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SIMULATIONS OF OIL DRIFT AND SPREADING AND OIL SPILL RESPONSE ANALYSIS

WP 4:	Environmental Protection and Management System for the Arctic
WP 4.2.2.2/ 4.2.2.3:	Simulation of Drift and Spreading of the Oil in open and ice-infested water / Oil Spill Response Analysis

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"SIMULATION OF DRIFT AND SPREADING OF THE OIL IN OPEN AND ICE-INFESTED WATER / OIL SPILL RESPONSE ANALYSIS "

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Short Description
The present report presents simulations of oil drift and oil spill response for possible spills from tanker transport of oil products from Pechora Sea to the Murmansk region (subtasks 4.2.2.2 and 4.2.2.3 of ARCOP WP 4). The oil drift simulations provide information on the area of influence from possible major oil spills in conjunction with tanker transport in the area of concern, while the response analysis will form the basis for setting up a framework and guidelines for preparing an oil spill plan for the area.

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DISCLAIMER

CONTENTS

1 INTRODUCTION

The present report concerns the oil drift modelling and oil spill response part of the ARCOP work package on Environmental Protection and Management System for The Arctic (WP 4). Work Package 4 was justified from the fact that sea transportation of oil and gas products from the Pechora and Kara Sea region as well as oil/gas exploration in arctic waters will increase the risk of oil spills in this highly vulnerable environment.

One basic task of WP 4 was to identify and quantify relevant impact factors in terms of e.g. shipping routes, ship types, and regular discharges to sea and emissions to air. Based on the inherent dynamics of the environment, in combination with key characteristics of the shipping activity, knowledge has provided on the temporal and spatial distribution of resources at risk as well as sailing routes and sailing frequency. On this basis, semi-quantitative and quantitative analyses of environmental risk will be made to identify “hot spots”, i.e. geographical areas and periods of time with significant environmental risk, which subsequently can form the basis for analyses of mitigating measures and remedial actions.

The general fate and weathering of oils spilled in open / ice-infested waters is documented in a ”state-of-the-art” study (Evers et al 2004). This study also reveals needs to perform (at a later phase, but not within this project) a more specific oil weathering study according to standardized methodology on relevant types of oil in connection to the planned transportation from the Pechora and Kara Sea region.

The performance capability of various oil spill response techniques (both existing and eventual new concepts) has been identified and documented (Singsaas and Rist Sørheim, 2005). This documentation is essential both in connection with oil response analysis and in order to build up efficient and cost-effective oil spill response solutions for the area.

The present report deals with subtasks 4.2.2.2 and 4.2.2.3 of WP 4, and is concerned with oil drift simulations and oil spill response analyses in the region of concern. The oil drift simulations provide information on the potential area of influence from major oil spills in conjunction with tanker transport in the area of concern, while the response analyses will form the basis for setting up a framework and guidelines for preparing an oil spill plan for the area. This plan will also evaluate the potential for improvements and come up with recommendations for further development and experimental research.

2 MODEL DESCRIPTION

Oil drift simulations are an important part of any EIA or ERA studies related to tanker transport or any other activity that can cause major releases of oil into the marine environment. Such simulations are in general made for specific spill sites, which in case of tanker transport could be “hot spots” identified from studies of sailing routes and distributions of environmental resources. For these potential spill sites, certain spill scenarios have to be defined in terms of type of oil, amounts of oil released, and duration of the release. On this basis, simulations of oil drift are made for a large selection of possible weather conditions, with the aim of depicting the potential area of impact from such spill events. In the present study, SINTEF’s OSCAR model is used for this purpose. The next sections include a brief description of this model, including model concepts and input data.

2.1 The OSCAR model

OSCAR is a 3-dimensional, state-of-the-art Oil Spill Contingency And Response model system running under the Windows operating system (Reed et al. 1995 a, b). Following is a brief description of the model system.

OSCAR is one of several models operating within the Marine Environmental Modelling Workbench (MEMW), providing a common graphical user interface (GUI) for worldwide applications. The GUI allows planar (latitude-longitude map) views of concentrations, bathymetry, velocity vectors, pollutant spatial distributions, visualization of global mass balances of the mixture of constituents released (one at a time or as a whole), and time-dependent animations of these fields. Vertical sections in the water column are also available for water column concentrations and Lagrangian particle positions.

The model allows multiple release sites, each with a specified beginning and end to the release. This allows time-variable releases at a given location, as well as throughout the study area. Both single oil spill scenarios and stochastic scenarios with variable start times can be calculated. The model is thus useful for both contingency planning, risk analysis and response support during actual spill events.

OSCAR calculates and records the distribution (as mass and concentrations) of contaminants on the water surface, on shorelines, in the water column, and in sediments. These data are recorded in three physical dimensions plus time. The model databases supply values for water depth, sediment type, ecological habitat, and shoreline type. The system has an oil physical-chemical database that supplies physical and chemical parameters required by the model (Figure 2.1).

The model computes surface spreading, slick transport, entrainment into the water column, evaporation, emulsification and shoreline interactions to determine trajectory and fate at the surface. In the water column, horizontal and vertical transport by currents, dissolution, adsorption, settling, and degradation are simulated. The varying solubility, volatility, and aquatic toxicity of oil components are accounted for, such that concentrations are relevant to quantification of impacts. The physical fates model computes both total and dissolved concentrations in the water column and sediments, and the area of water and shoreline covered by surface slicks in space and time.

OSCAR accepts as input both 2- and 3-dimensional current data from hydrodynamic models, and single point or 2-dimensional wind data from meteorological models. OSCAR will compute weathering based on crude assay data, although much more reliable results are produced if the target oil has been through a standardized set of laboratory weathering procedures established by the SINTEF laboratories.

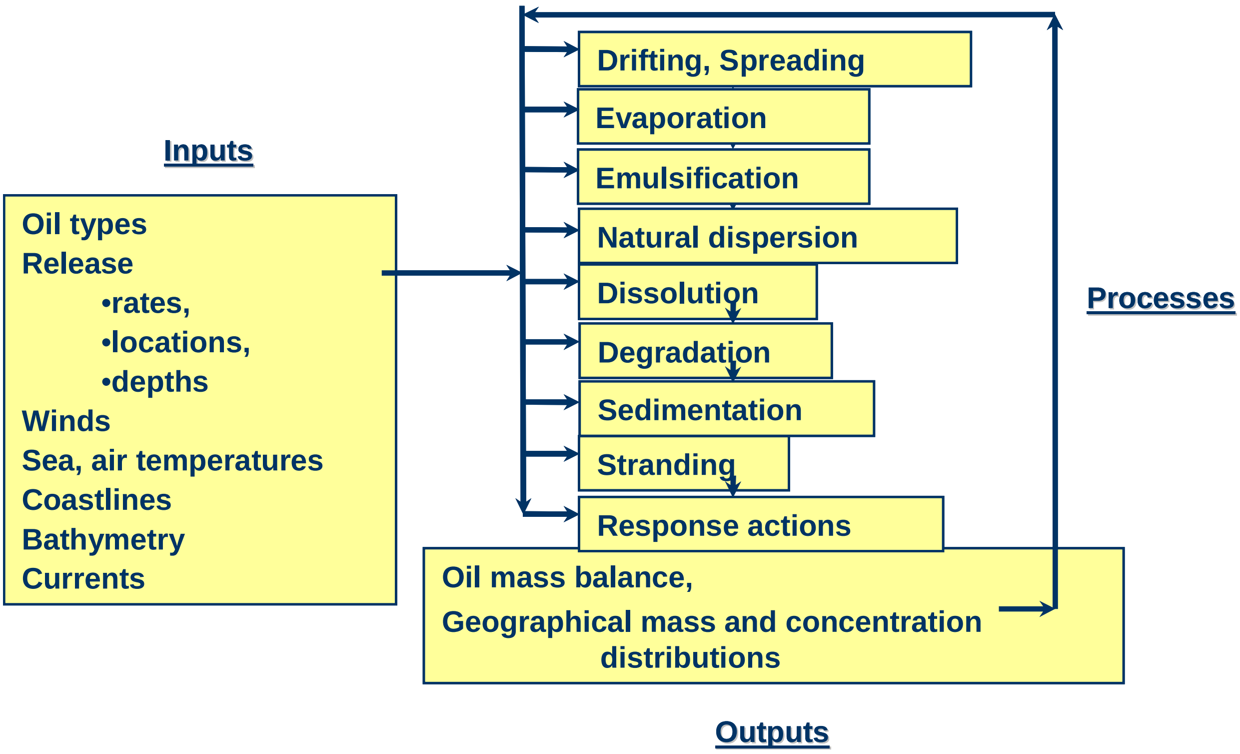


Figure 2.1 Schematic overview of OSCAR inputs, outputs, and internal processes.

Alternatively, the model may use oil weathering properties from oils for which data already exists, selecting the crude oil in the oil database that most closely matches the composition of the oil of concern.

The model is also prepared for applications in regions with seasonal sea ice. Sea ice will influence drift, spreading and weathering of the oil, as observed from laboratory studies and field experiments (Singsaas et al., 1994, Vefsnmo and Johannessen, 1994). In the OSCAR model, sea ice is accounted for in terms of temporal and spatial variations in ice coverage. Oil drift, spreading and weathering are modified as a function of ice coverage, relative to conditions in open water. Oil spreading is presumed to be retarded by sea ice, and the rate of the weathering processes (evaporation, emulsion formation and natural dispersion) are presumed to be reduced with increasing ice coverage. In dense sea ice, (more than 70 % ice coverage), oil is presumed to drift with the sea ice, while more open ice conditions (less than 30 % ice coverage) are presumed to have no influence on oil drift. In the present study, historical sea ice coverage data have been used to represent the temporal and spatial variations in ice coverage (see next section). Since this data set do not provide information on ice drift, ice drift has been estimated from historical wind and data on the prevailing current, much in the same way as oil drift is estimated from prevailing currents and wind induced drift. However, the drift factor used for sea ice differs from the drift factor used for oil.

2.2 Geophysical data

In the present study, we have applied geophysical data prepared by the Norwegian Meteorological Institute (MI), including gridded hindcast wind data, climatologic background current data, and ice coverage data. The background current data are based on hydrodynamic model simulations and are given as monthly mean values in a 20 × 20 km polar stereographic grid (Engedahl et al. 1998). The hindcast wind data are computed from analysed atmospheric pressure fields, and are stored at 6 hours intervals in a 75 × 75 km polar stereographic grid, covering the period from January 1970 through December 1992 (Eide et al.1985). The ice coverage data are derived from digitized weekly ice coverage maps, stored in a 20 × 20 km grid and interpolated to daily mean values. The data cover the same period as the wind data. Graphical presentations of the data are shown at Figures 2.2 to 2.4. Note that the graphical presentations show only a limited part of the geographical region covered by the data sets.

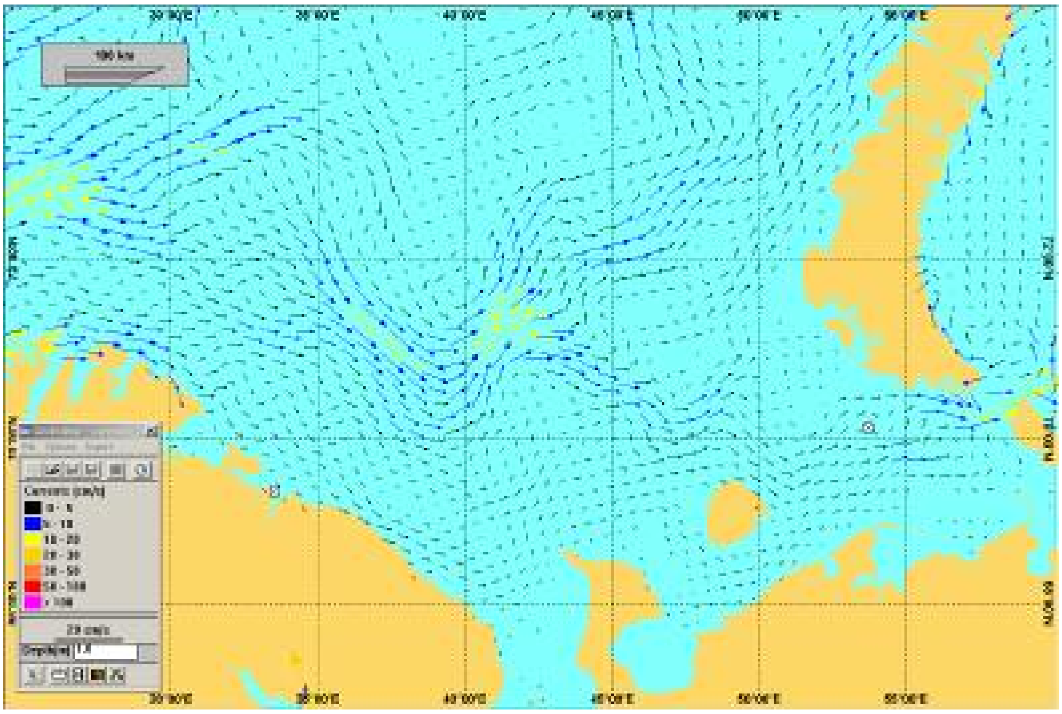


Figure 2.2 Example of climatologic current field for March. Monthly mean data in 20×20 km resolution provided by the Norwegian Meteorological Institute.

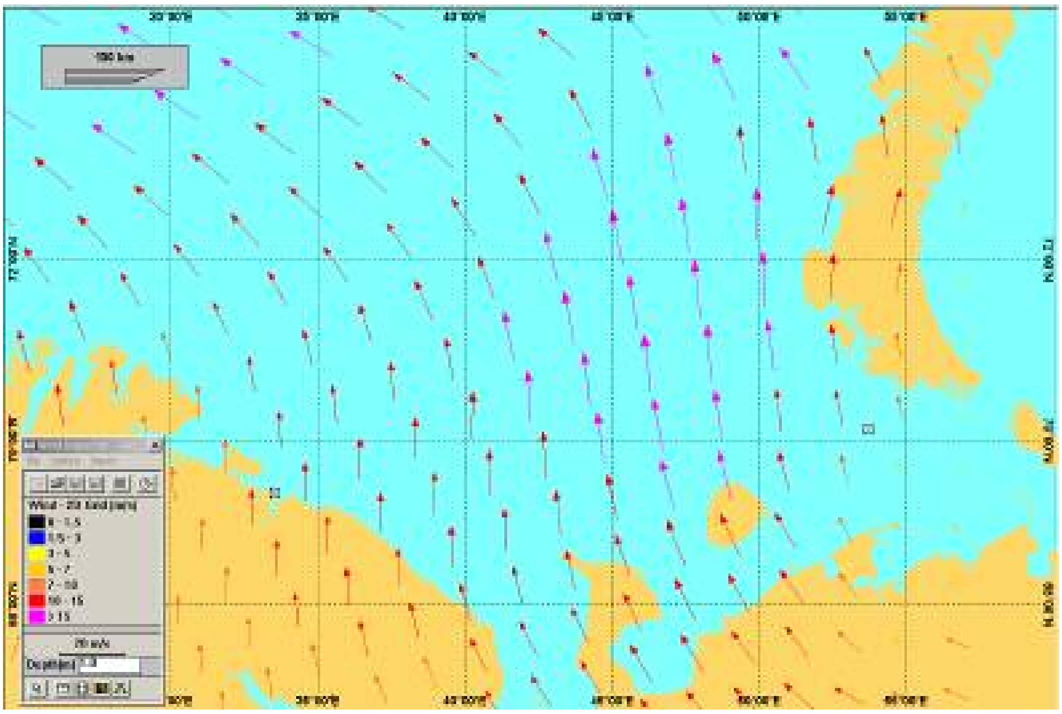


Figure 2.3 Example of hindcast wind field for March. Data at 6 hour intervals in 75×75 km resolution provided by the Norwegian Meteorological Institute.

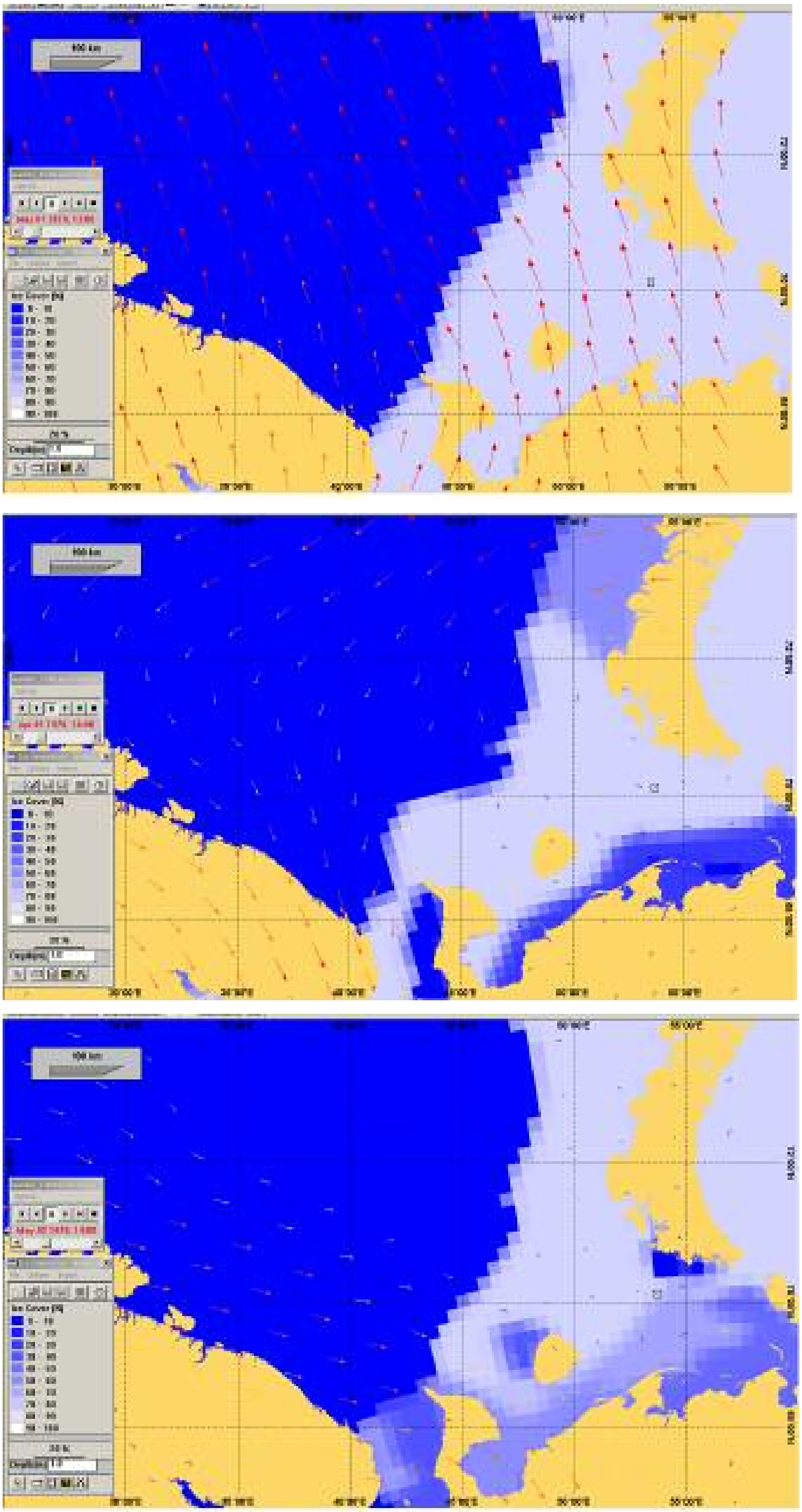


Figure 2.4 Examples of ice coverage and wind fields at the start of the oil drift simulations. Data at 24 hour intervals in 20 × 20 km resolution. Top March 1, middle April 1 and bottom May 2 1970. Data provided by the Norwegian Meteorological Institute.

2.3 Oil properties

The OSCAR model requires a detailed description of the properties of the released oil, both in terms of fresh and weathered oil properties. Since weathered oil properties are not available for the Varandey crude oils, the Troll crude oil from the North Sea has been used as model oil in the present study. The Troll crude is chosen based on a comparison of fresh oil properties (Table 2.1) and true boiling point curves (Figure 2.5). The weathering properties of Troll crude, including density, viscosity, water content, etc have been established by standardized tests at SINTEF's laboratories (Aamo et al., 1993). On that basis, predictions of the same properties can be made as a function of drift time at sea for different sea states (Figure 2.6).

Table 2.1 Physical and chemical properties of Troll crude and three crude oils from Varandey

Physical and chemical characteristic	*Varandey oil well number* 3	4	9	*Troll*
Density at 20°C, g/cm^3	0.894	0.897	0.907	0.893
Viscosity at 20°C, mm^2/s	26.2	28.2	40.8	27 (13°C)
Viscosity at 50°C, mm^2/s	11.9	10.3	12.2	
Pour point, °C	-49	-47	-45	-39
Flash point, closed cup. °C	-37	-37	8	-
Asphaltenes, %	4.4	4.3	4.5	0.2
Paraffines (wax), %	0.8	0.5	0.4	2.0

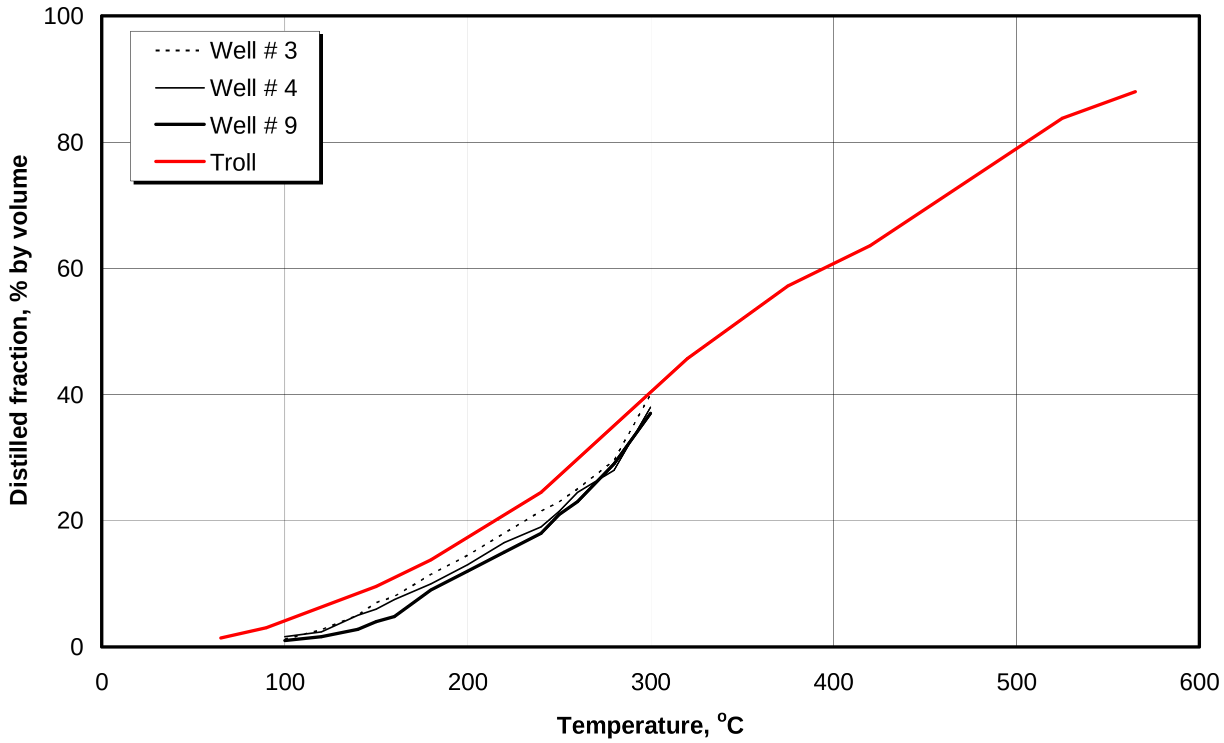
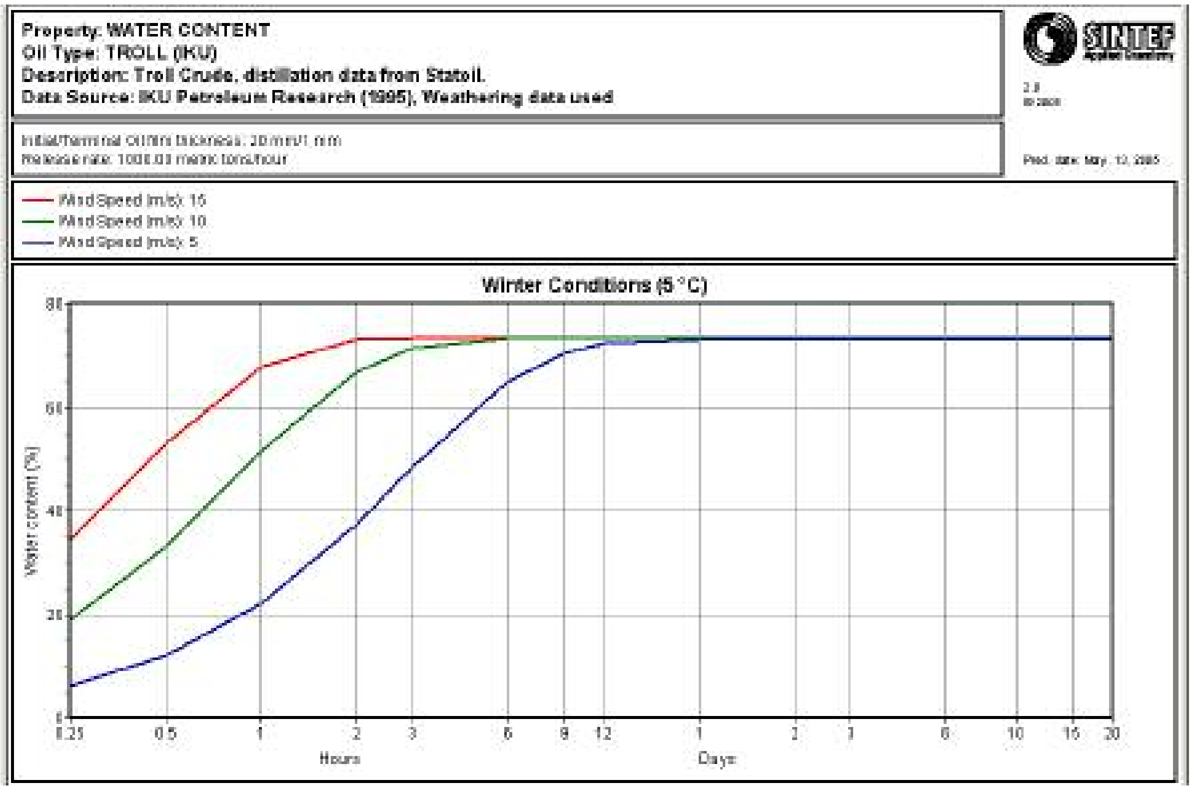


Figure 2.5 Boiling point curves for three Varandey crude oils (well # 3, 4, and 9), compared with Troll crude oil from the North Sea.



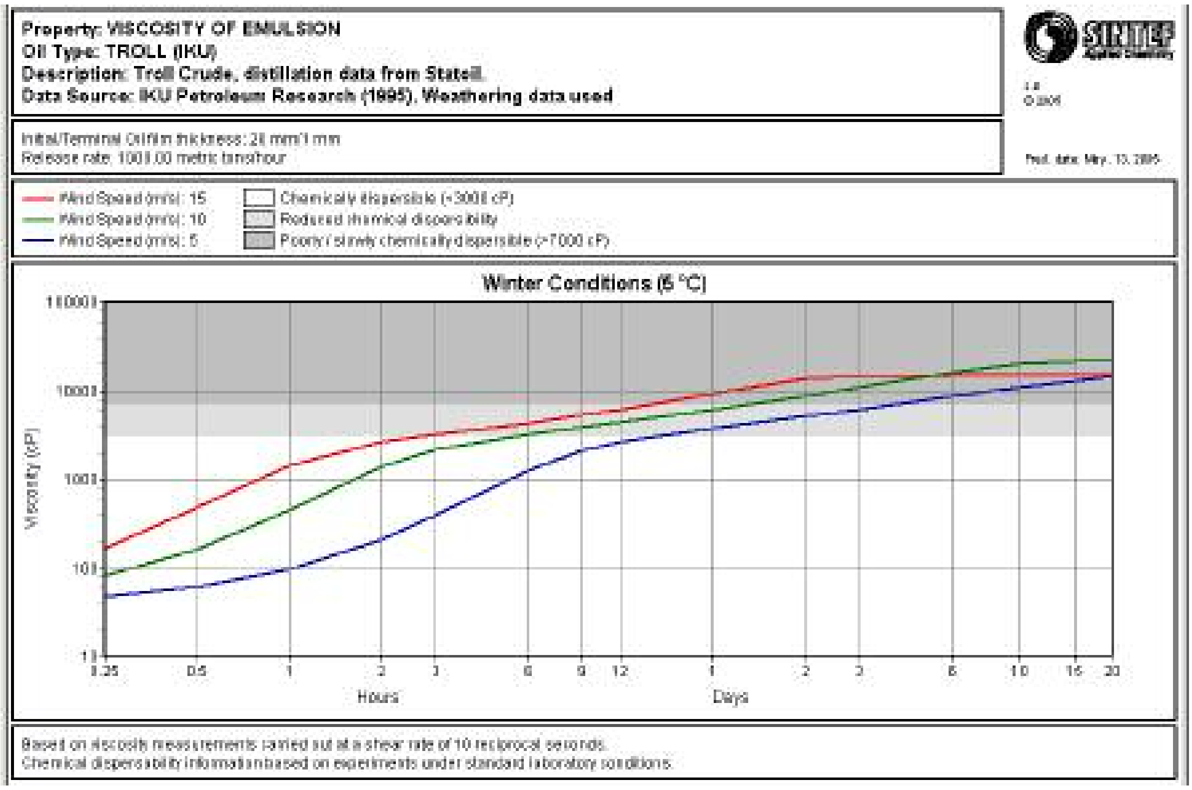


Figure 2.6 Predicted water content (top) and viscosity (bottom) of Troll crude oil at 5 °C.

3 OIL DRIFT SIMULATIONS

In the present study, two hypothetical spill sites have been chosen to illustrate the influence area of major oil spills from possible tanker accidents along the Varandey – Murmansk tanker route:

- Western spill site: Murmansk Fjord; E 33° 24' 00", N 69° 27' 00"
- Eastern spill site: Pechora sea; E 53° 41' 30", N 70° 07' 30"

The western site, located at the outlet of the Murmansk fjord represents a possible spill location in all-year ice free water, while the eastern site, located in the Pechora sea north-east of the Kolguyev island represents a location in regions with persistent seasonal ice (Figure 3.1). At both locations, the oil spills are presumed to amount to 10 000 m^3, released over a 10 hour period. The spilled oil is represented by a Troll crude oil from the North Sea with fresh oil properties similar to the Varandey crude oils.

Statistical oil drift simulations are made for both sites in two seasons; spring (March, April and May) and autumn (August, September and October). Each statistical simulation includes three oil drift scenarios per year in the period covered by the hindcast wind data set (23 years), i.e. a total of 69 oil drift scenarios (3 per year in 23 years). Each oil drift scenario is simulated for a 30 day period.

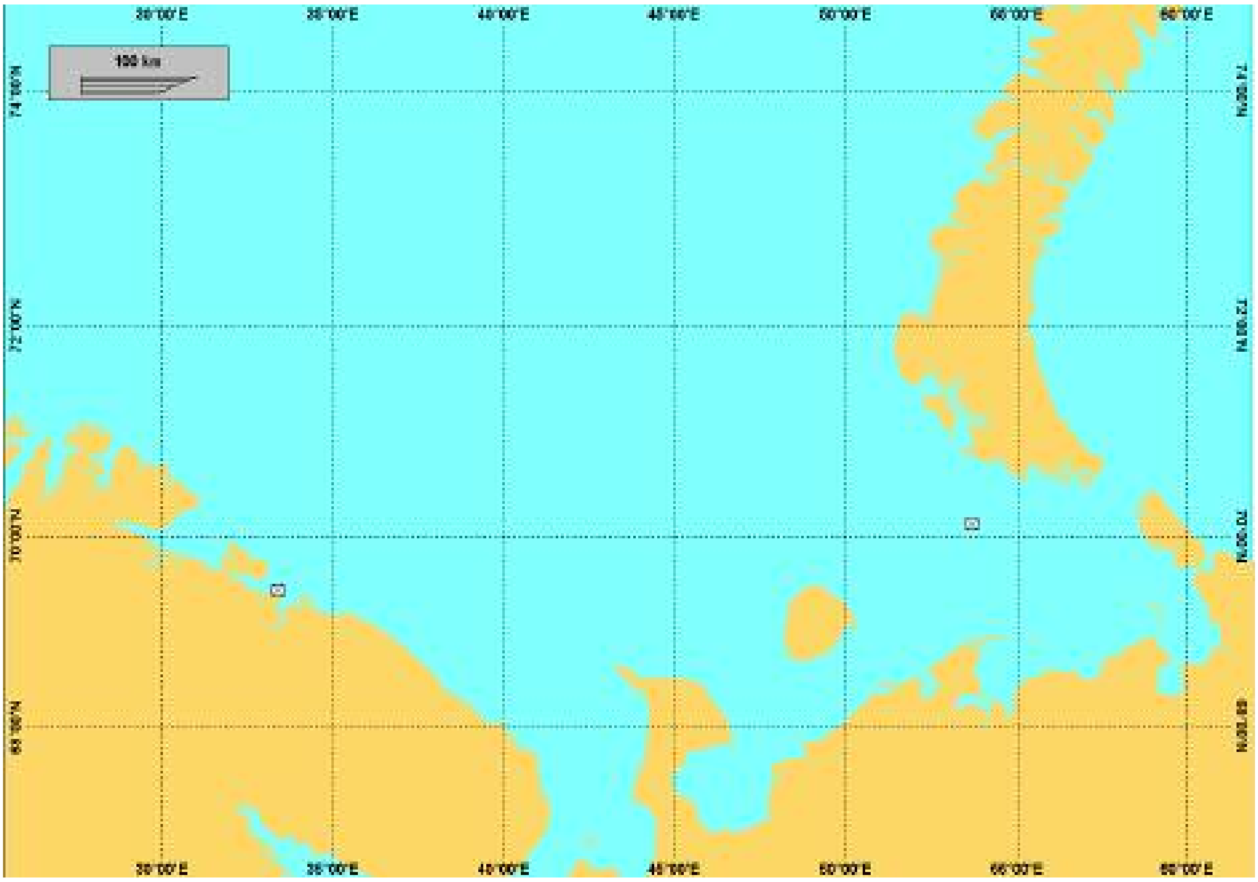


Figure 3.1 Spill sites shown by markers (crossed boxes). Western location: Presumed grounding at the outlet of the Murmansk Fjord. Eastern location: Presumed collision on the ship route from the Varandey terminal, passing north of Kolguyev Island.

The results from the two sites are presented in Figure 3.2 and 3.3, depicting the area of influence, defined as the area with a probability for oil contamination of 5% or more in a given oil spill scenario. The color code refers to the probability for contamination of a grid cell in a given oil drift scenario; a probability of 100 % implies that the grid cell has been contaminated by oil in every scenario.

The area of influence from the western spill site shows some seasonal variations, probably related to differences in the wind climate in the two seasons. More marked differences are seen for the eastern spill site, due to the presence of sea ice in the spring season. Sea ice will reduce drift and spreading of the oil, and thus limit the influence area in seasons with sea ice.

Figure 3.4 shows the combined area of influence for 11 spills sites positioned along a possible tanker route. The simulations are made for simultaneous releases in all spill sites with the aim of depicting the possible impact area for major spills at arbitrary locations along the tanker route. The marked differences between the spring and autumn simulations are mainly due to the presence of sea ice in the eastern part of the region in the spring season.

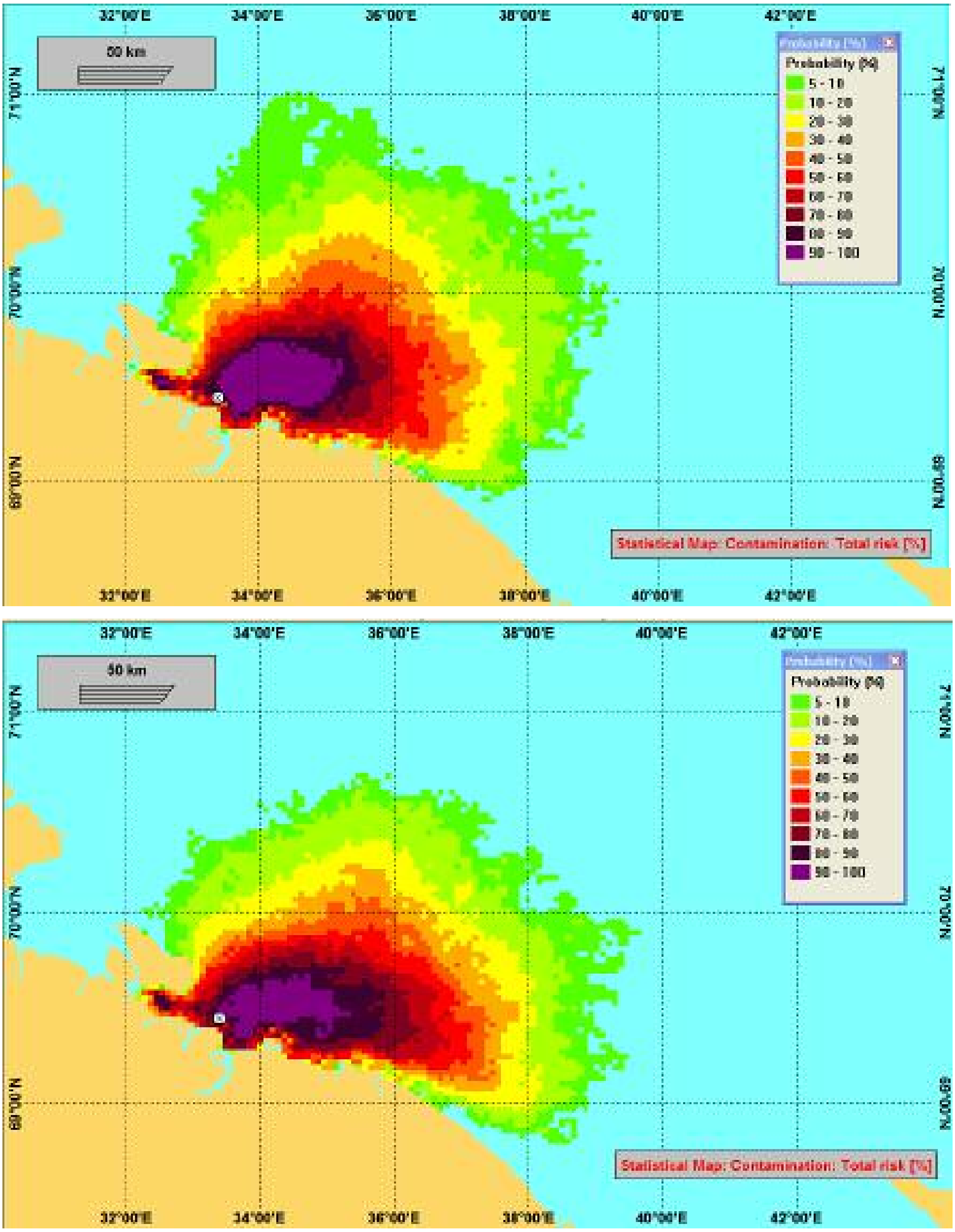


Figure 3.2 Statistical oil drift simulations for the western spill site (outlet of Murmansk Fjord). The maps show the area of influence for the spring scenario (top), and the autumn scenario (bottom).

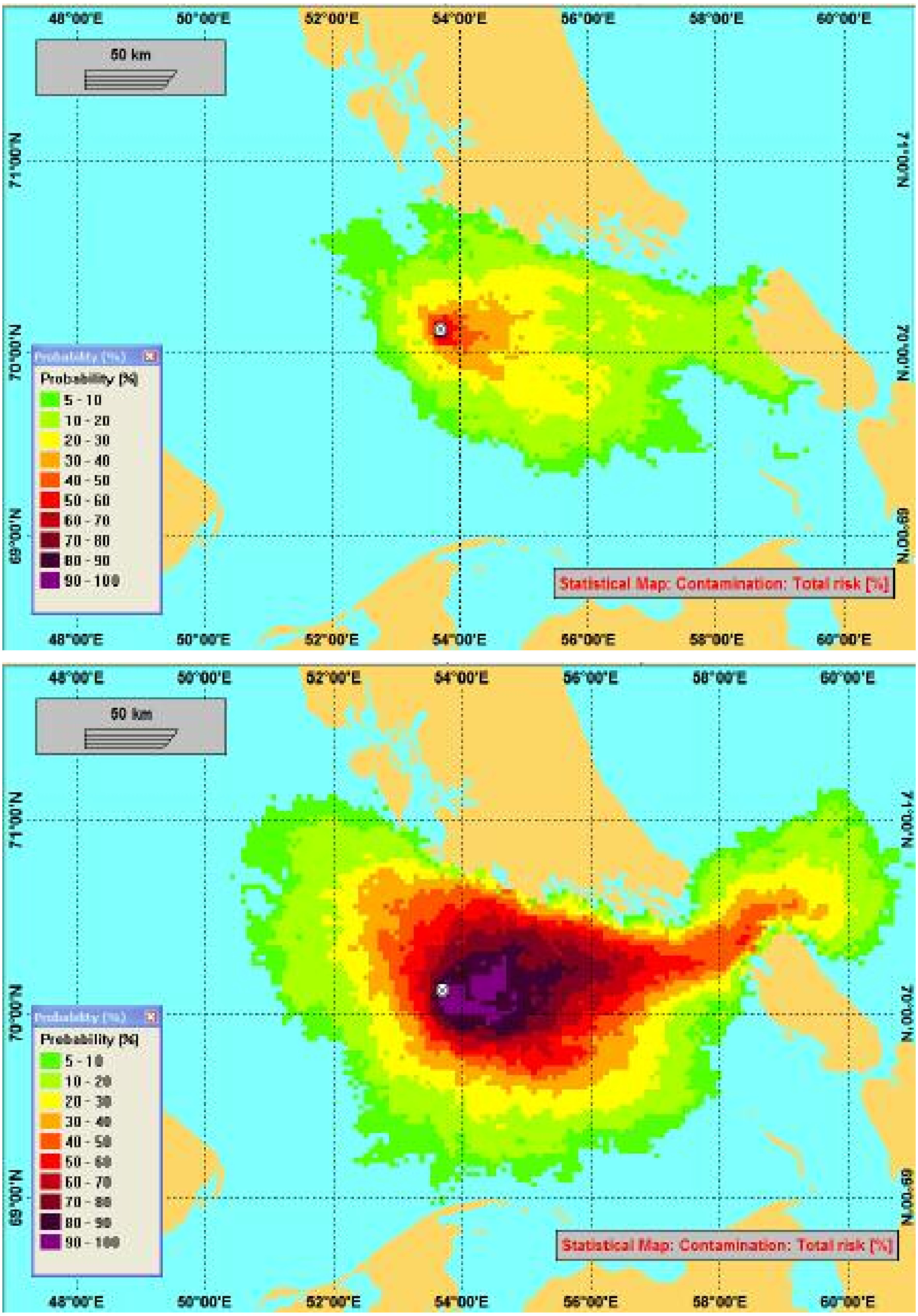


Figure 3.3 Statistical oil drift simulations for the eastern spill site. The maps show the area of influence for the spring scenario (top), and the autumn scenario (bottom). The marked difference between the spring and autumn simulations are mainly due to the precence of sea ice in the spring.

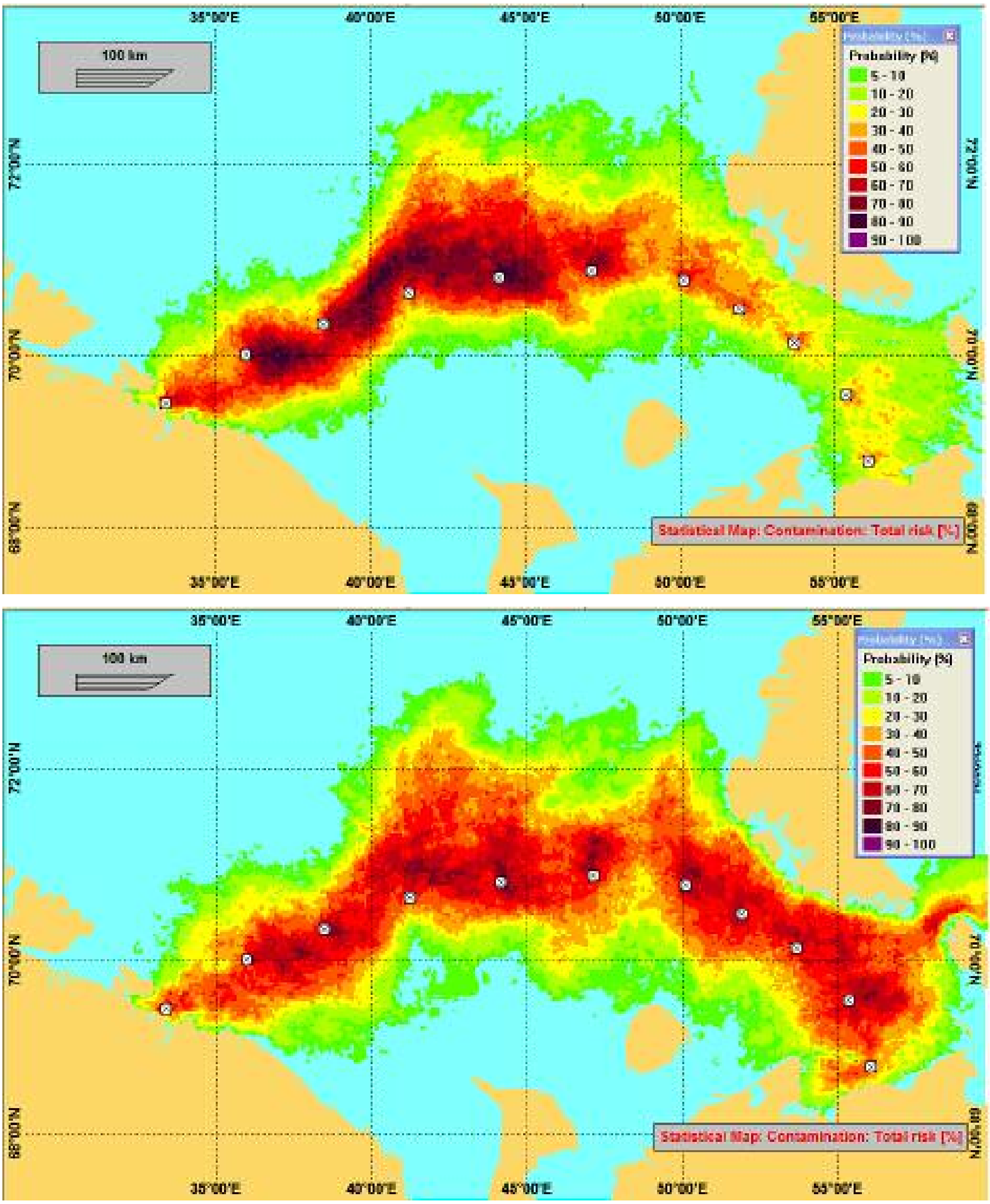


Figure 3.4 Statistical oil drift simulations for a possible tanker route. The route is represented by 11 possible release sites, where oil is released simultaneously in each oil drift scenario. The maps show the area of influence for the spring scenario (top), and the autumn scenario (bottom).

4 OIL SPILL RESPONSE ANALYSIS

In this chapter, different possible oil spill response options are simulated. All options are based on the offshore oil recovery system standardized by the Norwegian Clean Seas Association for Operating Companies (NOFO). NOFO is an oil spill response organization established by the operating companies on the Norwegian continental shelf. The system comprises a boom with a swath of approximately 180 m ("A" at Figure 4.1), towed by two vessels; a main vessel "C" and a towing vessel "D". The maximum towing speed of the system is 1 knot. The *Transrec* weir skimmer "B" is connected to the main vessel via a buoyant hose. The nominal pump capacity of the *Transrec* skimmer is 350 m^3/h, but the effective skimming rate during oil recovery operations is presumed to be approximately half of this rate. The main vessel has a 1000 m^3 storage tank for recovered oil. The system is found to operate efficiently at sea states up to about 3 m significant wave height.

The different oil response options considered in the present study represent combinations of two or more of these systems, each with different response times, i.e. sum of mobilization and transport times. The response options used for the two spill locations are summarized in Table 4.1.

Table 4.1 Oil spill response options.

	Murmansk Fjord	*Pechora Sea*
1. Base case	- One system mobilized from an oil response base in Murmansk Fjord with 6 hours response time. - One system from Norway with 18 hours response time.	Two systems mobilized from an oil response base near the Varandey oil terminal with 6 and 12 hour response times.
2. Strengthened response	Base case + one additional system from Murmansk with 12 hours response time.	Base case + one system from Murmansk with 40 hours response time.
3. Maximum response	Strengthened response + one additional system from Norway with 30 hours response time.	Strengthened response + one additional system from Murmansk with 46 hours response time.

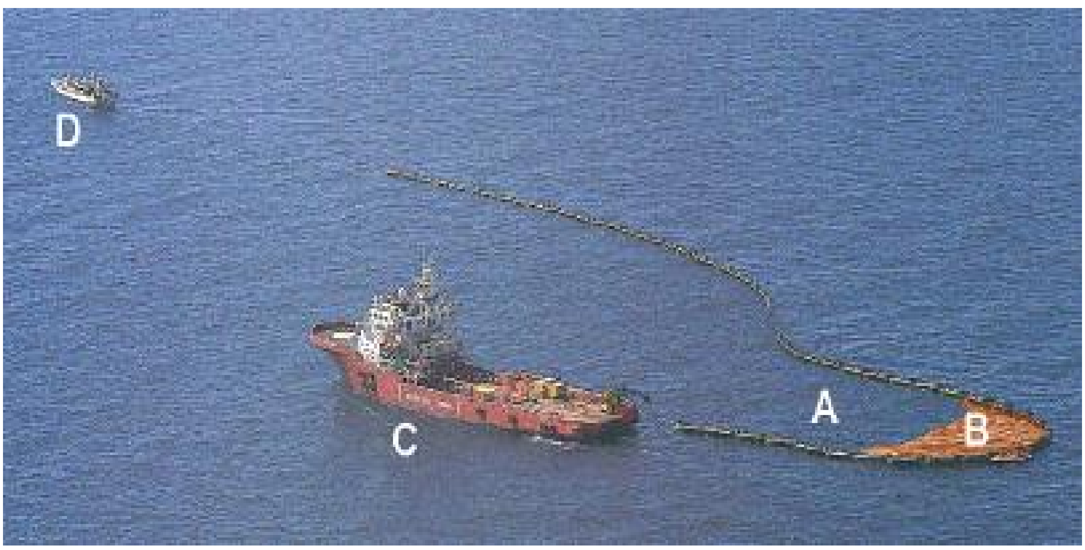


Figure 4.1 Offshore oil recovery system standardized by NOFO. A: boom; B: Transrec skimmer; C: main vessel; D: towing vessel.

Results of statistical simulations for the Murmansk Fjord spill are shown at Figures 4.2 and 4.3 for spring and autumn. The figures show a comparison between the area of influence with no oil spill response (top) and with the base case response option (bottom). The comparison shows that the base case response option gives a similar reduction in the influence area in the open sea for both seasons.

Figure 4.4 shows the statistical distribution of recovered oil and stranded oil for two response options (the base case option and the maximum response option). The distribution of stranded oil with no response is given for reference. The results show that the maximum response option causes a significant, but less than proportional increase in the amounts of oil recovered, compared with the base case option. However, the results also show that the maximum response effort gives a rather limited reduction in stranded oil, compared to the base case option.

This trend is partly caused by the fact that the spill location is located close to the shoreline. As a result, significant amounts of oil may reach the shoreline before arrival of the oil response systems. However, the spill scenario also implies release of large amounts of oil in a comparatively short time (10 000 m^3 in 10 hours). As no realistic response option can cope with such a release in real time, the response operation must continue after the end of the spill. By using NOFO's method for calculating system capacity, we find that four NOFO systems might recover such a spill in about 2 days:

Taking into account 20 % evaporative loss, and 3 times increase in volume due to emulsion formation (water content of about 70 %), the total volume to be handled will amount to about 25 000 m^3 water-in-oil emulsion. With an effective skimming rate of 170 m^3/h, and an effective operational time of 15 hours per day, each system can recover about 2500 m^3 of emulsion on a daily basis. Accounting for a boom efficiency of 80 % (20 % leak rate), the volume to be recovered will be 20 000 m^3 of emulsion, corresponding to 8 systems-days – or 4 systems working for 2 days. However, for near shore spills, it will be almost impossible to avoid stranding of oil remaining on sea in this two days period.

In theory, a significant improvement in the response performance can be obtained by increasing the number of systems and reducing the response time for all systems to a minimum, but these options will be limited by practical considerations.

Figures 4.5 and 4.6 show results from the statistical simulations for the eastern spill site (Petchora Sea). For this location, traditional oil response will be limited to the ice-free season, and oil recovery simulations have only been made for autumn. Figure 4.5 shows a significant reduction in the area of influence with the base case response option, and figure 4.6 shows that this option also implies a significant reduction in the stranded amounts of oil.

For this spill site, we have also made single scenario simulations to demonstrate the possible gain of an increasing response effort. The simulations were made for the oil drift scenario with maximum amounts of stranded oil. The map in Figure 4.7 shows the situation after 15 days with no oil spill response, while the bar chart on the same figure shows the mass balance for the different response options compared with the mass balance for the no response case. The bar chart indicates that significant reductions in stranded amounts of oil can be obtained by strengthened response efforts. This trend is due to the fact that the spill takes place at a considerable distance from the shore, i.e. 70 km, with a drift time to shore of more than 2 days, i.e. 60 hours. As demonstrated by Figure 4.8, this condition makes it possible to recover major fractions of the oil before the slick comes to the shore. The figure shows the time development of the oil mass balance for this oil drift scenario for two cases – the case with no response and the case with maximum response effort (four response systems).

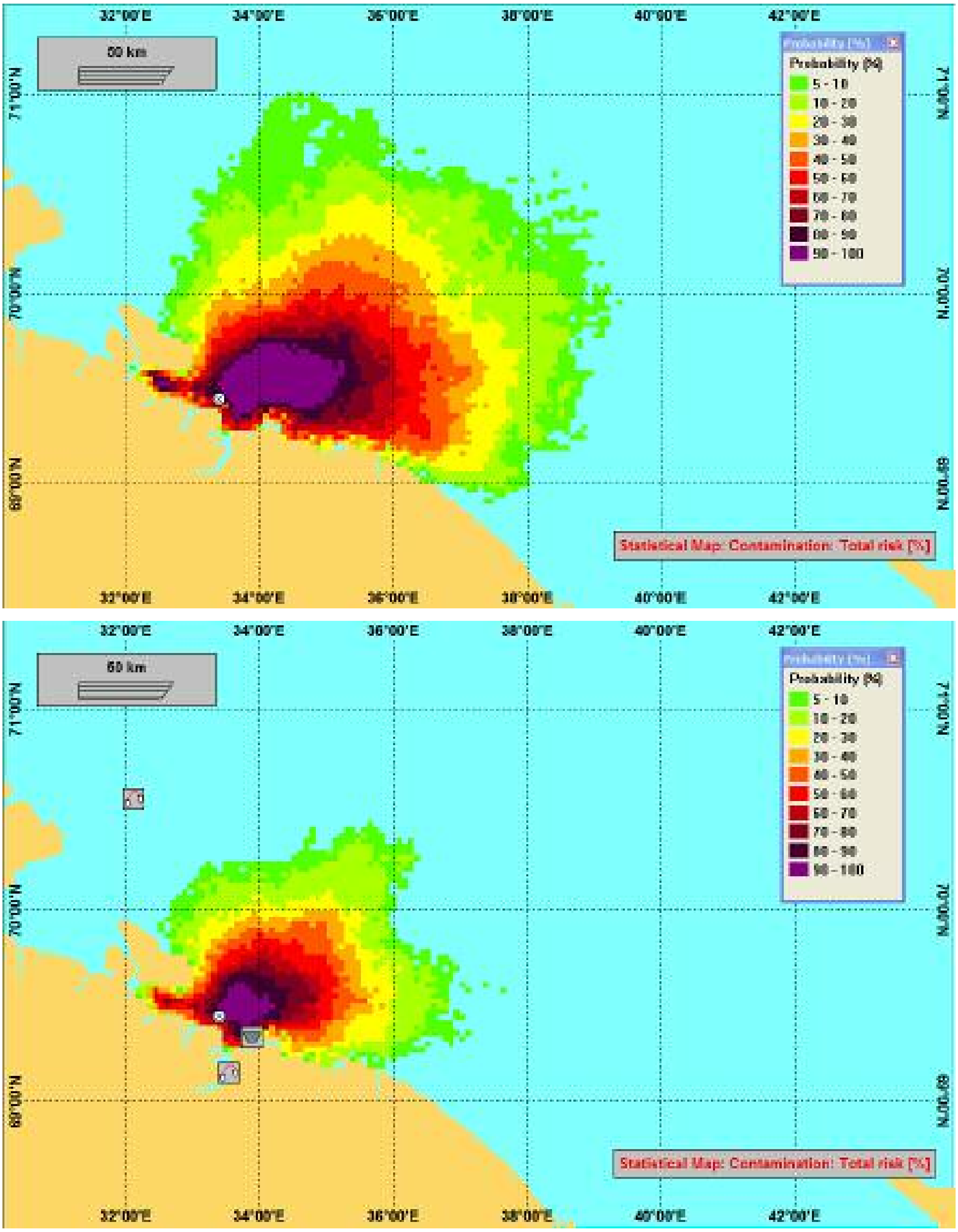


Figure 4.2 Statistical oil drift simulations for the western spill site (outlet of Murmansk Fjord). The maps show the area of influence for the spring scenario, with no oil spill response (top), and with the base case response option as defined in table 4.1 (bottom).

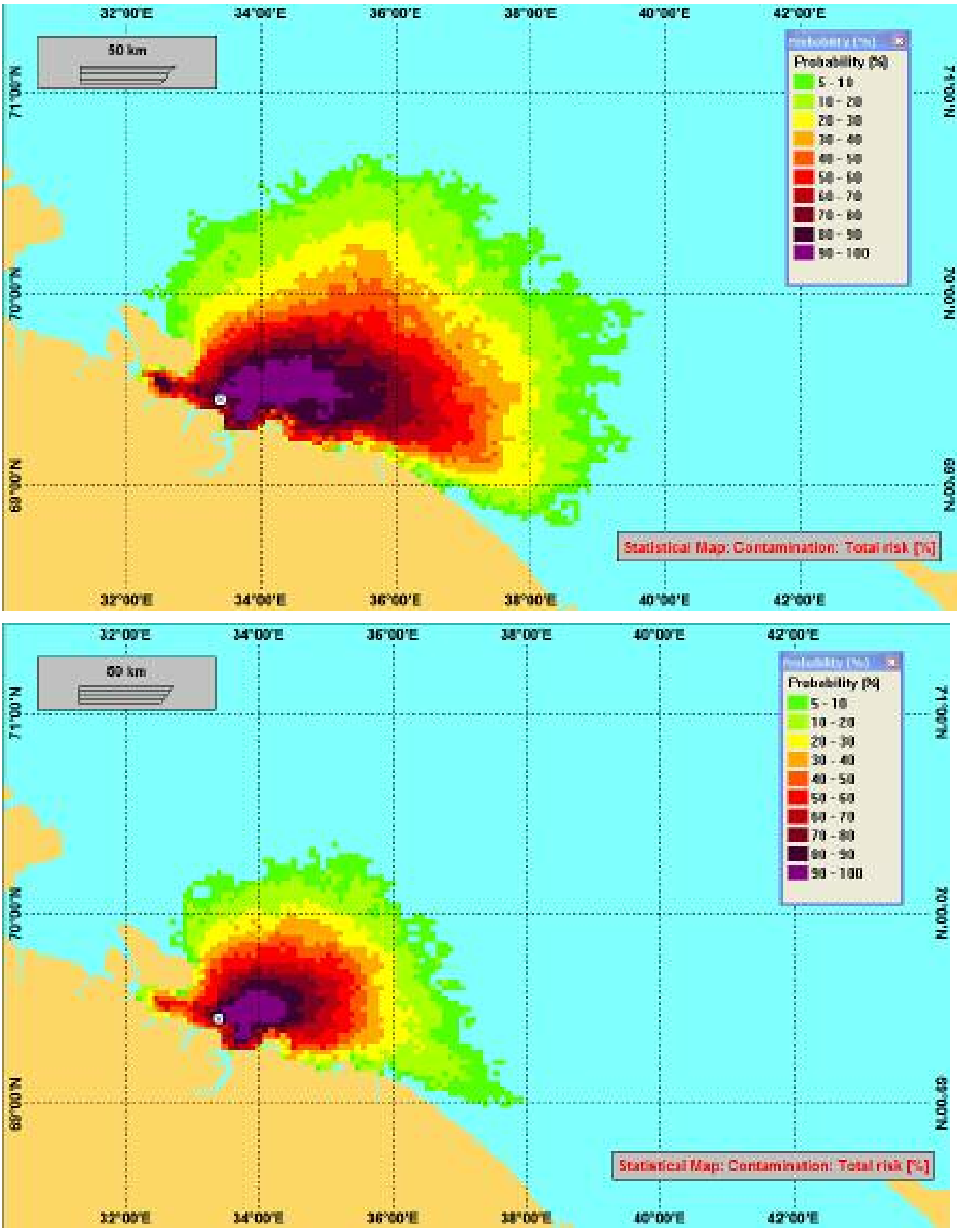
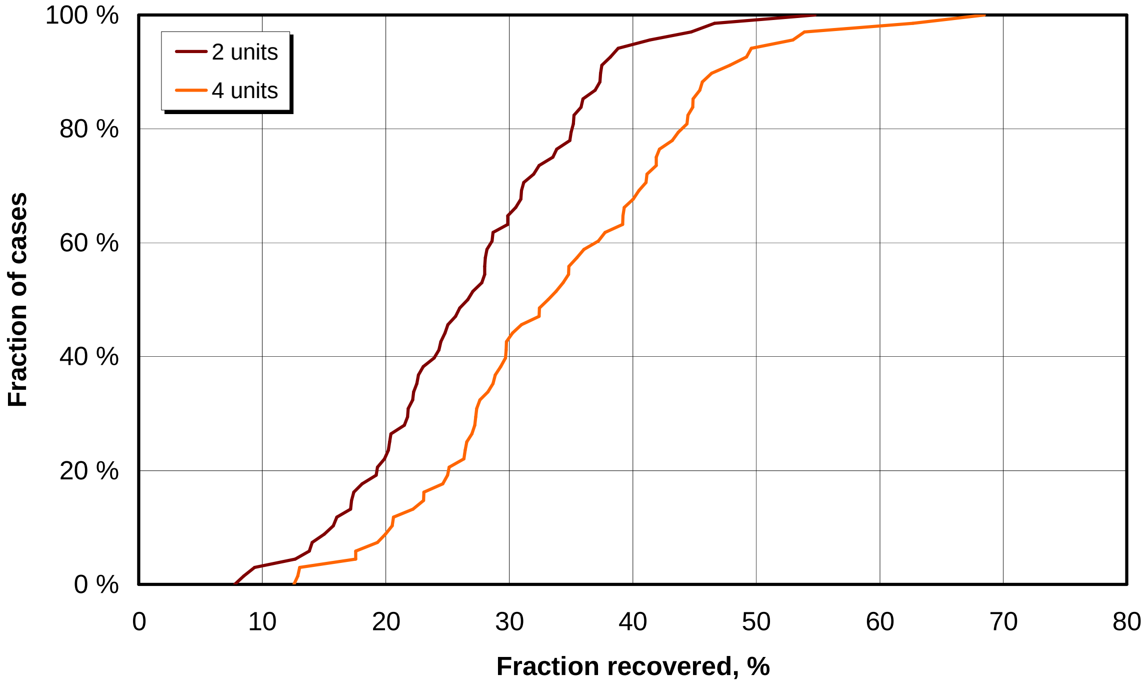


Figure 4.3 Statistical oil drift simulations for the western spill site (outlet of Murmansk Fjord). The maps show the area of influence for the autumn scenario, with no oil spill response (top), and with the base case response option as defined in table 4.1 (bottom).



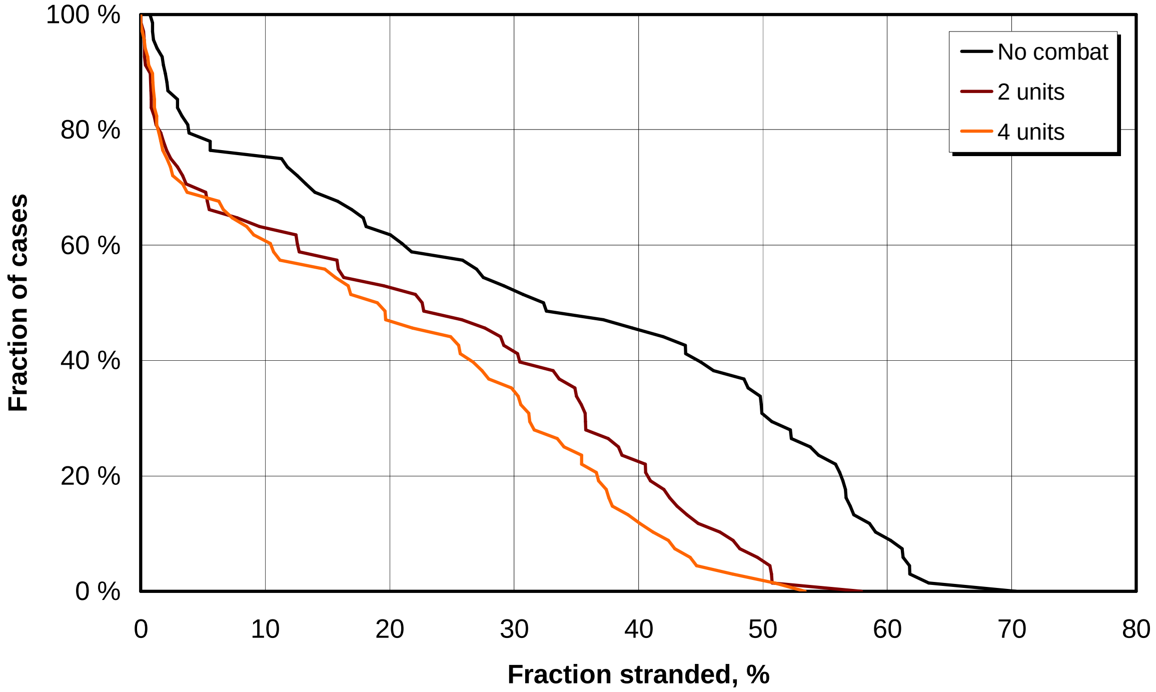


Figure 4.4 Statistical distribution of recovered oil (top) and stranded oil (bottom) for the Murmansk Fjord autumn scenario. The top graph shows results for the base case response option (2 units), and the maximum response option (4 units). The bottom graph compares stranded oil for the same response options with stranded oil with no response.

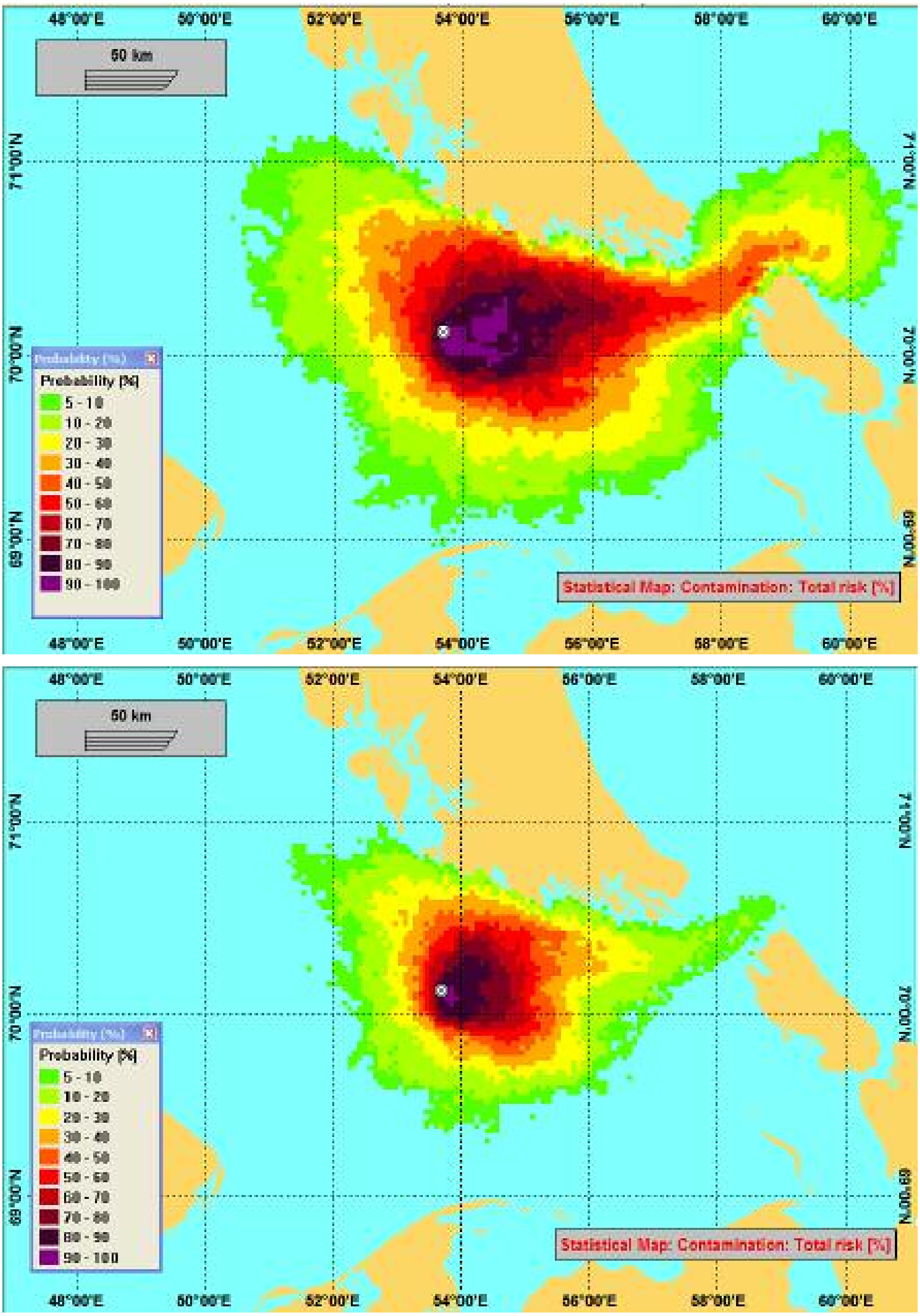
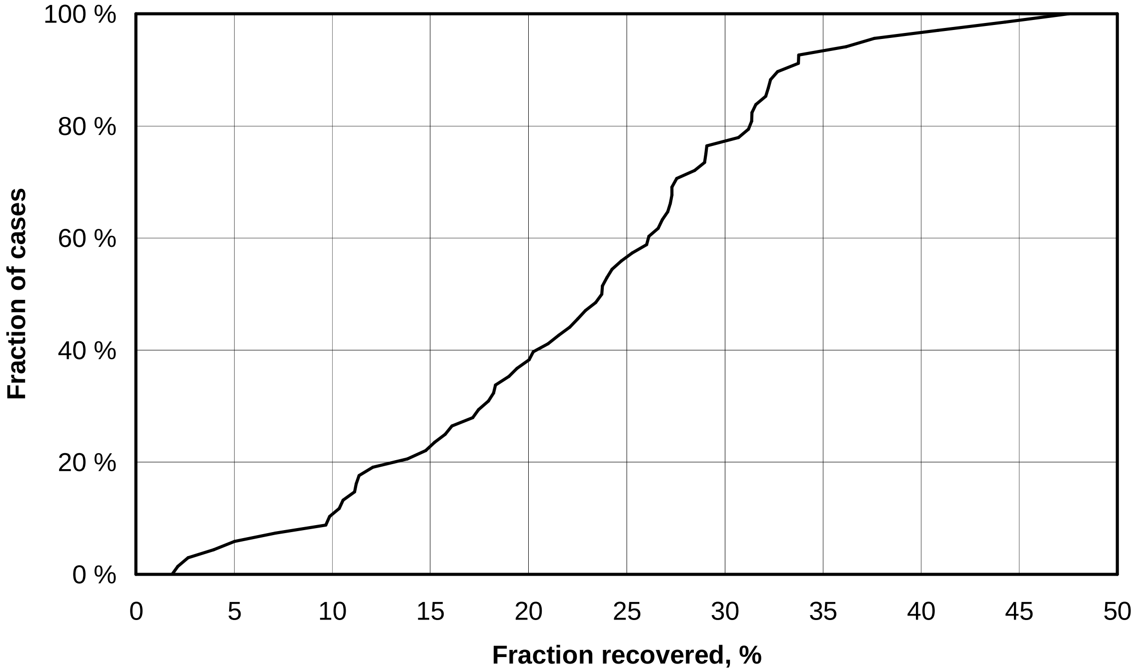


Figure 4.5 Statistical oil drift simulations for the eastern spill site (Pechora Sea). The maps show the area of influence for the autumn scenario, with no oil spill response (top), and with the base case response option as defined in table 4.1 (bottom).



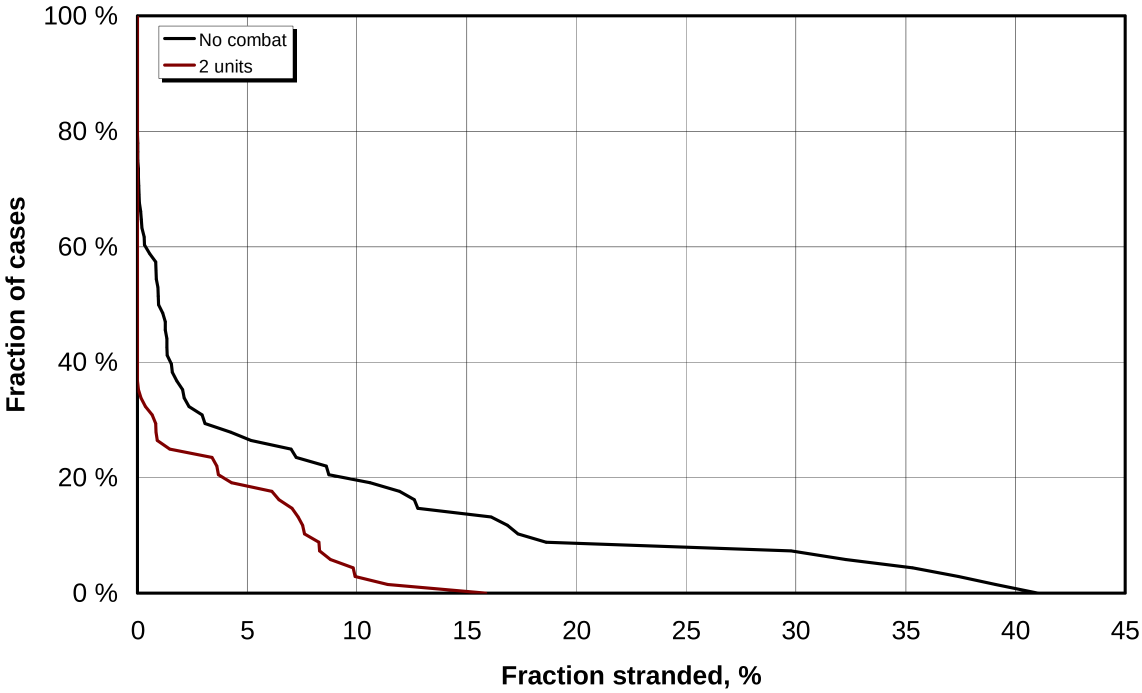
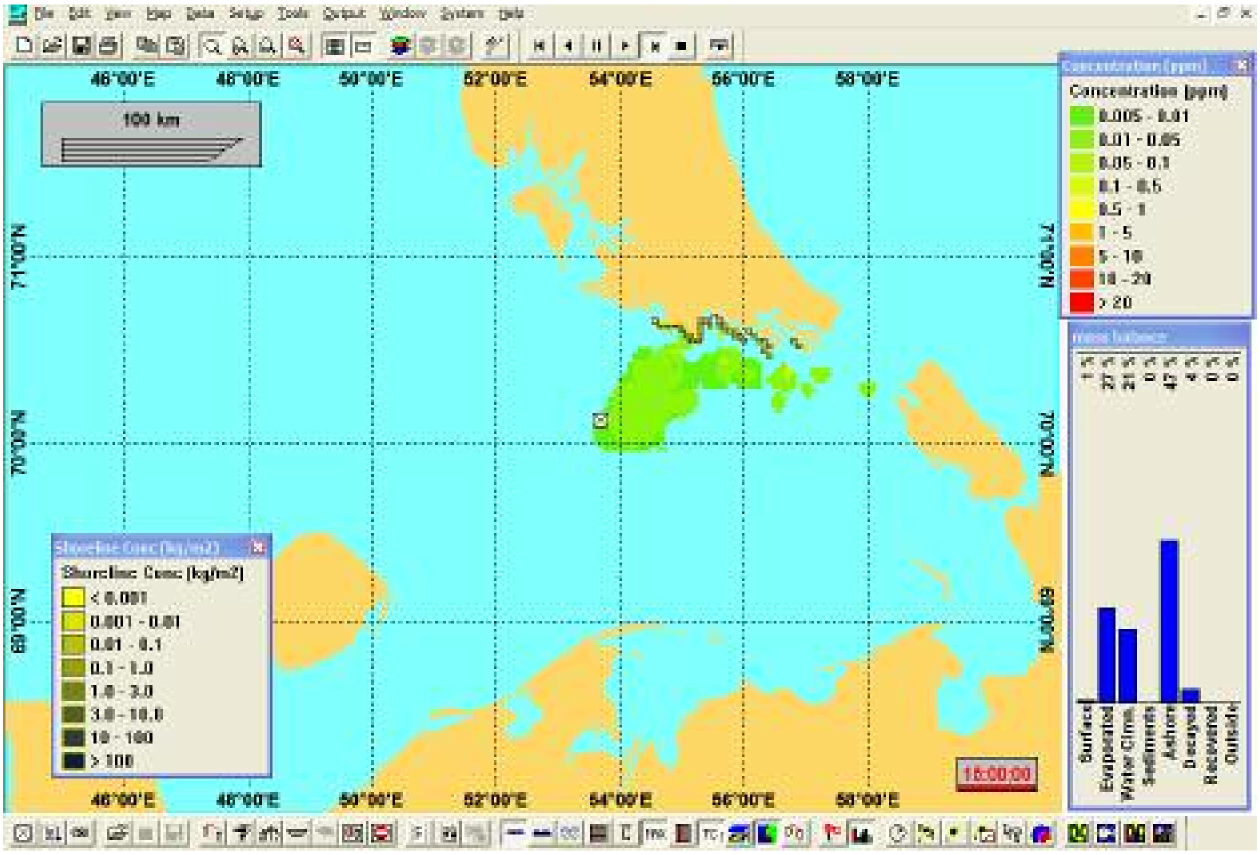


Figure 4.6 Statistical distribution of recovered oil (top) and stranded oil (bottom) for the Pechora Sea autumn scenario. The top graph shows results for the base case response option (2 units), The bottom graph compares stranded oil for the same response option with stranded oil with no response.



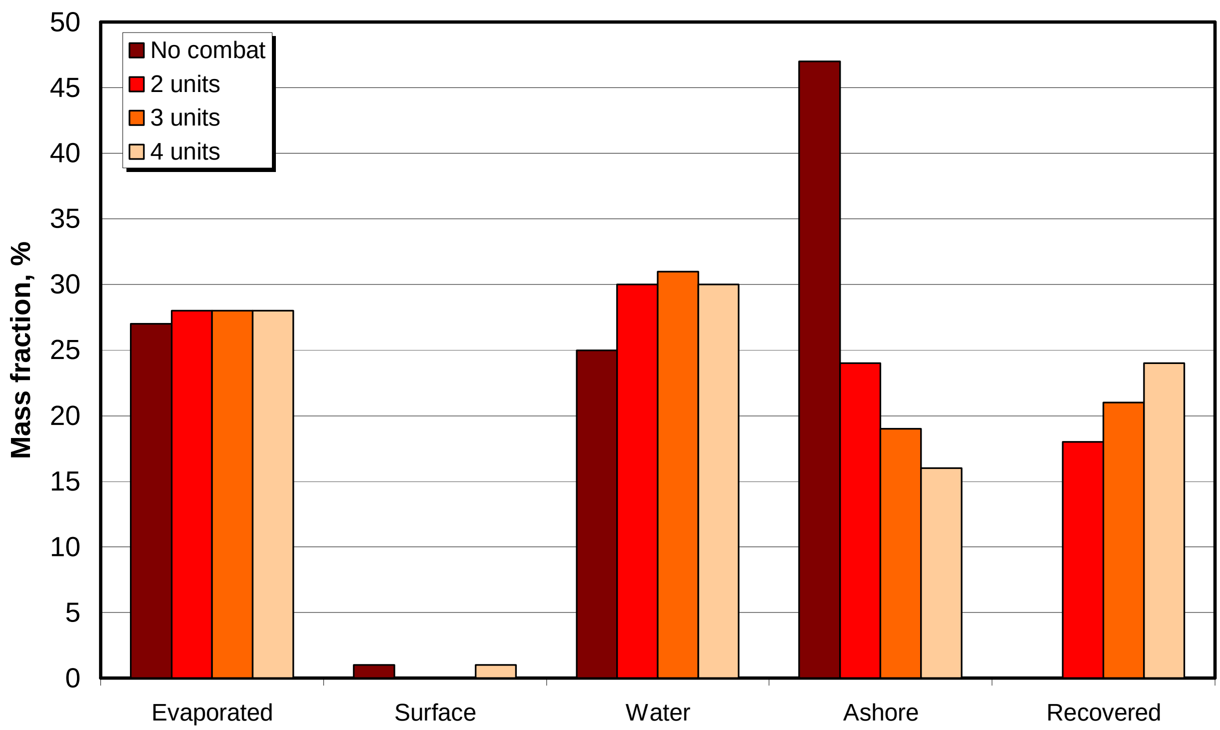
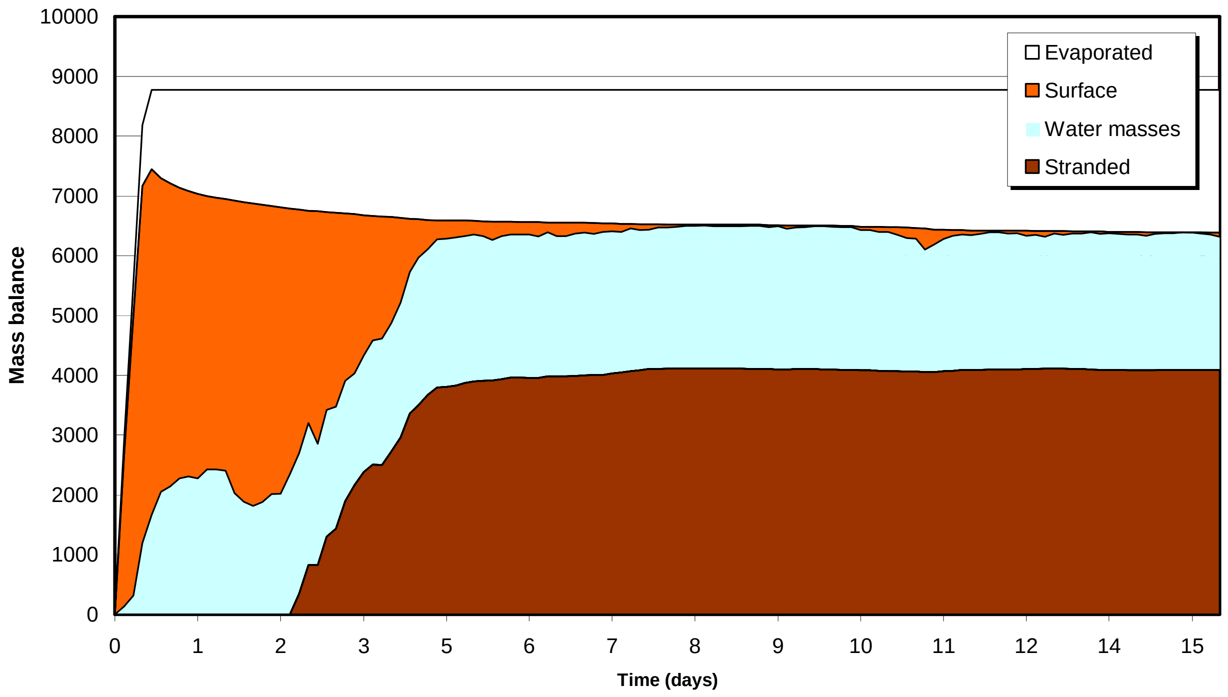


Figure 4.7 Results of single scenario simulations for the eastern spill site. The map (top) shows the situation after 15 days with the no response option, while the bar chart compares the mass balance for this case and the other response options.



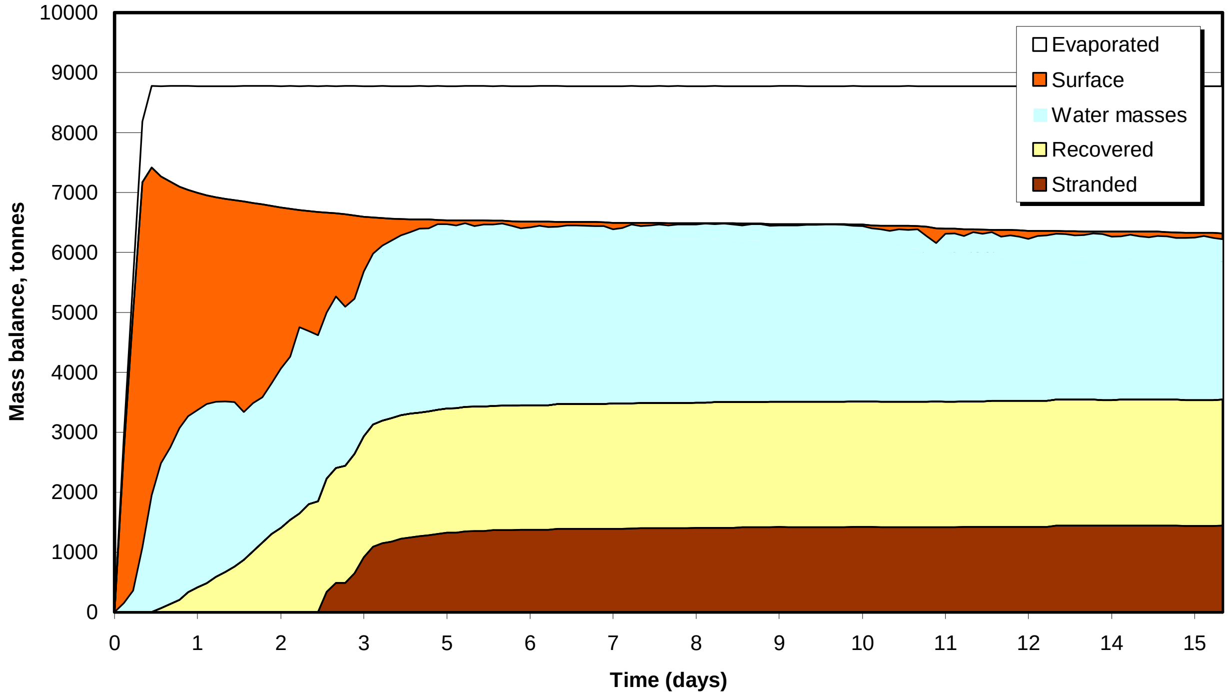


Figure 4.8 Time development of the oil balance for the single scenario run for the Eastern spill scenario. Top: no response. Bottom: four response systems (maximum response).

5 CONCLUSIONS AND RECOMMENDATIONS

The present report deals with simulations of oil drift and oil spill response for possible spills from tanker transport of oil products from Pechora Sea to the Murmansk region. The oil drift simulations provide information on the area of influence from possible major oil spills in conjunction with tanker transport in the area of concern, while the response analysis will form the basis for setting up a framework and guidelines for preparing an oil spill plan for the area.

5.1 Oil drift simulations

The oil drift simulations are made with SINTEF's OSCAR model, which is a state-of-the-art oil drift and fate model which can be run both in single scenario and statistical mode. Both modes are used in the present study. The statistical mode provides the geographical area of influence of a spill of a certain oil type, taking place at a given location within a certain season of the year. The statistics are obtained by running a set of oil drift scenarios within a specified season with spill starts within different years of available historical wind data. Worst case scenarios for the season of concern (e.g. maximum stranded oil) may be selected from this set of simulations, and single scenario runs may be made for these scenarios to reveal more details (e.g. time development of mass balance). In the present study, the simulations are based on gridded seasonal background current data and hindcast wind data provided by the Norwegian Meteorological Institute, supplemented by historical ice coverage data from the same source.

In the present study, we have focused on two potential spill sites – one located near the outlet of the Murmansk Fjord (the western location), and one located in the Pechora Sea in the passage between Novaya Zemlya and Kolguyev Island (the eastern location). The eastern location is chosen as representative for regions with seasonal sea ice, while the western location represents regions with all-year open water. For both locations, the release was presumed to amount to 10 000 m^3 of crude oil, discharged over a 10 hour period. A Norwegian crude oil (Troll) with fresh oil properties similar to the Varandey oils was used in the simulations

The results for the western location showed only minor differences in the area of influence in the two seasons considered (spring and autumn), while the results for the eastern location demonstrated a marked seasonal variation, depicted in terms of a significant reduction in the extent of the influence area due to the presence of sea ice in the spring season.

Statistical simulations were also made for multiple spill sites distributed along a possible tanker route. By combining such simulations with data on the spatial distribution of sensitive resources, such simulations can be used for assessments of environmental risk for optional tanker routes.

5.2 Oil spill response

The OSCAR model is designed to perform simulations of oil spill response. Oil spill response options are defined in terms of number of response systems, mobilization time and transfer time of each system from the base to the release site, in addition to boom and skimmer capacities, weather limitations, on-board storage volume etc. On this basis, the effect of a given response operation is simulated in terms of amounts of oil recovered and corresponding reductions in stranded oil in particular, and area of influence in general. In the present study, oil spill response simulations have been made both in single scenario mode and in statistical mode.

For the western site, statistical simulations were made for two response options – one option involving two response systems, and one option involving four response systems. The base case involved two response systems – one mobilized from a presumed oil contingency base in the Murmansk Fjord, and one from the Norwegian Sector. The second case represented a doubling of this response effort (two systems from the Murmansk Fjord; two from Norway). All systems were presumed to be equipped according to the standard defined by the Norwegian Clean Sea Association for Operating Companies (NOFO). The results indicate that only a marginal gain could be obtained by this increase in response effort: An almost insignificant reduction was obtained in the stranded amounts of oil by doubling the response effort. This rather discouraging result is typical for near-shore oil spills. In the period required for recovery of the spilled oil (about two days in the present case), stranding of oil remaining on sea can not be prevented due to the short drift time to the shoreline.

The oil spill response simulations for the eastern location were limited to the season with ice free conditions (autumn), as the potential effectiveness of conventional response options are not documented in the season with sea ice. The statistical simulations for the base case option (two response systems) demonstrated a significant reduction in the area of influence, as well as a significant reduction in the stranded amounts of oil, compared with simulations with no oil spill response. Single scenario simulations were performed for the worst case scenario (largest amount of stranded oil) to investigate effects of increased response efforts. The results showed that in this case, escalation of the response effort might give significant gains in terms of reduced amounts of stranded oil. This encouraging result was related to the fact that a significant part of the oil spill could be recovered before the oil would hit the shoreline (two days minimum drift time).

5.3 Recommendations for future work

Modelling of oil drift and fate in open waters may be considered as well established, based on many years of accumulated experience from laboratory and field studies, as well as hindcast studies of accidental spills. Due to limited experience, modelling of oil drift and fate in the presence of sea ice is more uncertain. Thus, in the present study, the influence of sea ice on oil drift and fate is accounted for in a simplified way, with the effect of sea ice parameterized in terms of the local ice coverage. This is a crude approximation, partly because the fate of the oil in ice is known to depend on the specific ice form (broken ice, brash ice etc.), and partly because the rate of weathering processes such as natural dispersion and formation of water-in-oil emulsions are influenced by non-local processes, e.g. wave attenuation by sea ice. Presently, however, lack of detailed ice information does not justify algorithms which accounts for various ice forms or wave attenuation in sea ice.

In the present study, simulations of oil drift and fate in sea ice have been based on historical ice coverage data, combined with climatological current data and hindcast wind data. In a state-of-the art operational oil drift forecasts system, we anticipate that sea ice data will be provided by ocean circulation models coupled with an ice drift model. This same approach might be used in impact assessments, based on one or more “design-years” of hindcast data from a coupled ocean current and sea ice model. This will provide a more realistic picture of the ice drift pattern, since simulated ice drift velocities will be available in addition to ice coverage.

In summary, we may conclude that:

- Future improvements in modelling of oil drift in regions with sea ice will to a large extent depend on relevant input on ice conditions. Coupled ocean circulation and ice drift models may provide data on ice coverage, ice drift velocities, and ice thickness, but information on ice forms (broken ice, brash ice etc.) are not readily available.
- The influence of sea ice on weathering processes such as natural dispersion and formation of water-in-oil emulsion depends on wave attenuation induced by the sea ice. This process is non-local, in the sense that the wave conditions at one location in the ice field will depend on the ice conditions (ice coverage and thickness) in the ice field upwind from that location. Wave prediction models that accounts for attenuation of waves in sea

ice may improve such predictions, but more studies on oil-ice interaction will also be required to establish empirical relations between local wave conditions and weathering rates of oil in ice.

In our view, the following enhancements should be considered on short terms:

- Findings from earlier oil-ice interaction studies should be reconsidered with the aim of formulating improved oil-in-ice drift and fate algorithms. Such improvements could for instance account for partitioning of oil in the ice: Oil found on the surface water between ice floes or in ice leads, on the surface of ice floes, or trapped under the ice will be subject to different weathering exposure.
- Simulated ocean current and ice data (coverage, ice drift and thickness) from coupled ocean circulation - ice drift models should replace the present historical ice coverage data and climatological currents.

Possible enhancements on longer terms depend to a large extent on the outcome of future research on oil-ice interactions, i.e. on the availability of relevant empirical data from laboratory studies and field tests. The major unanswered questions seem to be related to the influence of sea ice on weathering processes such as emulsification and natural dispersion. Prediction models for wave attenuation in sea ice may be useful in this context, but more research is also needed the establish correlations between sea state and weathering rates in various ice conditions.

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