 random start times to generate statistical oil spill data. This data is then evaluated in terms of time and amount of stranding of the oil on a coastal grid and the area of influence of the oil spill. Probabilities of these quantities are derived.

Following are some suggestions on clarifying points in the report and improving it.
Clarifications:

- Add figure showing the locations of the scenarios identified in Table 2.4
- What is the meaning of "rotating laboratory model" in the third paragraph of section 3.2.
- The open water oil drift model used in the simulation should be referenced.
- The start time and actual manner of running each simulation could be better explained. Is the only random factor the start time of the simulation and is that July-September period for any year between 1968 1997? Once a simulation starts does it then use actual historical time series data for wind, ice concentration etc.
- The meaning of Figures 5.14 to 5.16 on probability of oil contamination could be better explained. What is the measure of oil being present in a grid cell? Does a certain quantity of oil have to be present before a grid cell is considered to be

contaminated with oil. Does the quantity of oil in a grid cell have an impact on the probability?

Suggested Improvements:

- An oil spill has impacts both in the sea and on the shore, what is relative importance of these two?
- The objective of the work is to provide an environmenrtal risk assessment tool for quantifying the risk, however do you see that it cold also be used to aid in planning response to an actual oil spill.

Ottawa, 17 January 1999

Robert Frederking
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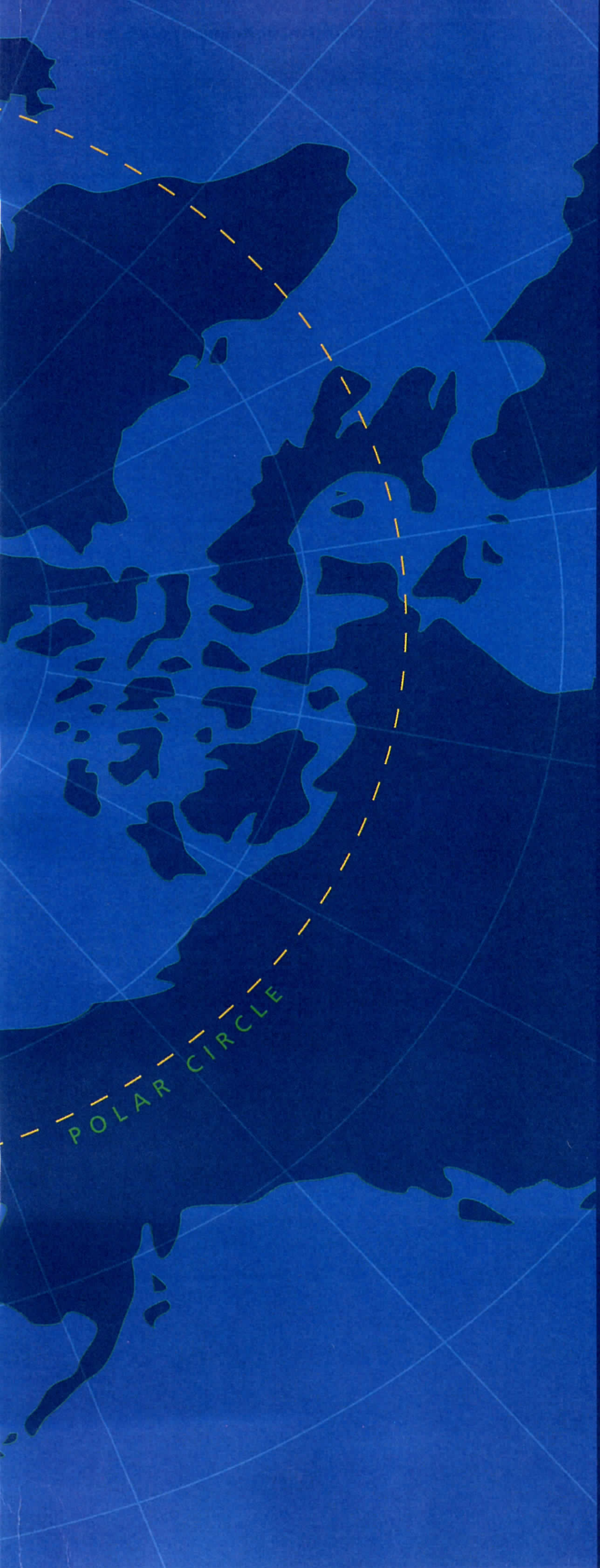

The three main cooperating institutions of INSROP

Ship & Ocean Foundation (SOF), Tokyo, Japan.
SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Sasakawa Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.

Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.
CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvment of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stockholding company.

The Fridtjof Nansen Institute (FNI), Lysaker, Norway.
FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute spesializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multidisciplinary approach, entailing extensive cooperation with other research institutions both at home and abroad. The INSROP Secretariat is located at FNI.