Trajectory and Fate Modelling in Support of the ExxonMobil Eastern Newfoundland Offshore Exploration Drilling Project

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Project Manager

Matthew Horn, Ph.D.

RPS
55 Village Square Dr.
South Kingstown, RI USA
02879-8248

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List of Contributors

Matthew Horn, PhD – Project Lead and Senior Scientist

matt.horn@rpsgroup.com

Lisa McStay – Ocean Engineer, oil spill modeller and report preparation

Jenna Ducharme – GIS Specialist, figure generation

Matthew Frediani –GIS Analyst, oil spill modeller and figure generation

Steven Tadros – Junior Scientist, oil spill modeller and report preparation

Alicia Morandi – Environmental Analyst, report preparation

Jeremy Fontenault –Senior GIS Specialist, report preparation

Deborah Crowley – Senior Scientist, Modeller

Tayebeh Bakhsh, PhD – Ocean Engineer, Metocean data preparation

Mahmud Monim – Oceanographer, Metocean data preparation

Daniel Torre – Junior Scientist, Data preparation

Deborah French McCay – Senior Scientist, Report review

Cheryl Morse – Programmer/Developer

Timothy Giguere – Programmer/Developer

Executive Summary

Oil spill trajectory and fate modelling were performed to support an Environmental Impact Statement for ExxonMobil Canada Ltd. Eastern Newfoundland Offshore Exploration Drilling Program. The Project Area includes portions of the easternmost edge of the Downing Basin, the Flemish Pass, and the northwestern portion of the Flemish Cap along the Sackville Spur. Modelling was performed at a representative site that was located approximately 400 km east of the Newfoundland Coast, with exploratory drilling anticipated in waters that range in depth from <80 m to >4,000 m. Hypothetical continuous unmitigated subsurface blowout scenarios of Ben Nevis crude oil were developed at one location in the Flemish Pass (EL 1134). The water depth is approximately 1,175 m for the hypothetical release location modelled within EL 1134. An unmitigated 30-day subsurface blowout at EL 1134 was simulated for 45 days, while an unmitigated 113-day subsurface blowouts at EL 1134 was simulated for 160 days. The release rate for the two modelled scenarios was 37,800 bbl/day, totaling 1,134,000 bbl for the 30-day release and 4,271,400 bbl for the 113-day release. These scenarios represent the range of time that is expected to be required to contain a release either by cap-and-contain methodologies or through the drilling of a new relief well. In addition, two additional "batch spill" scenarios were modelled as instantaneous unmitigated surface releases of 100 L and 1,000 L of marine diesel at EL 1134 and were simulated for 30 days.

In order to reproduce the dynamic and complex processes associated with deep subsea blowout releases, two models were used. The near-field model OILMAPDeep was used to characterize the dynamics of the jet and buoyant-plume phases of a subsurface blowout. It contains two sub-models, a plume model and a droplet size model. The plume model predicts the evolution of plume position, geometry, centerline velocity, and oil and gas concentrations until the plume either surfaces or reaches a terminal height, at which point the plume is trapped. The droplet size model is used to characterize the size and distribution of oil droplets, including the associated mass of oil being released at specific water depths, where the plume became neutrally buoyant. The output data from OILMAPDeep is used to initialize the SIMAP model, which simulates the far-field trajectory, fate, and potential exposure in the marine environment from following a release.

Geographical data including habitat mapping and shoreline identification and classification were obtained from multiple data sources. For Canadian areas, data from the New Brunswick Department of Natural Resources and Nova Scotia Department of Natural Resources were used. For the U.S. shoreline, the U.S. National Oceanic and Atmospheric Administration's Environmental Sensitivity Index and Maine Department of Environmental Protection's Environmental Vulnerability Index were used. Bathymetry

was characterized using databases provided by NOAA National Geophysical Data Center and GEBCO (General Bathymetric Chart of the Oceans).

Currents for the North Atlantic region were acquired from the U.S. Navy Global HYCOM (HYbrid Coordinate Ocean Model) circulation model. Wind data for this study were obtained from the U.S. National Centers for Environmental Prediction Climate Forecast System Reanalysis (CFSR) model. All data was acquired and used for the period between January 2006 and December 2012.

A stochastic analysis was conducted for each hypothetical release location, consisting of 179 individual model runs for the 30-day release scenario and 171 individual model runs for the 113-day release scenario. Each run was initialized with a different start date/time between 2006-2012 to sample a range of environmental conditions. The dates and times were selected randomly from within 14-day intervals spanning the entire seven years of data. Results of the stochastic analysis included probability footprints above specified thresholds for surface, water column, and shoreline contamination and minimum time to oil exposure. Because the runs spanned seven full years and included all of the associated seasonal variability, the complete set was referred to as annual summaries. To investigate seasonality, individual runs within the stochastic analysis were classified as either summer or winter, depending on whether the majority of the days within each modelled 45- or 160-day period had the presence (winter) or absence (summer) of ice cover.

Representative deterministic scenarios (i.e., single trajectory) were identified from each set of stochastic subsurface blowout results. Individual scenarios were selected based upon the length of shoreline contacted with oil based upon a highly conservative socio-economic threshold of:

- Shore oil average concentration >1.0 g/m^2

The selected cases include the 95th percentile model run based upon the length of shoreline exceeding the threshold for contamination identified from within each stochastic scenario. However, the 95th percentile run did not result in shoreline oil contamination for the 30-day scenario and therefore, the 98th percentile run was selected for the 30-day scenario. In addition to these two deterministic scenarios, two surface releases of marine diesel were modelled for two release volumes (100 L and 1,000 L).

It is important to note that although large footprints of oil contamination are depicted for stochastic analyses, they are not the expected distribution of oil from any single release. These maps do not provide any information on the quantity of oil in a given area. They simply denote the probability of oil exceeding the specified threshold passing through each grid cell location in the model domain over the entire model duration (45 or 160 days), based on the entire ensemble of runs (179 or 171 individual releases for all runs). Only probabilities of 1% or greater were included in the map output, as lesser probabilities represent random noise in each set of 179 or 171 trajectories. Stochastic maps of water column contamination of dissolved hydrocarbons depict the likelihood that concentration will exceed the identified threshold at any depth within the water column, but do not specify the depth at which this occurs and do not imply that the entire water column (i.e., from surface to bottom) will experience a concentration above the threshold.

Stochastic results are useful in planning for oil spill response, as they characterize the probability that regions may experience contamination above specified thresholds, taking into account the environmental variability that is expected from many potentially-different release scenarios over time (i.e., multiple years). Stochastic footprints for potential surface oil exceeding a thickness of 0.04 µm were between 2,265,000 – 2,495,000 km^2 for the 30-day releases and 3,402,000 - 3,528,000 km^2 for the 113-day releases. Within the footprints, the highest predicted likelihood of contamination above 0.04 µm occurred to the east and south of the release site, while there was a much lower probability (<25%) for oil being transported to the north or west towards Canadian waters. Footprints depicting higher probability contours (90%) yield only a fraction of the total footprint, ranging from 81,440 – 1,394,000 km^2 depending on the scenario. Seasonal variations were evaluated yielding different predicted surface oil results for summer versus winter scenarios. For both the 30- and 113-day releases, larger surface oil footprints associated with >90% probability contours were predicted for summer scenarios at both sites indicating more coherency in the predicted footprints of the releases. However, the areas associated with lower probabilities (i.e., 1% and 10%) are larger in the winter, indicating more extensive and variable transport with a high likelihood of entrainment.

The highest predicted potential (25%) for oil to make contact with shorelines exceeding 1 g/m^2 occurred within the 113-day releases that were modelled under wintertime conditions, with summer conditions typically resulting in a lower probability of contact with shorelines. The probability of oil making contact with shorelines above 1 g/m^2 within the 30-day releases was <5% for the 30-day release. The probability of oil making contact with the shoreline above 1 g/m^2 from the 113-day release was up to 25% on the Avalon Peninsula and primarily <10% on the northern and southern coasts of Newfoundland. Minimum time estimates for first shoreline oil exposure ranged from approximately 8-27 days for both the 30- and 113-day releases. Modelled oil from these subsurface releases had a higher potential to be transport to the west and southwest prior to surfacing, where surface currents and winds typically carried releases further offshore.

The amount of evaporation and degradation was relatively consistent between the two different duration model runs. Approximately 26-30% of the Ben Nevis crude oil releases was predicted to evaporate and another 19-39% to degrade by the end of the 45- or 160-day simulation. Most of the variability in the mass balances was associated with the amount of oil found either on the surface or entrained within the water column. The amount of oil remaining on that water surface at the end of the representative 45- and 160-day deterministic simulation was 47% and 10%, respectively. This degree of variability is expected, as the entrainment and resurfacing of oil occurs on timescale of minutes, depending on the wind and wave conditions at the specific time. Entrainment into the water column ranged between 3% and 7%. Shoreline contact was a small percentage of the total released oil, where even the worst case shoreline contact cases were predicted to have less than 0.2% of the total volume of released oil reaching shore. The amount of oil predicted to be on sediments at the end of the simulations was less than 0.01% of the total release volume.

Accidental discharges of marine diesel from small volume batch spills were modelled as near instantaneous releases. These small volume releases were predicted to result in far less contamination (spatially and concentration) when compared to the large volume blowout releases. By the end of the 30-day release simulations, 60-73% of the released diesel was predicted to evaporate and 17-28% degrade. A small portion of highly weathered diesel may continue to be transported at the surface or in the water column for some distance. However, this oil would be patchy and discontinuous. None of the oil from the batch spills was predicted to reach the Nova Scotia shoreline.

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List of Acronyms and Abbreviations

3D: Three dimensional, referring to the vertical and horizontal, as in x, y, and z directions

AL: Aliphatic portion of the total hydrocarbon, which is modelled as a volatile but insoluble fraction within the SIMAP model and can therefore evaporate.

AR: Aromatic portion of the total hydrocarbon, which is modelled as a volatile and soluble fraction within the SIMAP model and can therefore evaporate and dissolve.

BAOAO: Bonn Agreement Oil Appearance Code

BTEX: Benzene, toluene, ethylbenzene, and xylene

CERCLA: The U.S. Superfund or Comprehensive Environmental Response, Compensation, and Liability Act of 1980

EIS: Environmental Impact Statements

EL: Exploration License

GEBCO: The General Bathymetric Chart of the Oceans operated by the International Hydrographic Organization (IHO) and Intergovernmental Oceanographic Commission (IOC) of UNESCO.

HYCOM: The U.S. Navy HYbrid Coordinate Ocean Model used for currents

MAH: Monocyclic aromatic hydrocarbons (monoaromatic), with only one six carbon ring

MICOM: Miami Isopycnic-Coordinate Ocean Model

NCODA: U.S. Navy Coupled Ocean Data Assimilation

NOAA: U.S. National Oceanic and Atmospheric Administration

NRC: U.S. National Research Council

NRDA: The U.S. Natural Resource Damage Assessment

NRDAM/CME: Natural Resource Damage Assessment Model for Coastal and Marine Environments

PAH: Polycyclic aromatic hydrocarbons (polyaromatic), with two or more six carbon rings

PPB: Part per billion, as referring to concentration. Roughly equivalent to µg/L.

PPM: Part per million, as referring to concentration

SIMAP: Release Impact Model Application Package, a 3D trajectory and fate model developed by RPS

THC: Total hydrocarbon concentrations

UNESCO: United Nations Educational, Scientific, and Cultural Organization

WOA: World Ocean Atlas, a database from NODC NOAA containing observational data of physical and chemical parameters of seawater from many thousands of cruises.

1 Introduction

RPS (previously Applied Science Associates, Inc.) conducted trajectory and fate modelling in support of an Environmental Impact Statement (EIS) for the ExxonMobil Canada Ltd. Eastern Newfoundland Offshore Exploration Drilling Program proposed in the region of the Flemish Pass offshore Newfoundland. The EIS Project Area is located approximately 300 km east of the Newfoundland coast, overlapping the Grand Banks, Flemish Pass, and the Flemish Cap. Water depths in the Project Area range from <100 m to >4,000 m. Major currents, including the Labrador Current and the Gulf Stream, influence the circulation and biological productivity in this region.

This modelling was conducted to evaluate hypothetical unmitigated release events associated with exploration drilling, including large scale deep-water blowouts of a crude oil (Ben Nevis) from the wellhead at the seafloor and smaller scale batch spills of marine diesel at the surface. Three-dimensional (3D) oil spill trajectory and fate modelling and analyses were performed to support evaluation of the potential movement and behavior of oil following hypothetical releases into the Northwest Atlantic Ocean near Newfoundland. RPS's nearfield OILMAPDeep blowout model and the far-field Spill Impact Model Application Package (SIMAP) oil trajectory and fate models were used. This report provides a description of the Project Area and modelled scenarios, an overview of the modelling approach, details about the model input data used, and a presentation and discussion of the modelled results.

2 Background and Scenarios

2.1 Project Area

Newfoundland is comprised of a series of islands off the east coast of Canada, and along with Labrador forms the easternmost Canadian province. The relatively shallow waters of the continental shelf extend eastward into the northwest Atlantic Ocean up to 500 km off the Newfoundland coast. The Exxon Project Area (46.5-47.5 °N, 47-49 °W) contains portions of the Grand Banks, Flemish Pass, and Flemish Cap, in the northwest sector of the Jeanne d'Arc sedimentary rift basin, east of Newfoundland (Figure 2-1). This area is known to contain substantial petroleum resources. This biologically productive region sits atop the Hibernia, White Rose, and Terra Nova oil fields. Bathymetry in the area ranges from less than 100 m over the Grand Bank to greater than 4,500 m deep in the Labrador Basin. The model domain extends as far west as 72° W and east to 28°W, encompassing Canadian, U.S., and International waters. This modelled extent is much larger than the Project Area, as hypothetical releases of oil will be tracked for long periods of time (up to 160 days).

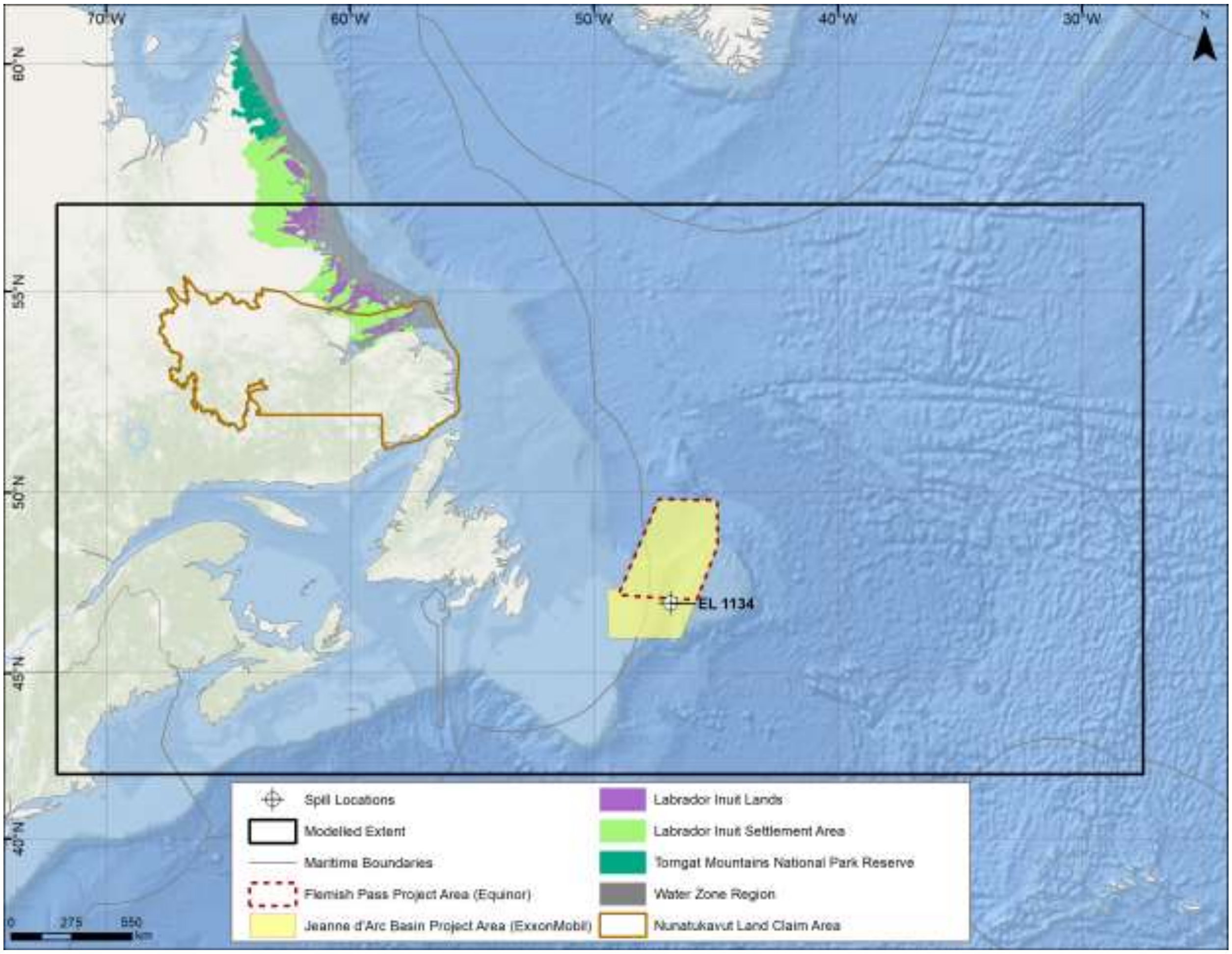


Figure 2-1. Map of the Project Area, including the hypothetical release location (EL 1134) and corresponding water depths. The black bounding box represents the modelling extent, while the smaller shaded boxes represent the EIS Project Areas.

2.2 Modelling Approach

This modelling study employed a combined stochastic and deterministic approach to determine the potential trajectory and fate of hypothetical hydrocarbon releases from one site east of Newfoundland (Table 2-1). Stochastic modelling provides a probabilistic view of the likelihood that a given region might be exposed to released hydrocarbons over specified thresholds given the range of possible environmental conditions that may occur within and across multiple years. A deterministic analysis provides a view of the time history of the specific movement and behavior of released product from a given (e.g., representative) individual release. Together, these methods provide a more complete view of both the likelihood and degree of potential exposure.

For this report, stochastic information is presented for predicted surface oil thickness, shoreline oil mass, and subsurface contamination for the full year (i.e., annual), and for different seasons with variable ice-cover conditions (i.e., summer/ice-free and winter/ice-covered). Individual representative deterministic trajectories that characterize single release scenarios are also presented. Stochastic analyses of hypothetical blowouts were modelled at one site using the physical-chemical properties of the specific oil type that may be released and seven years of variable environmental data, which are discussed in Section 3. At each location, a total of 171/179 individual oil release trajectories were modelled throughout the year including 80/88 winter and 91/91 summer for each 30/113-day stochastic simulation. The duration of each modelled simulation was 45 days for the 30-day blowout and 160 days for the 113-day blowout. In addition, surface batch spills of 100 liters (L) and 1,000 L of marine diesel were analyzed to evaluate potential discharges between surface vessels.

Table 2-1. Site and release information used for the stochastic and deterministic approaches.

<table>
<tr><th>Hypothetical Release Location</th><th>Depth of Release</th><th>Release Duration</th><th>Model Duration</th><th>Number of Model Runs</th><th>Released Product</th><th>Release Type</th><th>Release Volume</th></tr>
<tr><td rowspan="2">EL 1134 (46.98°N, 46.849°W)</td><td rowspan="2">1,175 m</td><td>30 days</td><td>45 days</td><td>179</td><td rowspan="2">Ben Nevis</td><td rowspan="2">Subsurface Blowout</td><td>1,134,000 bbl (37,800 bbl/day)</td></tr>
<tr><td>113 days</td><td>160 days</td><td>171</td><td>4,271,400 bbl (37,800 bbl/day)</td></tr>
<tr><td>EL 1134 (46.98°N, 46.849°W)</td><td>Surface</td><td>Instantaneous</td><td>30 days</td><td>2</td><td>Marine Diesel</td><td>Batch Spill</td><td>100 L & 1,000 L</td></tr>
</table>

2.2.1 Modelling Tools

Hypothetical release scenarios were simulated using the OILMAPDeep blowout model and the SIMAP, oil trajectory and fate model, both developed by RPS. OILMAPDeep was used to define the near-field dynamics of the subsurface blowout plume, which was then used to initialize the far-field modelling conducted in SIMAP. The dynamics of the near-field plume dynamics are modelled to predict the mass, location, and droplet size distribution of the subsurface plume of oil at the termination (i.e., trap) height of the buoyant oil and gas plume, when it becomes diluted enough with surrounding seawater to become neutrally buoyant, based upon the environmental conditions, the specific chemical and physical properties of the oil, and other release parameters. Typically, the near-field model is on the timescale of seconds and length scale of hundreds of meters, whereas the far-field model is on the scale of many hours/days and tens or even hundreds of kilometers.

OILMAPDeep Model

The OILMAPDeep model incorporates the basic dynamics of a subsurface oil and gas plume and the associated complexities of increased hydrostatic pressure at depths deeper than 200 m. It contains two sub-models, i.e., a plume model and a droplet size model. The plume model predicts the evolution of plume position, geometry, centerline velocity, and oil and gas concentrations until the plume either surfaces or reaches a terminal height (i.e., trap height), at which point the plume no longer rises by buoyant forces and the oil contained within the plume escapes to the surrounding water and rises based on the individual buoyancies of the droplets. The jet created by the blowout is modelled by considering the momentum of the oil discharge, the density difference between the expanding gas bubbles in the plume and the receiving water, the entrainment of water into the plume, the mixing by turbulence within the plume, hydrate formation, and transport by local ambient currents. The droplet size model predicts the size and volume (mass) distribution of the oil droplets in the release at the trap height or at the water surface, which influences trajectory and fates processes such as oil rise velocity and dissolution.

For oil discharged during a deep-water blowout, the oil droplet size distribution has a profound effect on how oil is transported and behaves after the initial release as a buoyant plume. The size of the individual droplets dictates buoyancy, which controls the length of time that oil will remain within the water column before surfacing. Large oil droplets surface faster than small ones, thus large droplets more quickly generate a floating oil slick, which may be transported by winds and surface currents. Small droplets remain in the water column longer than large droplets and are subjected to subsurface advection-diffusion processes and are therefore transported for a longer period of time. As oil is transported by subsurface currents away from the release location, natural dispersion of the oil droplets quickly reduces concentrations within the water column. However, the lower rise velocities associated with smaller oil droplets correspond to longer residence times of oil suspended in the water column, which can increase the dissolution of soluble components and potentially result in larger volumes of water being affected. Details of the OILMAPDeep model background theory, inputs, algorithms, and outputs can be found in Appendix A.

SIMAP Model

The SIMAP model originated from the oil fate sub-model within the Natural Resource Damage Assessment Models for Coastal and Marine Environments (NRDAM/CME). RPS developed the NRDAM/CME in the early 1990s for the U.S. Department of the Interior for use in "type A" Natural Resource Damage Assessment (NRDA) regulations under the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA). The most recent version of the type A models, the NRDAM/CME (Version 2.4, April 1996) was published as part of the CERCLA type A NRDA Final Rule (Federal Register, May 7, 1996, Vol. 61, No. 89, p. 20559-20614). The technical documentation for the NRDAM/CME is in French et al. (1996). While the NRDAM/CME was developed for simplified NRDAs of small releases in the U.S., SIMAP was further developed to evaluate fate and exposure of both real and hypothetical releases in marine, estuarine, and freshwater environments worldwide. Additions and modifications to SIMAP include increasing model resolution, allowing site-specific input data, incorporating spatially and temporally varying current data, evaluating subsurface releases and movements of subsurface oil, tracking multiple chemical components of the oil, enabling stochastic modelling, and facilitating analysis of results.

The 3D physical fates model estimates the distribution of whole oil and oil components on the water surface, on shorelines, in the water column, and in sediments as both mass and concentration. Because oil contains many chemicals with varying physical and chemical properties, and the environment is spatially and temporally variable, the oil rapidly separates into different environmental compartments through multiple fates processes. Oil fate processes included in SIMAP are oil spreading (gravitational and by shearing), evaporation, transport, randomized dispersion, emulsification, entrainment (natural and facilitated by dispersant), dissolution of the soluble fraction of oil into the water column, volatilization of dissolved hydrocarbons from the surface water, adherence of oil droplets to suspended sediments, adsorption of soluble and sparingly-soluble aromatics to suspended sediments, sedimentation, and degradation. Oil trajectory and weathering endpoints include surface oil, emulsified oil (mousse), tar balls, suspended oil droplets, oil adhered to particulate matter, dissolved hydrocarbon compounds in the water column and pore water, and oil on and in bottom sediments and shoreline surfaces. Details of the SIMAP model background theory, inputs, algorithms, and outputs can be found in Appendix A.

2.2.2 Stochastic Approach

A stochastic approach was employed to determine the footprint and probability of areas that are at increased risk of oil exposure based upon the variability of meteorological and hydrodynamic conditions that might prevail during and after a release. A stochastic scenario is a statistical analysis of results generated from many different individual trajectories of the same release scenario, with each trajectory starting at a randomized time from a relatively long-term window. For this project, individual trajectory start dates were selected randomly every 14 days throughout the window of environmental data coverage to ensure that the data was adequately sampled. This stochastic approach allows for the same type of release to be analyzed under varying environmental conditions (e.g., summer vs. winter or one year to the next). The results provide the probable behavior of the potential releases based upon this environmental variability.

In order to reproduce the natural variability of winds and currents, the model requires both spatially- and temporally-varying datasets. Historical observations and models of multiple-year wind and current records were used to perform the simulations within the coinciding time period. These datasets allow for reproduction of the natural variability of the wind and current speeds and directions. Optimally, the minimum time window for stochastic analysis is at least five years so that various weather patterns from year to year are represented. Using wind and current data from throughout this long time period, a sufficient number of model runs will adequately sample the variability in the time sequences of wind and current speeds and directions in the region of interest, and will result in a prediction of the probable oil pathways for a release at the prescribed location.

Stochastic analyses provide two types of information: 1) the areas associated with probability of oil exposure at some time during or after a release, and 2) the shortest time required for oil to reach any point within the areas predicted to be exposed above a specified threshold. The left panel of Figure 2-2 depicts four individual trajectories predicted by SIMAP for a generic example scenario. Because these trajectories were started on different dates and times, they experienced varying environmental conditions, and thus traveled in different directions. To compute the stochastic results, tens to hundreds of individual trajectories like the four depicted here were overlain and the number of times that each given location throughout the modelled domain was intersected by the different trajectories was used to calculate the probability of oil exposure for each specific location. This process is illustrated by the stacked runs in the right panel of Figure 2-2. The predicted footprint is the cumulative oil-exposed area for all of the ten to hundreds of individual releases combined. The color-coding represents a statistical analysis of all the individual trajectories to predict the probability of oil at each point in space, based upon the environmental variability. The footprint of any single release of oil, be it modelled or real, would be much smaller than the cumulative footprint of all the runs used in the stochastic analysis.

Similarly, the footprint of oil from any individual release at a single time step (snapshot in time) would be even smaller than the cumulative swept area depicted here.

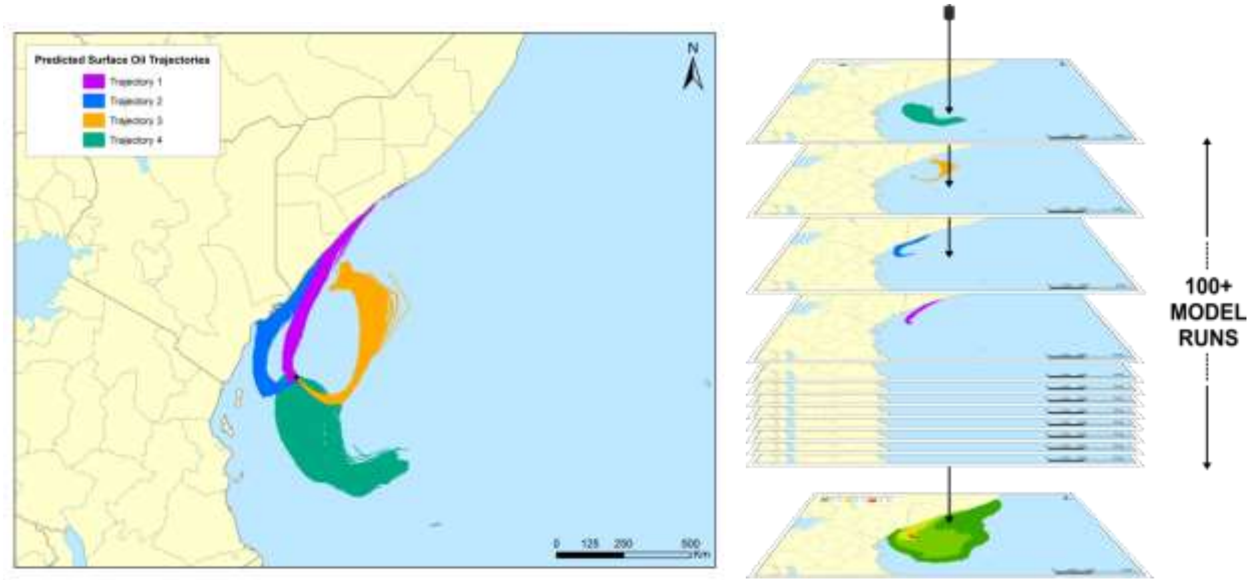


Figure 2-2. Examples of four individual release trajectories predicted by SIMAP for a generic release scenario simulated with different start dates and therefore environmental conditions. Tens to hundreds of individual trajectories are overlain (shown as the stacked runs on the right) and the frequency of contact with given locations is used to calculate the probability of threshold exceedance during a release.

The number of individual trajectories and the timeframe of a given stochastic analysis play roles in the spatial extent of the resulting stochastic footprints. More individual runs may incorporate greater environmental variability, which may result in larger footprints. As the number of trajectories modelled increases, the confidence and resolution of reported probabilities also increases. Annual footprints result in the largest footprint, encompassing all environmental variability throughout the years. Seasonal footprints may be smaller, encompassing only the environmental variability expected within the smaller time period (e.g., prevailing winds, seasonal patterns, etc.). It is important to note that a single trajectory encounters only a small portion of an overall stochastic probability footprint (e.g., an individual trajectory may be less than 10% of an annual stochastic footprint). Maps of probability and minimum time to oil exceeding identified thresholds are provided in Section 4.1.

2.2.3 Thresholds of Interest

In a stochastic analysis, multiple model runs (10's to 100's of releases) are overlaid upon one another to create a cumulative footprint of the potential trajectories. When combined with one another, the many individual deterministic footprints can be used to generate an area of probability that describes the potential areas that may be exposed to oil contamination from the entire suite of modelled conditions. To determine the probability or likelihood of potential exposure, specific thresholds for surface oil thickness, oil on shorelines and sediments, and in-water contamination were required (Table 2-2). Above these thresholds, previous studies have identified that there is the potential that negative effects may occur. Figures and further analyses in this study include the more conservative lower socioeconomic thresholds of concern calculated from stochastic results.

Floating surface oil is expressed as mass per unit area, averaged over a defined (grid cell) area. If the oil is evenly distributed in that area, it would be equivalent to a mean thickness, where 1 micron (µm) of thickness corresponds to a layer of oil that has a mass concentration of approximately 1 g/m^2. Surface oil thickness is typically associated with visual appearance by aerial observation for responders (NRC 1985; Bonn Agreement 2009, 2011; NOAA, 2016; Table 2-3). As an example, barely visible sheens may be observed above 0.04 µm and silver sheens correspond with surface oil thickness of approximately 0.3 µm. Crude and heavy fuel oils greater than 1 mm thick typically appear as black oil while light fuels and diesels that are greater than 1mm thick may appear brown or reddish. Because of the differences between oils and their degree of weathering, as well as the weather conditions and sea state at the time of observations, floating oil will not always have the same appearance. As oil weathers, it may be observed in the form of scattered floating tar balls and tar mats where currents converge. Typically, oil slicks in the environment would be observed as a range of visual appearances including silver sheen, rainbow sheen, and metallic areas simultaneously, as a combination of thicknesses may be present (Figure 2-3). Thus, a model result presented as average oil mass per unit area or “thickness” is actually a region with patches of oil of varying thickness, which when distributed evenly in the area of interest, would be on average a certain thickness.

Table 2-2. Thresholds used to define areas and volumes exposed above levels of concern.

Threshold Type	Cutoff Threshold	Rationale/Comments (Socio-economic, Response, Ecological)	Visual Appearance	References
Oil Floating on Water Surface	0.04 g/m^2	**Socio-economic:** A conservative threshold used in several risk assessments to determine effects on socioeconomic resources (e.g., fishing may be prohibited when sheens are visible on the sea surface). Socio-economic resources and uses that would be affected by floating oil include commercial, recreational and subsistence fishing; aquaculture; recreational boating, port concerns such as shipping, recreation, transportation, and military uses; energy production (e.g., power plant intakes, wind farms, offshore oil and gas); water supply intakes; and aesthetics.	Fresh oil at this minimum thickness corresponds to a slick being barely visible or scattered sheen (colorless or silvery/grey), scattered tarballs, or widely scattered patches of thicker oil.	French McCay et al., 2011; French McCay et al., 2012; French McCay, 2016; Lewis, 2007, Bonn Agreement
	10 g/m^2	**Ecological:** Mortality of birds on water has been observed at and above this threshold. Sublethal effects on marine mammals, sea turtles, and floating Sargassum communities are of concern.	Fresh oil at this thickness corresponds to a slick being a dark brown or metallic sheen.	French et al., 1996; French McCay, 2009 (based on review of Engelhardt, 1983, Clark, 1984, Geraci and St. Aubin 1988, and Jenssen 1994 on oil effects on aquatic birds and marine mammals); French McCay et al., 2011; French McCay et al., 2012; French McCay, 2016
Shoreline Oil	1.0 g/m^2	**Socio-economic/Response:** A conservative threshold used in several risk assessments. This is a threshold for potential effects on socio-economic resource uses, as this amount of oil may trigger the need for shoreline cleanup on amenity beaches, and affect shoreline recreation and tourism. Socio-economic resources and uses that would be affected by shoreline oil include recreational beach and shore use, wildlife viewing, nearshore recreational boating, tribal lands and subsistence uses, public parks and protected areas, tourism, coastal dependent businesses, and aesthetics.	May appear as a coat, patches or scattered tar balls, stain	French-McCay et al., 2011; French McCay et al., 2012; French McCay, 2016
	100 g/m^2	**Ecological:** This is a screening threshold for potential ecological effects on shoreline flora and fauna, based upon a synthesis of the literature showing that shoreline life has been affected by this degree of oiling. Sublethal effects on epifaunal intertidal invertebrates on hard substrates and on sediments have been observed where oiling exceeds this threshold. Assumed lethal effects threshold for birds on the shoreline.	May appear as black opaque oil.	French et al., 1996; French McCay, 2009; French McCay et al., 2011; French McCay et al., 2012**;** French McCay, 2016
In Water Concentration	1.0 ppb (µg/L) of dissolved PAHs; corresponds to ~100 ppb (µg/L) of whole oil (THC) in the water column (soluble PAHs are approximately 1% of the total mass of fresh oil)	Water column effects for both **ecological** and **socioeconomic** (e.g., seafood) resources may occur at concentrations exceeding 1 ppb dissolved PAH or 100 ppb whole oil; this threshold is typically used as a screening threshold for potential effects on sensitive organisms.	N/A	Trudel et al. 1989; French-McCay 2004; French McCay 2002; French McCay et al. 2012

*Thresholds used in supporting stochastic results figures. For comparison, a bacterium is 1-10 µm in size, a strand of spider web silk is 3-8 µm, and paper is 70-80 µm thick. Oil averaging 1 g/m^2 is roughly equivalent to 1 µm.

Table 2-3. Oil appearances based on NOAA Job Aid (2016) and BAOAC.

Code	Description	Layer-Thickness		Concentration	
		microns (µm)	Inches (in.)	m^3 per km^2	bbl/acre
S	Silver Sheen	0.04 - 0.30	1.6×10^{-6} - 1.2×10^{-5}	0.04 - 0.30	1×10^{-3} - 7.8×10^{-3}
R	Rainbow Sheen	0.30 - 5.0	1.2×10^{-5} - 2.0×10^{-4}	0.3 - 5.0	7.8×10^{-3} - 1.28×10^{-1}
M	Metallic Sheen	5.0 - 50	2.0×10^{-4} - 2.0×10^{-3}	5.0 - 50	1.28×10^{-1} - 1.28
T	Transitional Dark (or true) Color	50 - 200	2.0×10^{-3} - 8×10^{-3}	50 - 200	1.28 - 5.1
D	Dark (or true) Color	>200	$>8 \times 10^{-3}$	>200	>5.1
E	Emulsified	Thickness range is very similar to that of dark oil.			

Chart from Bonn Agreement Oil Appearance Code (BAOAC) May 2, 2006, modified by A. Allen

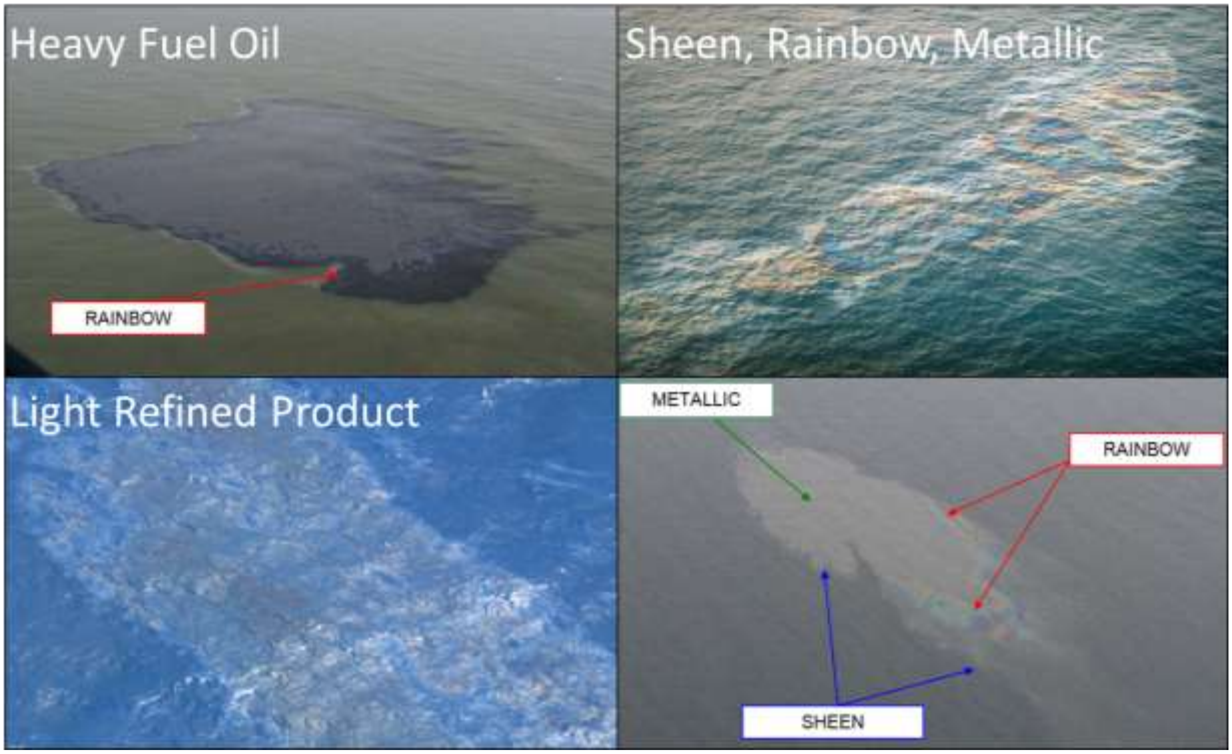


Figure 2-3. Aerial surveillance images of released oil in the environment as examples of different visual appearances based on surface oil thickness and product type (images from Bonn Agreement, 2011).

2.2.4 Deterministic Approach

Individual trajectories of interest were identified and selected from the stochastic ensemble of results for the deterministic analysis. The deterministic trajectory and fate simulations provided an estimate of the oil's fate and transport through the environment as well as its physical and chemical behavior for a specific set of environmental conditions. While the stochastic analysis provides insight into the probable behavior of oil spills given historic wind and current data for the Project Area, the deterministic analysis provides individual trajectory, oil weathering information, expected concentrations and thicknesses of oil contamination, mass balance, and other information related to a single release at a given location and time.

Each single run within a stochastic analysis represents a specific set of wind and current conditions for the modelled time period. When analyzed together, tens to hundreds of stochastic simulations provide a range of expected exposures. The exposures between cases may differ greatly, as the trajectory of each individual modelled release is unique. Therefore, the movement and behavior, as well as the resulting area of surface oil, mass of oil along the shoreline, and mass of oil within the water column, will be different for each modelled simulation. The 95th percentile "worst case" exposure for shoreline for each spill scenario were identified based upon the length of shoreline that oil that was predicted to contaminate. For the shorter duration release (30-day blowout modelled for 45 days) no shoreline oiling was predicted in the 95th percentile case and therefore the 98th percentile case was identified as the representative worst case. In addition, deterministic analyses of batch surface releases at EL 1134 were conducted for small (100 L) and large (1,000 L) release volumes to evaluate any potential discharges during bunkering operations (i.e., transfer from a vessel) between surface vessels. Scenarios were chosen to occur during the calmest wind-speed period during the summer/ice-free conditions as they would result in the largest amount of oil on the surface. Each simulation has its own trajectory, mass balance, surface oil thickness, in-water concentration of dissolved hydrocarbons, etc. reported individually.

The results of the deterministic simulations provide a time history of the fate and weathering of oil over the duration of the release (mass balance), expressed as the percentage of released oil on the water surface, on the shoreline, evaporated, entrained in the water column, and degraded. In addition, cumulative footprints of the individual trajectories over the course of the entire modelled duration will depict the cumulative path of floating surface oil, mass of shoreline oil, and the maximum concentration of dissolved hydrocarbons in the water column at any instant in time. These results figures are presented in Section 4.

2.3 Unmitigated Model Scenarios

One release location was used for modelling at the EL 1134 site (Figure 2-1). Subsurface blowouts near the seafloor were modelled at the location in a stochastic analysis that included 179 (30-day) and 171 (113-day) individual model runs. This analysis investigated the influence of environmental variability, throughout the year and over multiple years, on the trajectory and fate of released oil (Table 2-4). Results from stochastic analyses were broken into two seasons depending on the majority of modelled days falling within either ice free conditions (summer) from May – October or periods with ice-cover (winter) from November – April. Analysis of representative deterministic scenarios were conducted for individual trajectories that were identified as the representative worst case for length of shoreline contact from blowouts near the seafloor modelled in the stochastic analysis, as well as for instantaneous surface batch spills of marine diesel (Table 2-5).

Table 2-4. Hypothetical subsurface release location and stochastic scenario information.

Scenario Parameter	Release Location of Unmitigated Subsurface Blowout Scenarios	
	EL 1134	
Latitude	46° 58' 45.5 N	
Longitude	46° 50' 56.9 W	
Water Depth of Release	1,175 m	
Product	Ben Nevis	
Release Duration	30 d	113 d
Gas to Oil Ratio	520 scf/bbl	
Pipe Diameter	12.25 in.	
Oil Discharge Temperature	50°C	
Release Rate	37,800 bbl/d	
Total Released Volume	1,134,000 bbl	4,271,400 bbl
Model Duration	45 d	160 d
Number of Individual Simulations Within Each Stochastic Scenario	179 annual (88 winter & 91 summer)	171 annual (80 winter & 91 summer)

Table 2-5. Selected representative deterministic scenarios at EL 1134.

Scenario Parameter	Release Parameters for Representative Unmitigated Deterministic Scenarios			
			Batch Releases	
Representative Scenario	98th Percentile Length of Shoreline Contacted	95th Percentile Length of Shoreline Contacted	Small Volume	Large Volume
Release Site	EL 1134			
Release Type	Subsurface Blowout		Batch Spill	
Depth of Release	1,175 m		Surface	
Released Product	Ben Nevis		Marine Diesel	
Release Rate	37,800 bbl/day		n/a	
Release Duration / Model Duration	30 d/45 d	113 d/160 d	Instantaneous / 30 d	
Total Release Volume	1,134,000 bbl (45 d scenario) & 4,271,400 bbl (160 d scenario)		100 L	1,000 L
Modelled Start Date and Season	06/01/2012 Summer	04/09/2011 Summer	6/15/2009 summer (calmest site-specific period identified between 1/2006-12/2012)	6/15/2009 summer (calmest site-specific period identified between 1/2006-12/2012)

2.4 Model Uncertainty and Validation

The SIMAP model has been developed over several decades to include past and recent information from laboratory-based experiments and real-world releases to simulate the trajectory and fate of discharged oil. However, there are limits to the complexity of processes that can be modelled, as well as gaps in knowledge regarding the affected environment. Assumptions based on available scientific information and professional judgment were made in the development of the model, which represent a best assessment of the processes and potential exposures that could result from oil releases.

The major sources of uncertainty in the oil fate model is:

- Oil contains thousands of chemicals with differing physical and chemical properties that determine their fate in the environment. The model must, out of necessity, treat the oil as a mixture of a limited number of components, grouping chemicals by physical and chemical properties.
- The fates model contains a series of algorithms that are simplifications of complex physical-chemical processes. These processes are understood to varying degrees.
- The model treats each release as an isolated, singular event and does not account for any potential cumulative exposure from other sources of contamination.
- Several physical parameters including but not limited to hydrodynamics, water depth, total suspended solids concentration, and wind speed were not sampled extensively throughout the entire modelled domain. However, the data that did exist was sufficient for this type of modelling. When data was lacking, professional judgment and previous experience was used to refine the model inputs.

In the unlikely event of an actual release of oil, the trajectory and will be strongly determined by the specific environmental conditions, the precise locations, and a myriad of details related to the event and specific timeframe of the release. Modelled results are a function of the scenarios simulated and the accuracy of the input data used. The goal of this study was not to forecast every detail that could potentially occur, but to describe a range of possible consequences and exposures of oil releases under various representative scenarios.

3 Model Input Data

3.1 Oil Characterization

Two hydrocarbon products at one release site (EL 1134) was modelled for this study:

1. Ben Nevis crude oil, and
2. Marine diesel in the surface vessel transfer batch-spill deterministic scenarios.

The physical and chemical data used to characterize these oils was provided by ExxonMobil with additional assays and measurements by S.L. Ross Environmental Research Ltd. (2016) and Intertek (2016).

Ben Nevis may be characterized as between a light and medium crude oil (Table 3-1 and Table 3-2). Ben Nevis is an intermediate density oil (on the lighter end), with a low viscosity and low soluble and volatile hydrocarbon content. The marine diesel modelled is a standard diesel (light oil) that has a low viscosity and high content of soluble hydrocarbons. The low viscosity and high soluble content of these oil products provide conservative approximations of anticipated concentrations in the water following a release, as a relatively large proportion of constituents have the potential to dissolve into the water column, when compared to oils with lower soluble content. These oils would likely behave similarly in the event of a release, with Marine diesel being least persistent and Ben Nevis being the most persistent.

The “pseudo-component” approach is used to simplify the tracking of thousands of chemicals comprising oil for modelling (Payne et al., 1984; 1987; French et al., 1996a; Jones, 1997; Lehr et al., 2000). Chemicals in the oil mixture are grouped by physical-chemical properties, and the resulting component category behaves as if it were a single chemical with characteristics typical of the chemical group. In this component breakdown, aromatic (AR) groups are treated as both soluble (i.e., dissolve into the water column) and volatile (i.e., evaporate to the atmosphere), while the aliphatic (AL) groups are only volatile. The total hydrocarbon concentration (THC) within the boiling range of volatile components is the sum of all AR and AL components. The remainder of the oil is considered to be residual oil, which does not dissolve or volatilize but will degrade over time.

Table 3-1. Physical properties for the two oil products used in modelling.

Physical Property	Ben Nevis Crude Oil	Marine Diesel
Density (g/cm^3)	0.87616 @16°C	0.83100 @25°C 0.83089 @16°C
Viscosity (cP)	3.9 @79.7°C 39.655 @5°C	2.76 @25°C 2.76 @15°C
API Gravity	30	38.8
Pour Point (°C)	-10	-50
Interfacial Tension (dyne/cm)	21.6	27.5
Emulsion Maximum Water Content (%)	75	0

Table 3-2. Fraction of the whole oil comprised of different distillation cuts for the two oil products. Note that the total hydrocarbon concentration (THC) is the sum of the aromatic (AR) and aliphatic (AL) groups. Numbers of carbons in the included compounds are listed.

Distillation Cut[1]	Boiling Point (°C)	Description	Ben Nevis Crude Oil	Marine Diesel
AR1	<180	highly volatile and soluble monoaromatic hydrocarbons (BTEX[2] and MAHs C6-C9)	0.017200	0.019333
AR2	180 - 264	semi-volatile and soluble 2-ring aromatics (MAHs and PAHs C10-C12)	0.015020	0.011410
AR3	265 - 380	low volatility and solubility 3-ring aromatics (PAHs C13-C18)	0.023231	0.015605
AL1	<180	highly volatile aliphatics (C4-C8)	0.100521	0.144667
AL2	180 - 280	semi-volatile aliphatics (C9-C16)	0.105093	0.478690
AL3	280 - 380	low volatility aliphatics (C17-C23)	0.162535	0.303295
THC1	<180	total hydrocarbon fraction 1 (sum of AR1 and AL1)	0.117721	0.164000
THC2	180 - 280	total hydrocarbon fraction 2 (sum of AR2 and AL2)	0.120113	0.490100
THC3	280 - 380	total hydrocarbon fraction 3 (sum of AR3 and AL3)	0.185766	0.318900
Residuals	>380	aromatics ≥4 rings and aliphatics >C20 that are neither volatile nor soluble	0.57640	0.02700

3.2 Geographic and Habitat Data

For geographical reference, SIMAP uses rectilinear grids to designate the location of the shoreline, the water depth (bathymetry), and the shore or habitat type. The grids were generated from a digital shoreline using ESRI geoprocessing and Spatial Analyst Extension tools and the cells were coded for depth and habitat type. Geographical data were obtained from multiple international sources to provide the geographic and environmental data required for modelling (Table 3-3). Habitat data were used to define the bottom type and vegetation found in subtidal areas, areas of extensive mud flats and wetlands, and the shoreline type (e.g., sandy beach, rocky shoreline, etc.).

[1] Note that the terms “aromatic” and “aliphatic” are used in a modelling context. “Aromatic” refers to all soluble and volatile hydrocarbons and may include actual aliphatic compounds in the chemical sense that are soluble. In the modelling context, “aliphatic” refers to insoluble and volatile hydrocarbons.
[2] BTEX (benzene, toluene, ethylbenzene, xylene), MAHs (monocylic aromatic hydrocarbons), and PAHs (polycyclic aromatic hydrocarbons) are the more soluble, bioavailable, and potentially toxic components in oil.

Table 3-3. Sources for habitat, shoreline, and bathymetry data.

Data Type	Data Source	Geographic Location	Reference
Habitat/Shoreline	Environment and Climate Change Canada	Canada	Therrien, A. 2017
	National Oceanic and Atmospheric Administration Environmental Sensitivity Index	United States (except Maine)	NOAA 2016
	Maine Environmental Vulnerability Index	United States - Maine	MDEP 2016
Bathymetry	General Bathymetric Chart of the Oceans Digital Atlas	Global	GEBCO 2003

The model used these grids to identify the location of the shoreline and amount of oil that may adhere once contact of the oil with the shoreline was made (Figure 3-1). Retention of oil on a shoreline depends on the shoreline type, physical and chemical properties (e.g., viscosity) of the oil, tidal amplitude in estuarine areas, and wave energy. The resolution of the habitat grid was approximately 1.8 km North-South by 2.5 km East-West (0.02225° on each side). Bathymetry data define the water depths within the modelled extent. The General Bathymetric Chart of the Oceans (GEBCO) one arc-minute interval grid was used, but was resampled into a grid with the same resolution as the habitat grid (Figure 3-1).

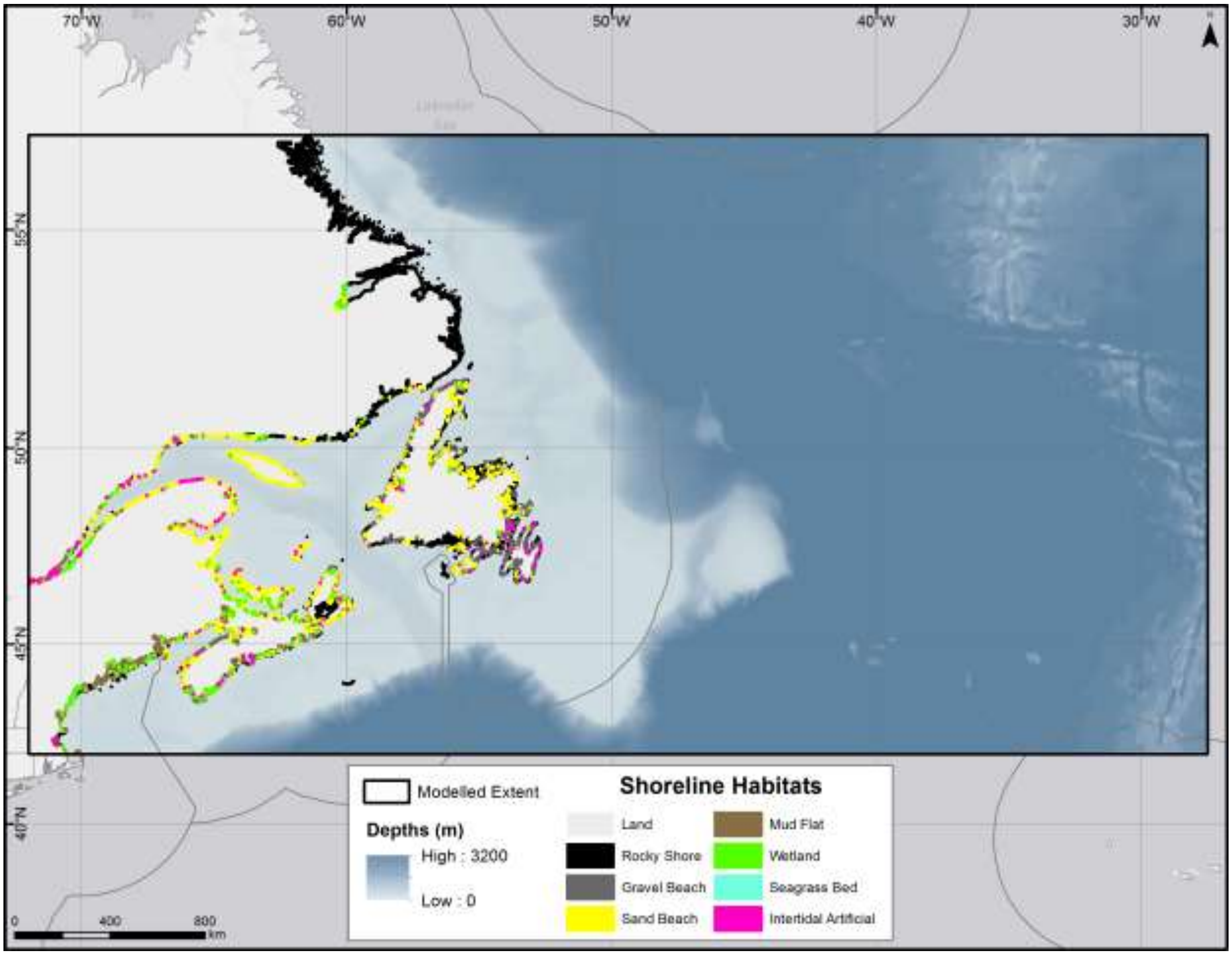


Figure 3-1. Shoreline habitat data and depth throughout the modelled domain. The black box represents the modelled extent.

3.3 Ice Cover

Sea ice is formed in the autumn in the Arctic and sub-Arctic regions of the world. The growth rate of sea ice depends on surface temperature and the heat flux in the underlying water. The formation and development of sea ice follows a progression of stages. The exact timing of these stages at any location is not the same from year to year because of subtle differences in climatic conditions. In the Northern Hemisphere during September and October, the air temperature lowers sufficiently to form a thin sheet of ice on the sea surface. The freezing temperature for average ocean salt water with a salinity of 35 ppt is about -2°C (NOAA 2014).

The movement and behavior of released oil is greatly affected by the presence of ice (Figure 3-2). Oil trapped in or under sea ice will weather more slowly than oil released in open water. Algorithms in SIMAP for modelling the movement and behavior of oil in the presence of sea ice are based on the percent of ice coverage. From 0 to ~30% coverage, the ice has no effect on the advection or weathering of surface floating oil. From approximately 30 to 80% ice coverage, oil advection is forced to the right of ice motion in the northern hemisphere, surface oil thickness generally increases due to ice-restricted spreading, and evaporation and entrainment are both reduced by damping/shielding the water surface from wind and waves. Above 80% ice coverage, surface oil moves with the ice and evaporation and entrainment cease.

The ice thickness and can vary greatly based upon prevailing weather conditions. If oil is released under ice, water column exposures can be greater, due to the "capping" effect of the ice. Ice cover limits or prevents evaporative losses and could result in substantially greater dissolution of hydrocarbons into the water column. Appendix A contains a brief summary of the algorithms implemented in the SIMAP model for oil releases in sea ice conditions.

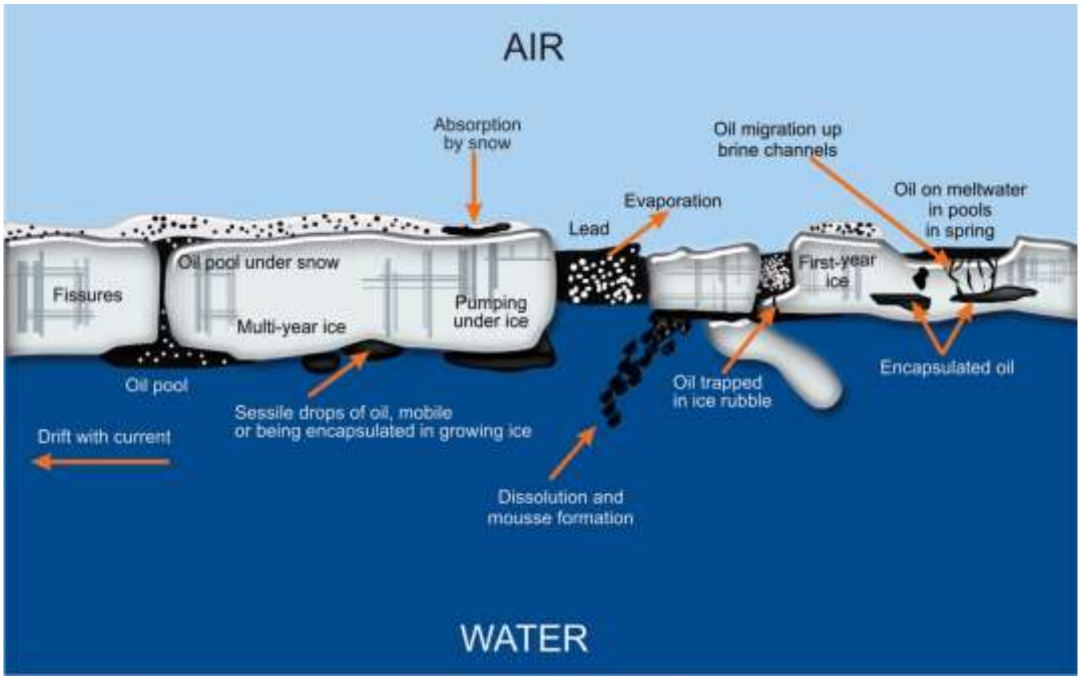


Figure 3-2. Oil and ice interactions at the water surface.

Ice data used as modelling inputs were obtained from the Canadian Ice Service (CIS; ECCC 2017) in weekly files spanning January 2006 to December 2012. These data were in the form of polygon data, with information on total ice concentration and stage of development. For each ice polygon, concentration codes were converted to concentration percentages. Average ice thickness was calculated based on the proportional concentration of the various stages of ice present for each week of the season over seven years. The CIS data provides a range of thicknesses for each ice category and stage of development. In most cases, the mid-point of those ranges was used in the calculation of average ice thickness. If the stage was not identified, but there were concentrations provided, then sea ice stage was assumed to be first year medium ice (Table 3-4). The ice data was gridded at a resolution matching the habitat grid (0.0225º). A representative map depicting percentage of ice cover and thickness of ice for the first week of February 2010 is presented (Figure 3-3).

Table 3-4. Sea ice thickness used in the modelling characterized by CIS stage of development.

CIS Ice Category or Sea Ice Stage	Concentration	CIS Thickness Range (cm)	Model Applied Thickness (cm)
Ice Free	0%	n/a	n/a
Open Water	30%	n/a	50
Landfast Ice	100%	n/a	assumed full
First year thick ice	Total concentration converted from tenths to percent ice cover	>120	120
First year medium ice*		70 – 120	95
First year thin ice		30 – 70	50
Young ice		10 – 30	20
Grey white ice		15 – 30	22.5
Grey ice		10 – 15	12.5
New ice		<10	5
Icebergs		unknown	100

*Default sea ice stage assumed when none was identified in the data.

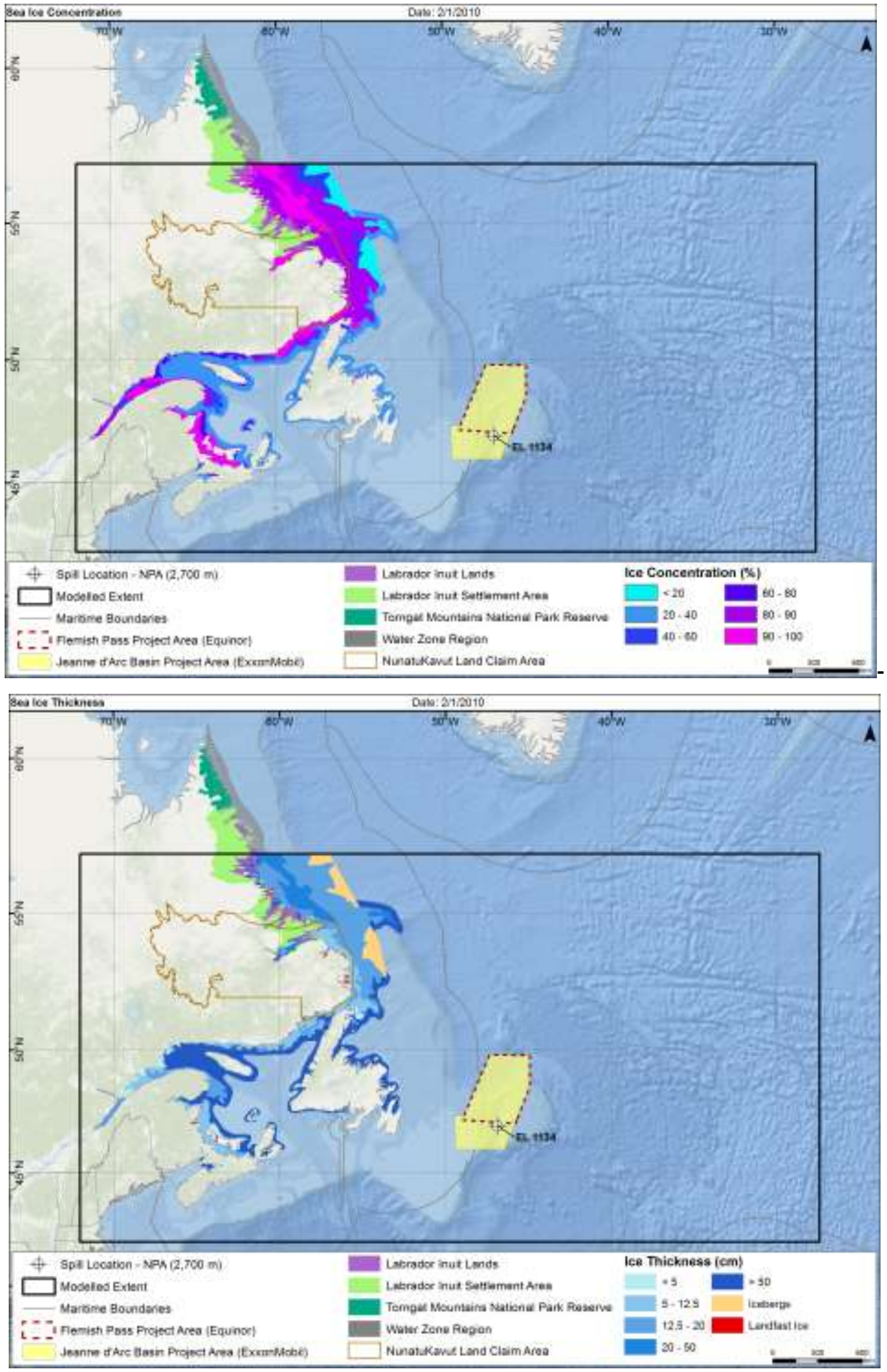


Figure 3-3. Percentage ice cover (top) and corresponding thickness (bottom) for the first week of February 2010, provided as a representative of the weekly files that were used in the modelling.

3.4 Wind Data

A multiyear dataset of wind speed and direction was used to capture the variability that occurs from on short timescales over multiple years. Oil release trajectories simulated using long-term wind datasets are representative of possible wind conditions at the site, assuming the temporal variability is on the timescale of changes in speed and direction. Because winds can change on time scales of minutes to hours, it is best to acquire data at the highest temporal resolution possible (typically every six hours for large global models, or at the very least daily averages). Oil released over long periods of time (e.g., the 113-day blowout modelled here for 160 days) has the potential to travel long distances by wind transport. To effectively model this, the wind speed and direction data must encompass a large geographic area in order to capture the spatial extent and any spatial variability in potential transport that may occur. Winds may physically transport oil on the water surface, thus wind speed and direction at the water surface may be the driving force between a simulation with limited versus extensive transport. The SIMAP model use time-varying wind speeds and directions for the period over which the release was simulated.

Wind data for this study were obtained from the National Centers for Environmental Prediction Climate Forecast System Reanalysis (CFSR) product for 2006 through 2012. The CFSR was designed and executed as a global, high-resolution, coupled atmosphere-ocean-land surface-sea ice system to provide the best estimate of the state of these coupled domains (Saha et al. 2010). The CFSR includes coupling of atmosphere and ocean, as well as assimilation of satellite radiances. The CFSR global atmospheric resolution is ~38 km, with 64 vertical levels extending from the surface to 0.26 hPa. CFSR winds were also used as one of the main driving forces in the hydrodynamic dataset used for modelling (see Section 3.5). The CFSR time series acquired for this study was available at 0.5-degree horizontal resolution at 6-hourly intervals.

Averaged annual wind data at the EL 1134 site was most frequently from the west-southwest direction (Figure 3-4). Monthly average wind speeds varied between 7 and 12 m/s throughout the year, with highest speeds occurring during winter months (November – March) and lowest speeds in August (Figure 3-5). These winds would be expected to transport oil generally away from nearby shorelines further into the open ocean.

Winds over the Grand Banks and Flemish Pass are predominantly from the southwest and west throughout the year. Winter season winds are most frequently from the west and northwest with higher velocity than summer season winds, which typically come from the southwest (Figure 3-4 and Figure 3-5). Spring and fall months are more dynamic transitional periods between the more consistent summer and winter wind regimes. Low pressure systems, tropical, and extra-tropical storms pass through the Grand Banks on a regular basis generating substantial wind speeds for short periods of time.

Significant wave heights are typically highest from November – February, in regions with no ice (C-NLOPB, 2014).

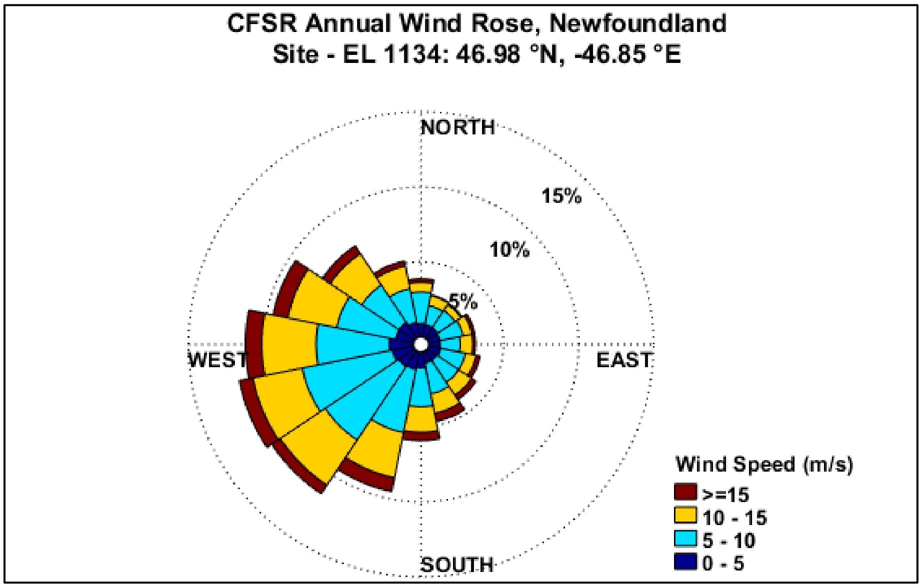


Figure 3-4. Annual CFSR wind rose near the EL 1134 release site. Wind speeds are presented in m/s, using meteorological convention (i.e., direction wind is coming from).

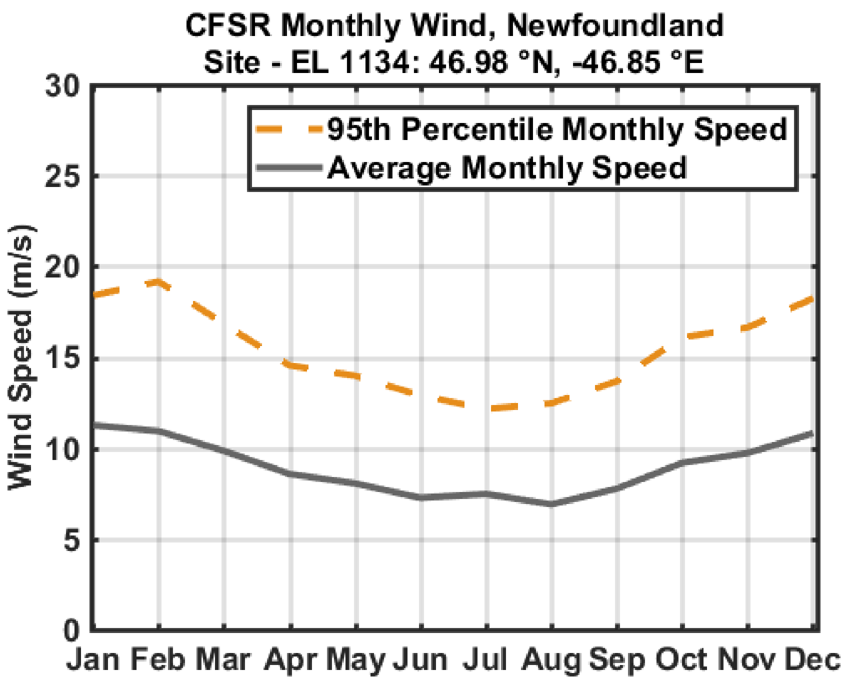


Figure 3-5. Average and 95th percentile monthly wind speeds near the EL 1134 site.

3.5 Currents

The Labrador Current dominates the large-scale ocean circulation in the Newfoundland region originating in the Arctic Ocean and flowing south along the coasts of Labrador and Newfoundland (Figure 3-6). This southerly current intensifies as waters funnel through the offshore branch, which follows the Flemish Pass between the Grand Banks and Flemish Cap. To a lesser extent, a portion of the Labrador Current flows through an inshore branch, which follows the Avalon Channel between Newfoundland and the Grand Banks. Over parts of the Grand Banks, currents can be generally weak and flow southward (Petrie and Isenor, 1985). Maximum current speeds in the upper 200 m of the water column range from 0.3 – 2.0 m/s (C-NLOPB, 2014). The strong southerly current dominates the yearly average flow and winds may only account for approximately 10% of current variability in this region (Petrie and Isenor, 1985). South of the Flemish Pass, the Labrador Current mixes with the North Atlantic current. The boundary where these two currents converge produces extremely energetic and variable frontal systems and eddies on smaller scales, on the order of kilometers (Volkov, 2005). Due to these eddies, local transport may advect parcels of water in nearly any direction. Satellite and drifter studies of current dynamics demonstrate this complexity; however, drifting parcels generally move to the south and east (Han and Tang, 1999; Petrie, 1983; Richardson, 1983) where they intersect with the North Atlantic current.

Currents for the North Atlantic region were acquired from the HYCOM (HYbrid Coordinate Ocean Model) circulation model. HYCOM is a primitive-equation ocean general circulation model that evolved from the Miami Isopycnic-Coordinate Ocean Model (MICOM) (Halliwell, 2002; Halliwell et al., 1998, 2000; Bleck, 2002). MICOM has become one of the premier ocean circulation models, having been subjected to validation studies (Chassignet et al., 1996; Roberts et al., 1996; Marsh et al., 1996) and used in numerous ocean climate studies (New and Bleck, 1995; New et al., 1995; Hu, 1996; Halliwell, 1997, 1998; Bleck, 1998). The HYCOM global ocean system is a 3D dynamic model that is run each day, providing a 5-day hindcast and 5-day forecast of oceanic currents that works effectively in both deep and shallow waters. Hindcast data are used to validate the accuracy of each run to determine if modelled forcings produce results that match observational data. HYCOM uses Mercator projections between 78°S and 47°N and a bipolar patch for regions north of 47°N to avoid computational problems associated with the convergence of the meridians at the pole. The 1/12° equatorial resolution provides gridded ocean data with an average spacing of ~7 km between each point. Several studies have demonstrated that at least 1/10° horizontal resolution is required to resolve boundary currents and mesoscale variability in a realistic manner (Hurlburt and Hogan, 2000; Smith and Maltrud, 2000; Chassignet and Garaffo, 2001).

Data is assimilated through the Navy Coupled Ocean Data Assimilation (NCODA) system (Cummings, 2005). The NCODA system employs a Multi-Variate Optimal Interpolation scheme, which uses model forecasts as a first guess and then refines estimates from available satellite and in-situ temperature and salinity data that are applied through the water column using a downward projection of surface information (Cooper and Haines 1996). Bathymetry is derived from the U.S. Naval Research Laboratory BDB2 dataset. Surface forcing is derived from the Navy Operational Global Atmospheric Prediction System, which includes wind stress, wind speed, heat flux (using bulk formula), and precipitation.

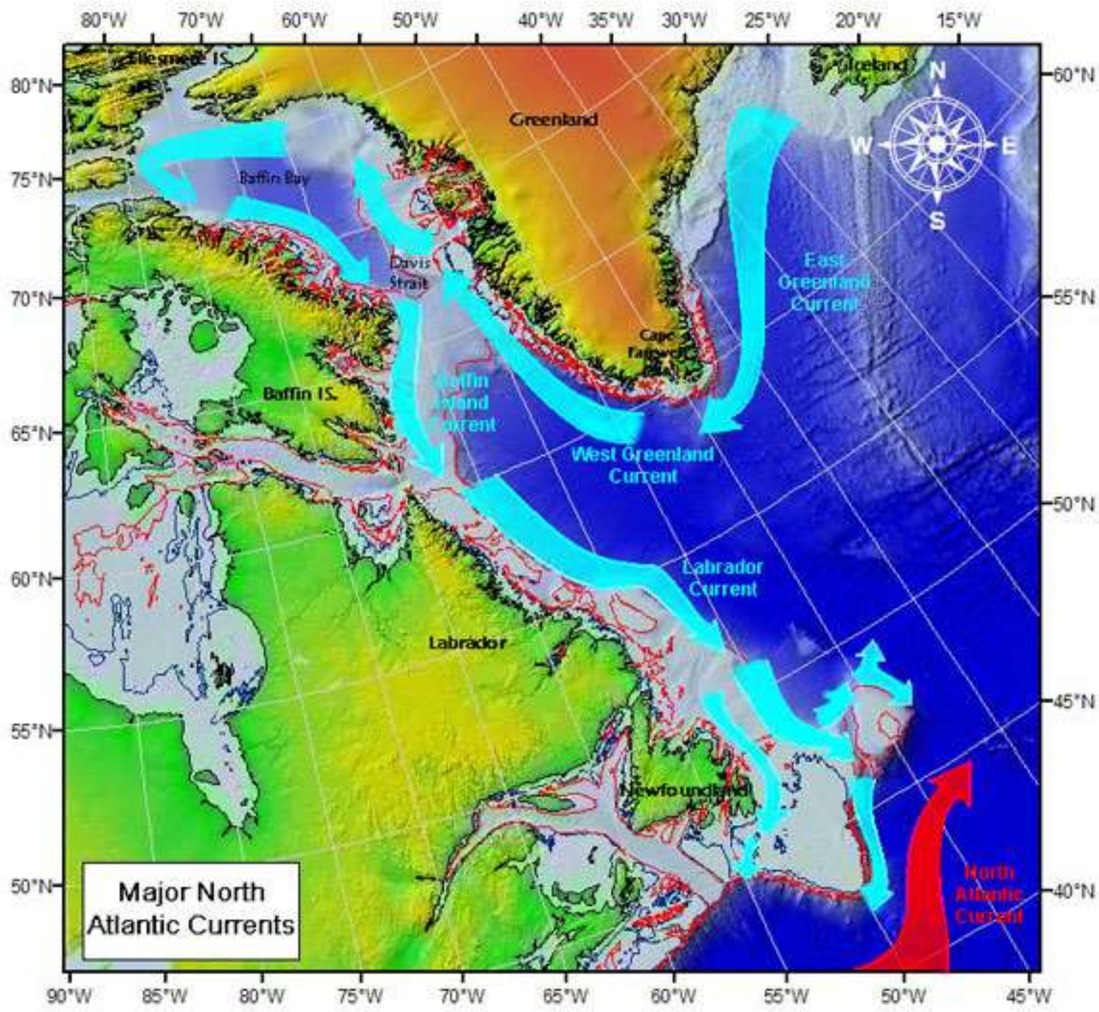


Figure 3-6. Large scale ocean currents in the Newfoundland region (USCG 2009).

For this study, daily current data were obtained for the period of January 1, 2006 through December 31, 2012 for the North Atlantic region (HYCOM, 2016). Since the data spanned seven years, the variability in winds and currents would sample daily, weekly, seasonal, and inter-annual variability, which included calm periods, seasonal storms, and the full range of environmental forcing over the entire time period. While this subset of data is not the most recent five years of data, currents and winds in the study area are very similar to those from 5-10 years ago and the data used in this study would be representative of environmental conditions present today. Similarly, while there may be questions regarding general circulation during specific time periods, it is important to note that trajectories are influenced by day to day currents, as opposed to averages. Surface forcing is derived from 1-hourly CFSR wind data with a horizontal resolution of 0.3125° and induced wind stress, wind speed, heat flux, and precipitation with bathymetry derived from the GEBCO dataset (HYCOM 2016). Average surface current speeds offshore Newfoundland from January 2006 – December 2012 can be used to depict larger scale features such as the Labrador current, North Atlantic Current, as well as bathymetric steering of currents around the Grand Banks and Flemish Cap (Figure 3-7). Current speed and direction are also depicted at higher resolution to denote the location of EL 1134 with respect to large scale features (Figure 3-8). While these figures depict an average current speed and direction for visual purposes, oil transport was defined by the daily currents throughout each modelled simulation.

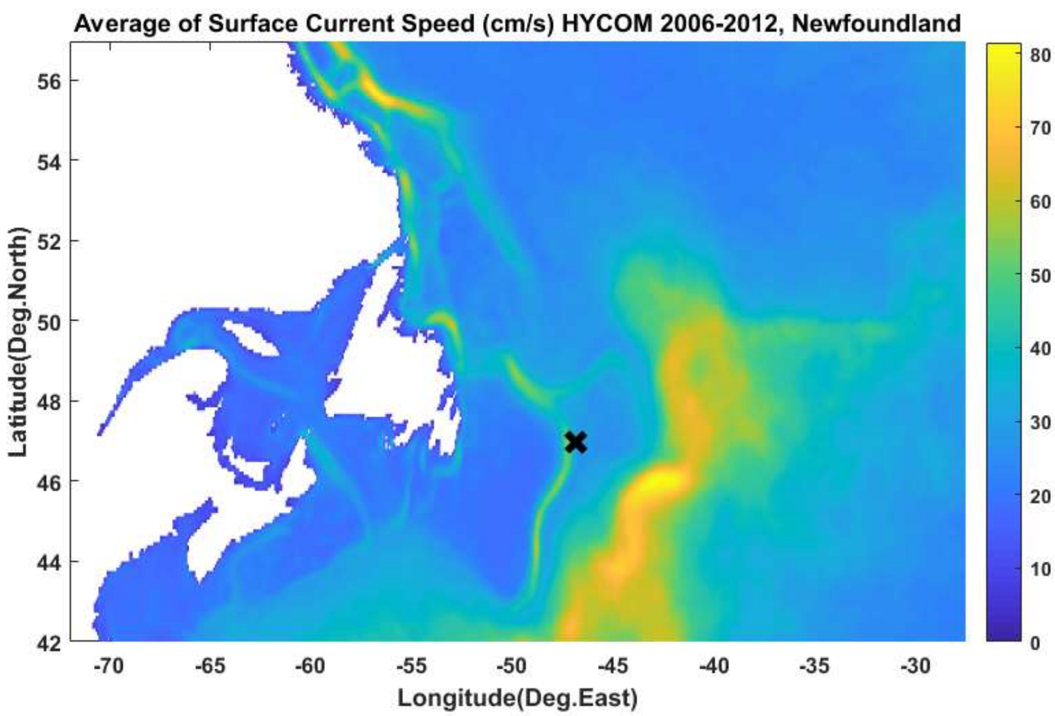


Figure 3-7. Average HYCOM surface current speeds (cm/s) off the coast of Newfoundland from 2006 – 2012. Black marker indicates the spill location. This figure is for illustration purposes to highlight large scale features. Daily currents were used in the oil spill modeling.

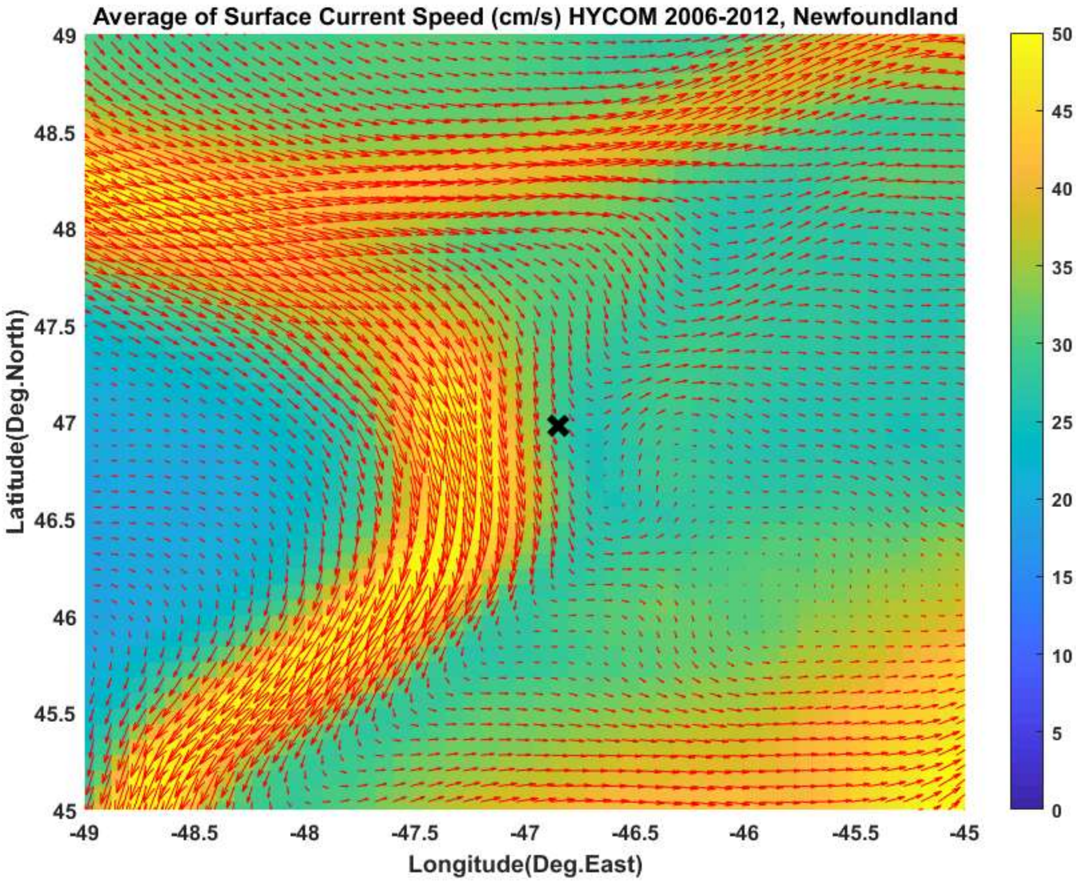


Figure 3-8. Averaged surface current speed (cm/s) in color, and direction presented as red vectors in the vicinity of the hypothetical release location offshore Newfoundland from HYCOM (2006 – 2012). The black marker indicates the spill location.

3.6 Water Temperature & Salinity

Temperature and salinity values throughout the water column influence a number of oil transport and fate calculations. Temperature and salinity data have been obtained from the World Ocean Atlas (WOA) 2013 high-resolution dataset, Version 2, which is compiled and maintained by the U.S. National Oceanographic Data Center (Levitus et al., 2014). The WOA originated from the Climatological Atlas of the World Ocean (Levitus, 1982) and was updated with new data records in 1994, 1998, 2001 (Conkright et al., 2001), and 2013. These data records consist of observations obtained from various global data management projects. The dataset includes up to 57 depth bins from the sea surface to the seabed and include averaged yearly, seasonally, and monthly data over a global grid with a 1/4° horizontal resolution.

3.7 Blowout Model Scenarios and Results

The nearfield model OILMAPDeep was used to predict the initial droplet size distribution associated with subsurface blowouts of the hydrocarbon product that were modelled at the hypothetical release location. Oil and gas were introduced to the water column near the seafloor to simulate an uncontrolled release from the wellhead frequently referred to as a blowout. The modelled release depth was 1,175 m at the sediment/water interface. The droplet size model predicts the distribution of oil volume (mass) within different size ranges (measured by diameter) in response to the turbulence of the release, the gas content, the water depth, and the properties of the oil. The droplet model predicted the initial droplet size distributions for each scenario as well as the depth or "trap height" in the water column where the droplets would be released to the water column and rise according to their individual buoyancies. These values were then used to generate input files defining the size, mass, and depth of oil droplets entering the water column for use within the SIMAP far-field model.

Initial droplet sizes are primarily a function of the energy of the release, the chemical and physical parameters of the released oil, the gas to oil ratio (GOR), dispersant application, and several other factors. As an example, if the energy of a release or the amount of dispersant added were to increase, or if the viscosity of the released oil were lower, the resulting droplet sizes would be smaller. In the scenarios simulated for this study, the oil was assumed not to be treated with dispersant. The energy of the release is a function of the volumetric flow rate and discharge orifice size, with higher energy releases occurring as greater volumes pass through smaller openings more quickly.

Two subsurface blowout release events were evaluated as part of this study:

(1) Site EL 1134 – 30-day release of Ben Nevis, through a 12 ¼ inch orifice at a depth of 1,175 m and rate of 37,800 bbl/d; and
(2) Site EL 1134 – 113-day release of Ben Nevis, through a 12 ¼ inch orifice at a depth of 1,175 m and rate of 37,800 bbl/d.

The predicted droplet size distribution was represented by seven discrete size bins for each modelled release scenario at site EL 1134 (Table 3- 1). The non-uniform spacing between the droplet size bins is the result of the non-linear functionality of droplet size distribution. Each of the seven bins were determined such that an equal proportion of the released oil by mass (14.29%) was within each bin.

Oil droplets rise through the water column at rates based on drag, calculated using their diameter (treated as a sphere) and the buoyancy, the density difference between the oil and the water, which varies with changing temperature and salinity by depth (Figure 3- 1). Rise times for oil to reach the surface varied between minutes to many hours, depending on droplet size and depth of release. Rise time estimates are approximated, based on the initial droplet size, initial droplet density, and bottom water density; neglecting dispersion, dissolution, and degradation (which were tracked within the oil spill model and modified the rise rates). The longest rise times were associated with the smallest droplets, with some rise times exceeding a day.

Table 3- 1. Summary of droplet size distribution results for both of two modelled subsurface blowout release events.

Median Droplet Size in Each of Seven Equal-Mass Bins, by Diameter (µm)
EL 1134 - Ben Nevis Crude Oil
1,257
2,873
3,575
4,306
5,192
6,503
11,431

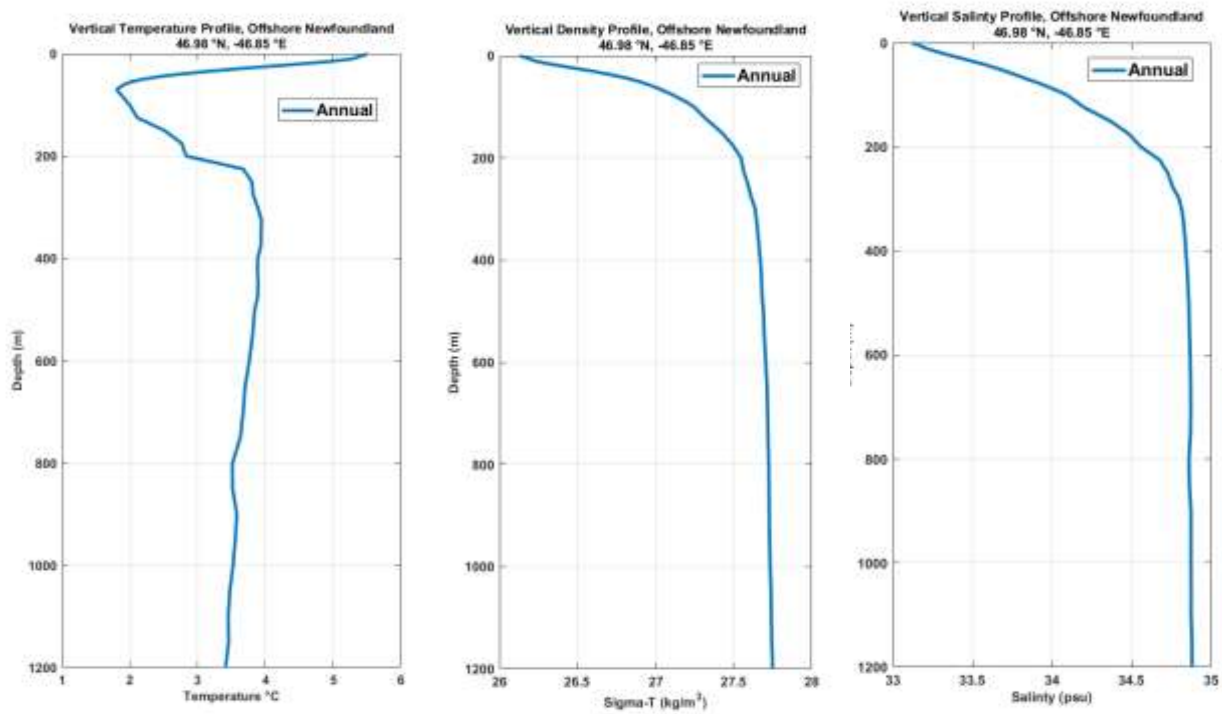


Figure 3- 1. Water column profiles of temperature (left), salinity (right) and corresponding density (middle), represented as sigma-t. The density profile was generated based on the temperature and salinity profile using equations of state as published by UNESCO, 1981 (EOS – 80).

4 Model Results

4.1 Stochastic Analysis Results

Stochastic analyses characterize results from many tens to hundreds of individual modelled releases. This study included modelling 179 and 171 individual releases over the course of seven years of environmental data at the EL 1134 site to capture the natural variability in the environment. The 30- and 113-day runs were modelled for a total of 45 and 160 days, respectively.

Because ice cover can affect the trajectory and fate of oil, stochastic model runs were separated into two groups of individual runs based upon the specific time periods modelled that included ice cover or ice-free conditions. Statistics for all releases within a stochastic scenario are referred to as “annual”, as they include all releases in any month over the course of the entire seven years. Ice cover in the region is present from November through April, while May through October is mostly ice-free. Modelled releases that have the majority of their simulated days (≥ 81 of the 160-day modelled duration or ≥23 of the 45-day modelled duration) experiencing mostly ice-free periods are referred to as “summer” analyses (91 modelled releases), while those that have a majority of days experiencing periods with ice cover are referred to as “winter” analyses (80 and 88 modelled releases). Ice cover very rarely extended far enough offshore to reach within kilometers of the release location, and when it did, <10% ice cover was predicted. However, ice was present along most of the coastline in winter months, with February typically having the largest expanses of 90-100% ice cover (Figure 3-3).

The figures presented in this stochastic modelling results section illustrate the predicted spatial extent of surface floating oil, water column concentrations of dissolved hydrocarbons, and shoreline contact including both the probabilities and associated minimum times to threshold exceedance (Table 4-1) for the hypothetical release scenarios. The probability maps define the area of potential exposure and the associated probability with which sea surface oil, shoreline oil, or water column contamination are expected to exceed the specified thresholds at any point of time throughout the 45- or 160-day modelled duration. The colored contours in the stochastic maps signify the boundary for given percentiles of areas that may experience oil at or above the specified threshold for each release scenario. Darker color contours denote areas that are more likely to exceed the specified threshold while lighter color contours are less likely. Note that the lightest minty green line represents areas where oil may exceed the specified threshold at a single point in time within only 1% of the modelled release simulations. In other words, the likelihood that any oil exceeding the identified threshold would leave the area bounded by the minty green line within the modelled time period is <1%. The area between this contour and the next (10%) has between a 1-10% probability of exceeding the threshold, given a release of the modelled scenario has occurred.

The probabilities of oil exposure were calculated from a statistical analysis of the ensemble of individual trajectories modelled for each release scenario. The fundamental assumption for this modelling was that a release did occur. Therefore, probability contours should be interpreted as “In the unlikely event of a release, the probability that any one specific area may experience contamination above the specified threshold is X%”. Stochastic figures do not imply that the entire contoured area would be covered with oil in the event of a single release, nor do they provide any information on the quantity of oil in a given area. Additionally, these figures do not provide the likelihood of a blowout occurring in any given year. Rather, these stochastic figures denote the probability of oil exceeding identified thresholds at any modelled time step (over 45 or 160 days), for each point within the modelled domain, assuming a release were to occur at some point in time.

In addition, stochastic maps depicting water column contamination by dissolved hydrocarbon concentrations do not specify the depth at which the threshold exceedance occurs. The maps depict the vertical maximum at any time during or after the release. Thus, images do not imply that the entire water column (i.e., from surface to bottom) will experience a concentration above the threshold, but rather a concentration may be exceeded at a specific depth (typically within the surface few meters) in the mapped location.

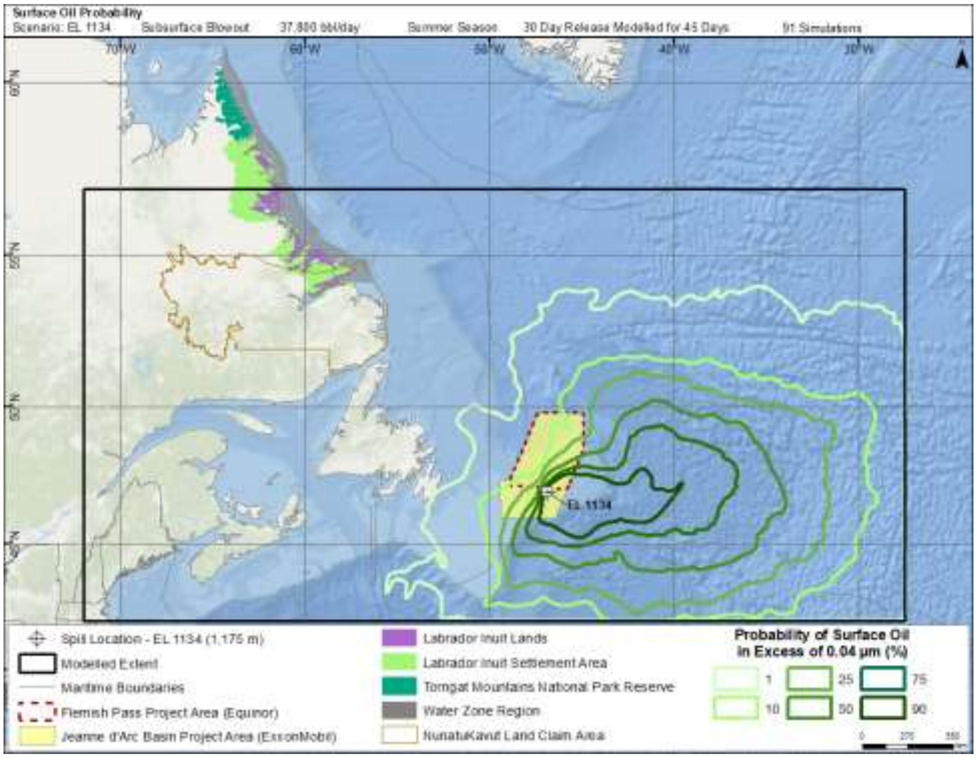
The minimum time footprints correspond with the associated probability of oil exposure map. Each figure illustrates the shortest amount of time required (from the initial release) for each point within the footprint to exceed the defined threshold. The time reported is the minimum value for each point considering the entire ensemble of trajectories. Together, probability and minimum time figures can be interpreted together to read: “There is X% probability that oil is predicted to exceed the identified threshold at a specific location, and this exceedance could occur in as little as Y days”.

The Exclusive Economic Zone for Canada and the U.S., as well as the international border, are depicted on each map to provide context for the spatial extent and potentially affected territorial waters from any potential release (VLIZ, 2014).

All figures depict data where probability of a region exceeding the threshold is >1%. When comparing annual to seasonal results, the predicted percent exceedance depends on the total number of releases investigated in each subset of releases. Therefore, while only one scenario might be required to exceed the 1% threshold for visualization in seasonal results (80 to 91 modelled simulations), two scenarios would be required to exceed the same threshold in the annual analysis (171 or 179 modelled simulations), due to a greater number of modelled releases in the annual set of runs being analyzed.

Figures depicting stochastic results are provided for surface oil thickness >0.04 µm, dissolved hydrocarbon contamination >1 µg/L, and shoreline contact >1 g/m^2 for annual, summer, and winter scenarios for EL 1134 (Figure 4-1 through Figure 4-18).

4.1.1 EL 1134 Release Site



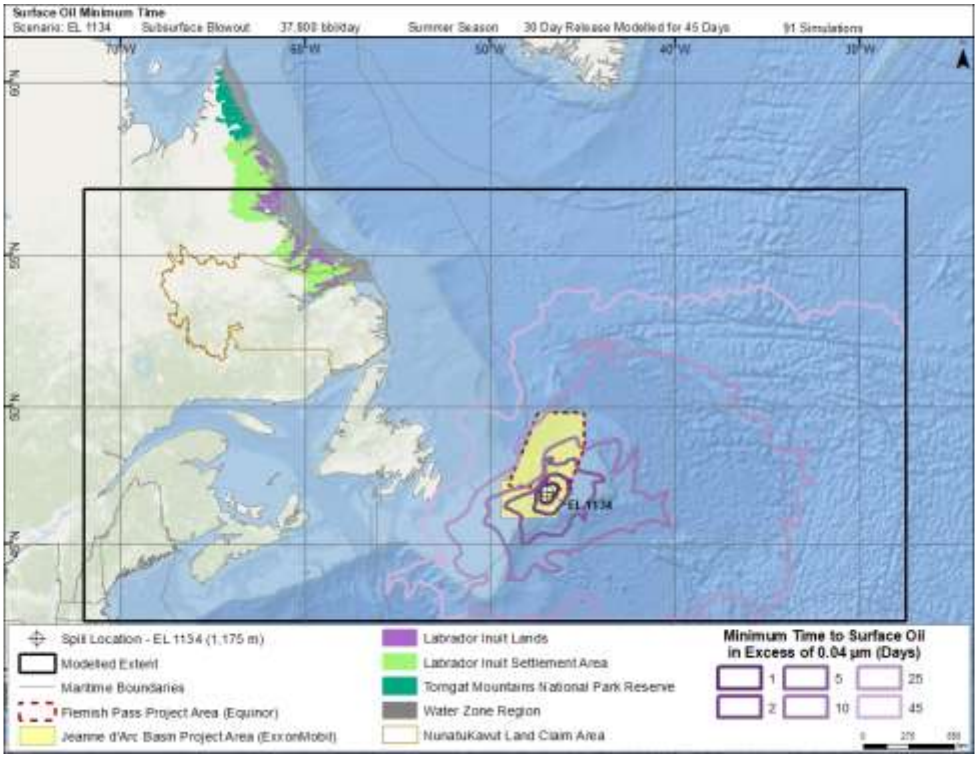


Figure 4-1. Summer probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 30-day subsurface blowout at the EL 1134 site.

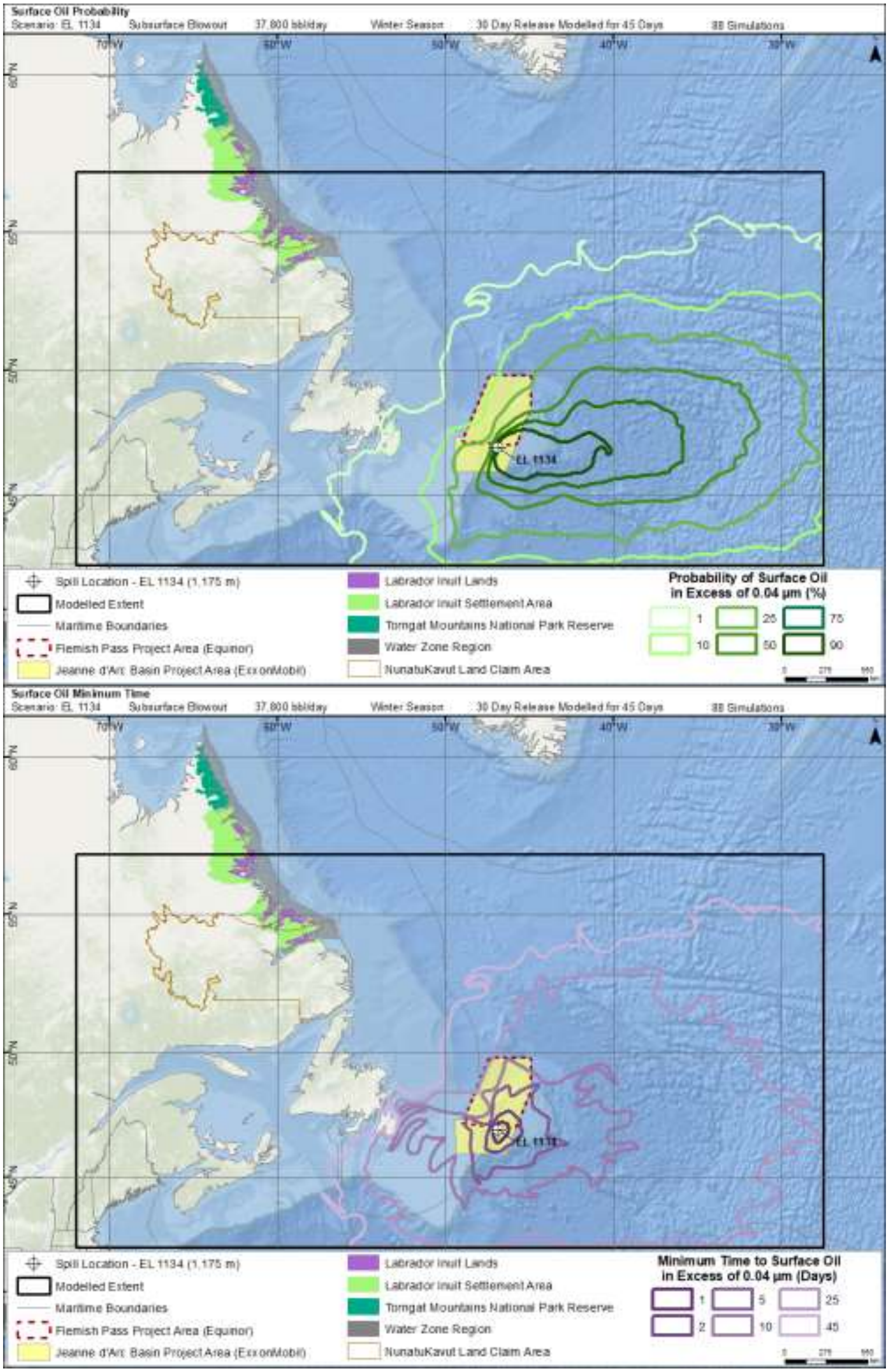


Figure 4-2. Winter probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 30-day subsurface blowout at the EL 1134 site.

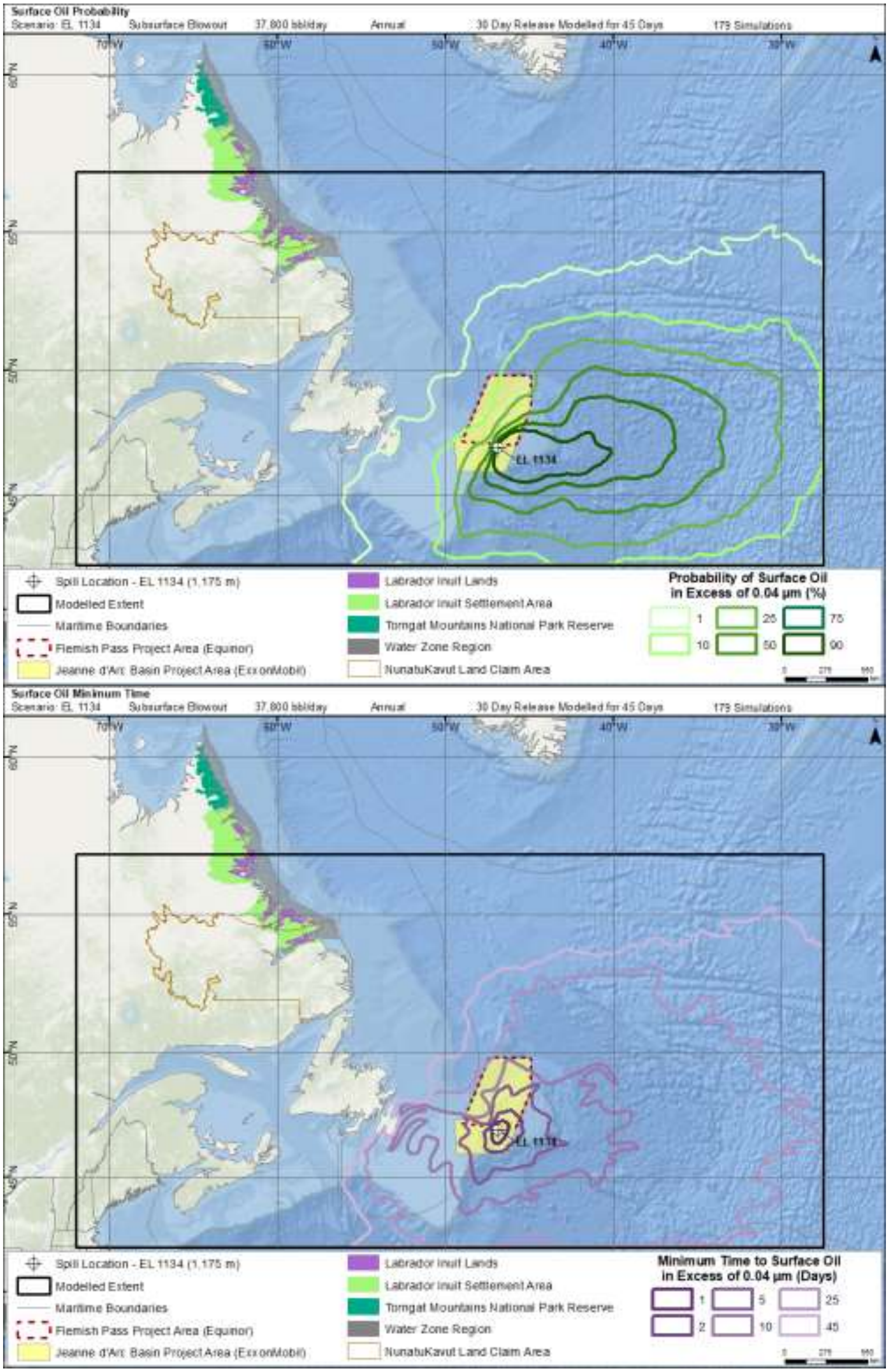


Figure 4-3. Annual probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 30-day subsurface blowout at the EL 1134 site.

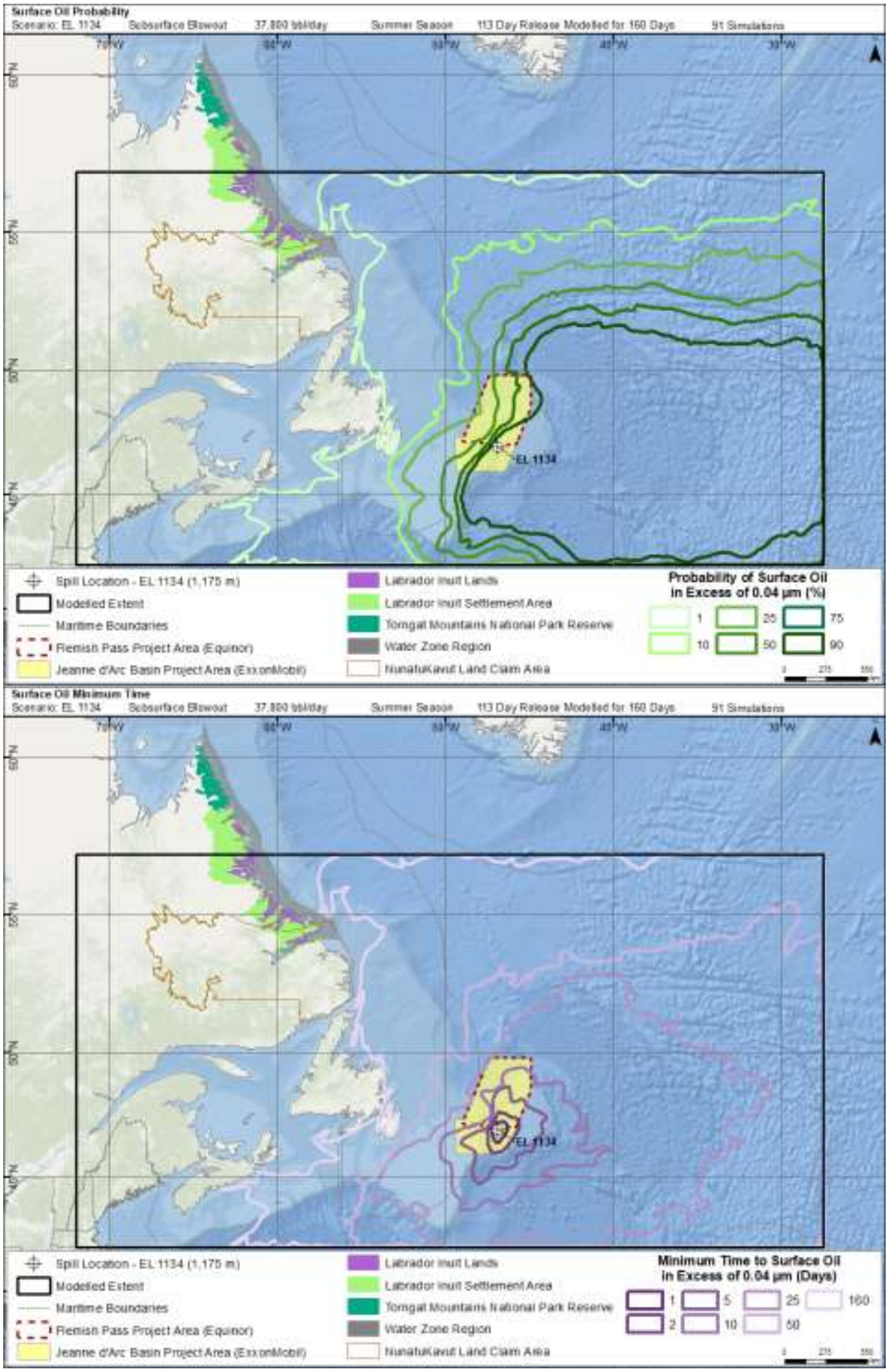


Figure 4-4. Summer probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 113-day subsurface blowout at the EL 1134 site.

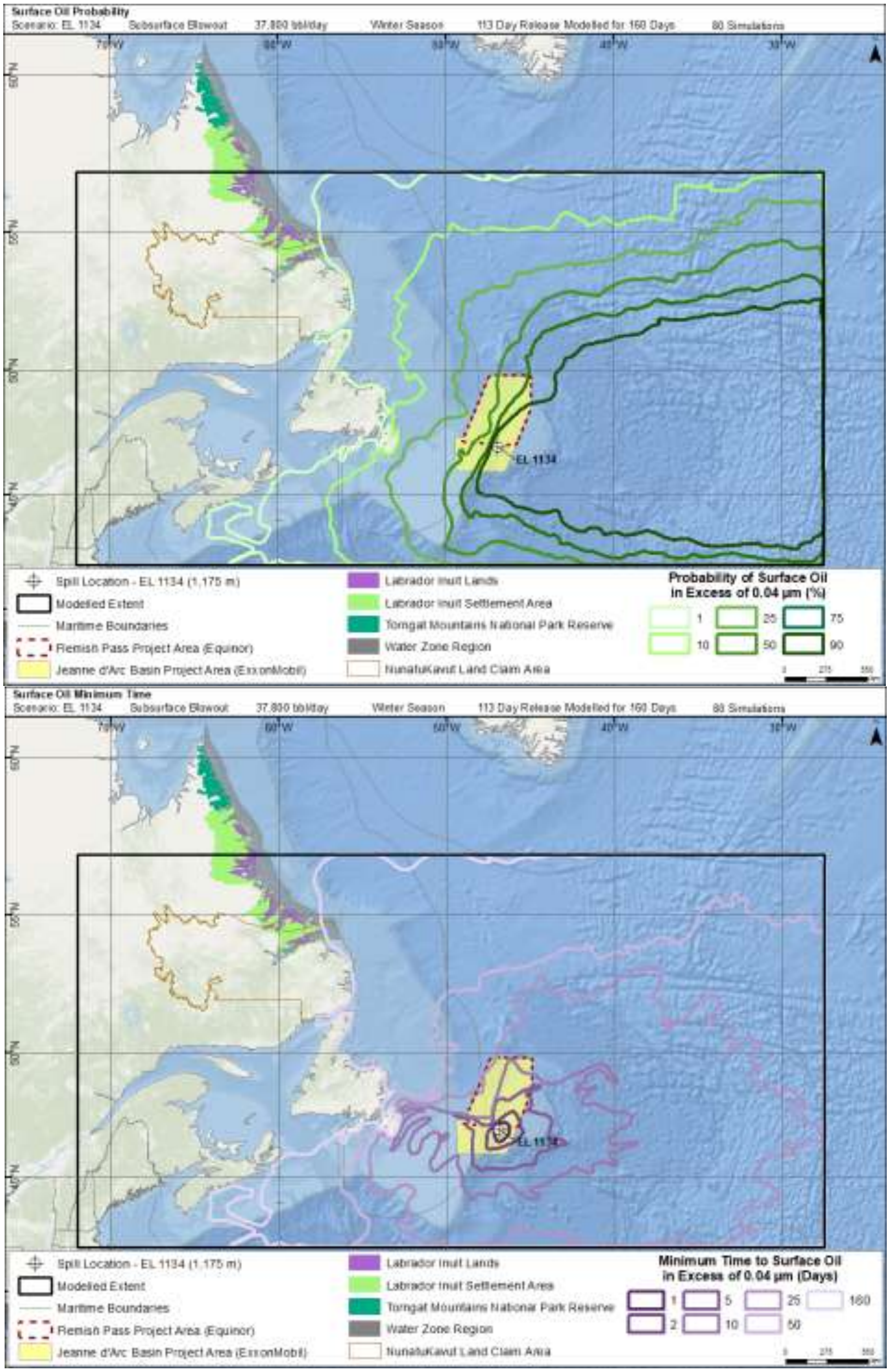


Figure 4-5. Winter probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 113-day subsurface blowout at the EL 1134 site.

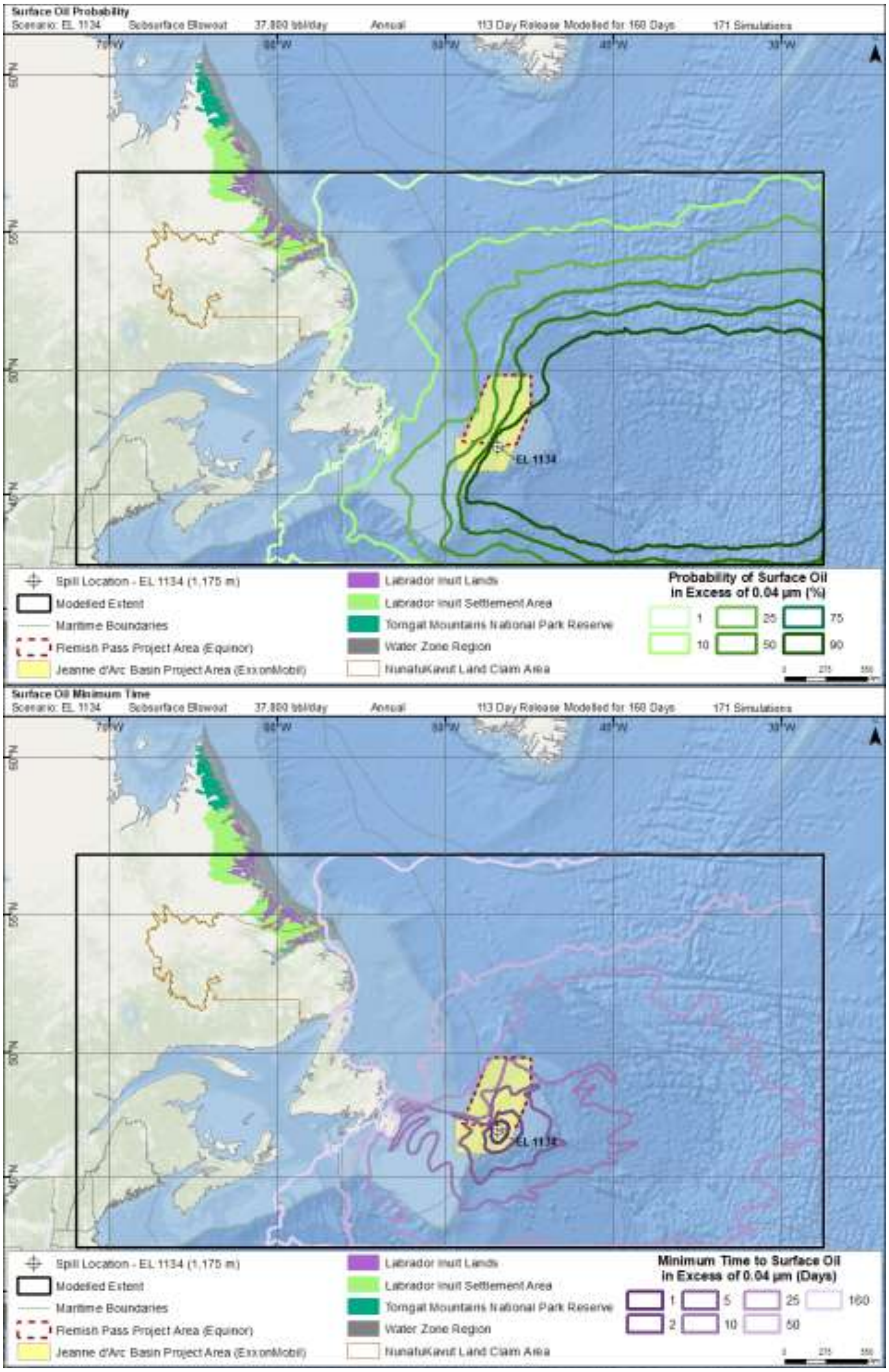


Figure 4-6. Annual probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 113-day subsurface blowout at the EL 1134 site.

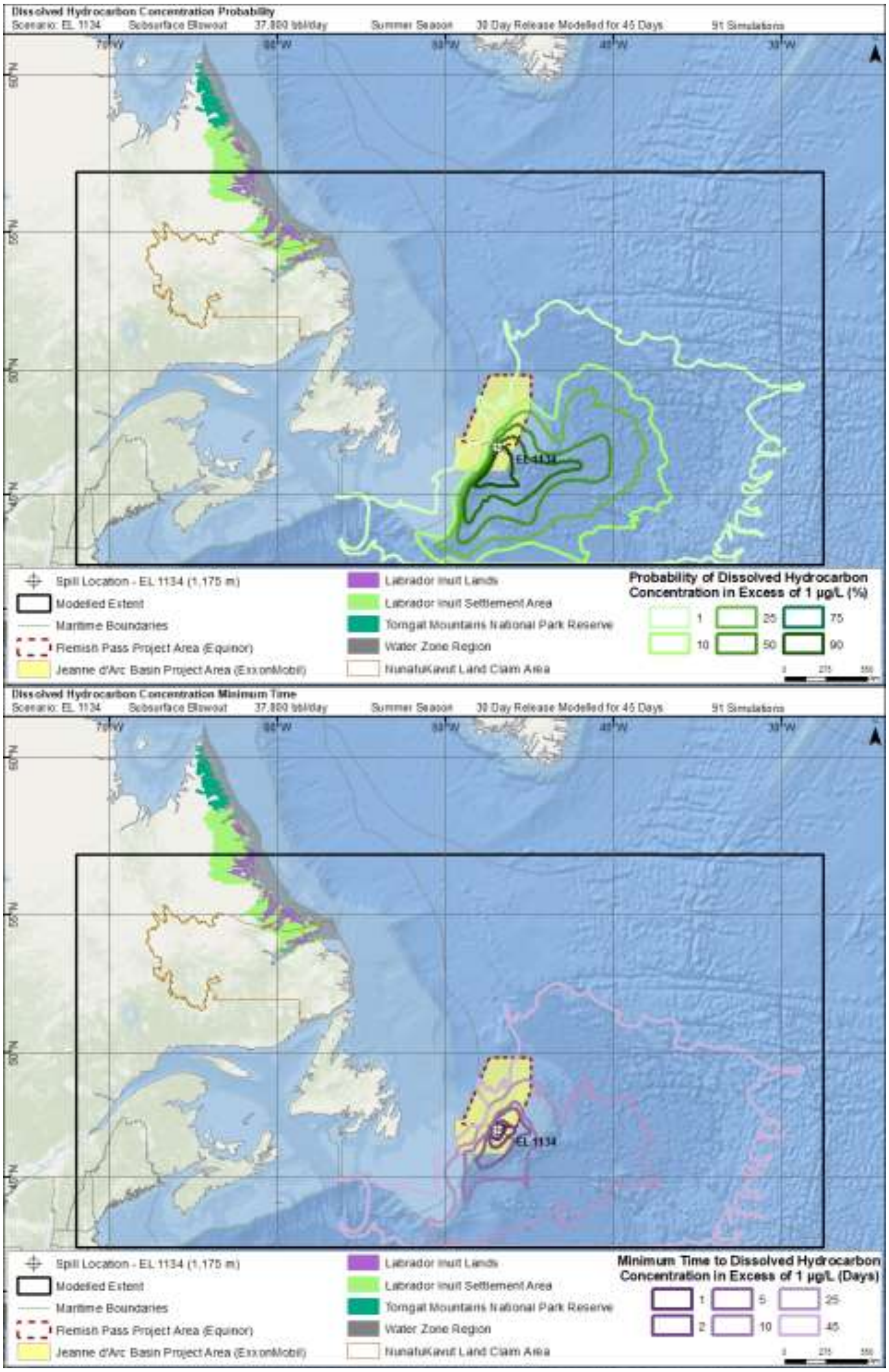


Figure 4-7. Summer probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 30-day subsurface blowout at the EL 1134 site.

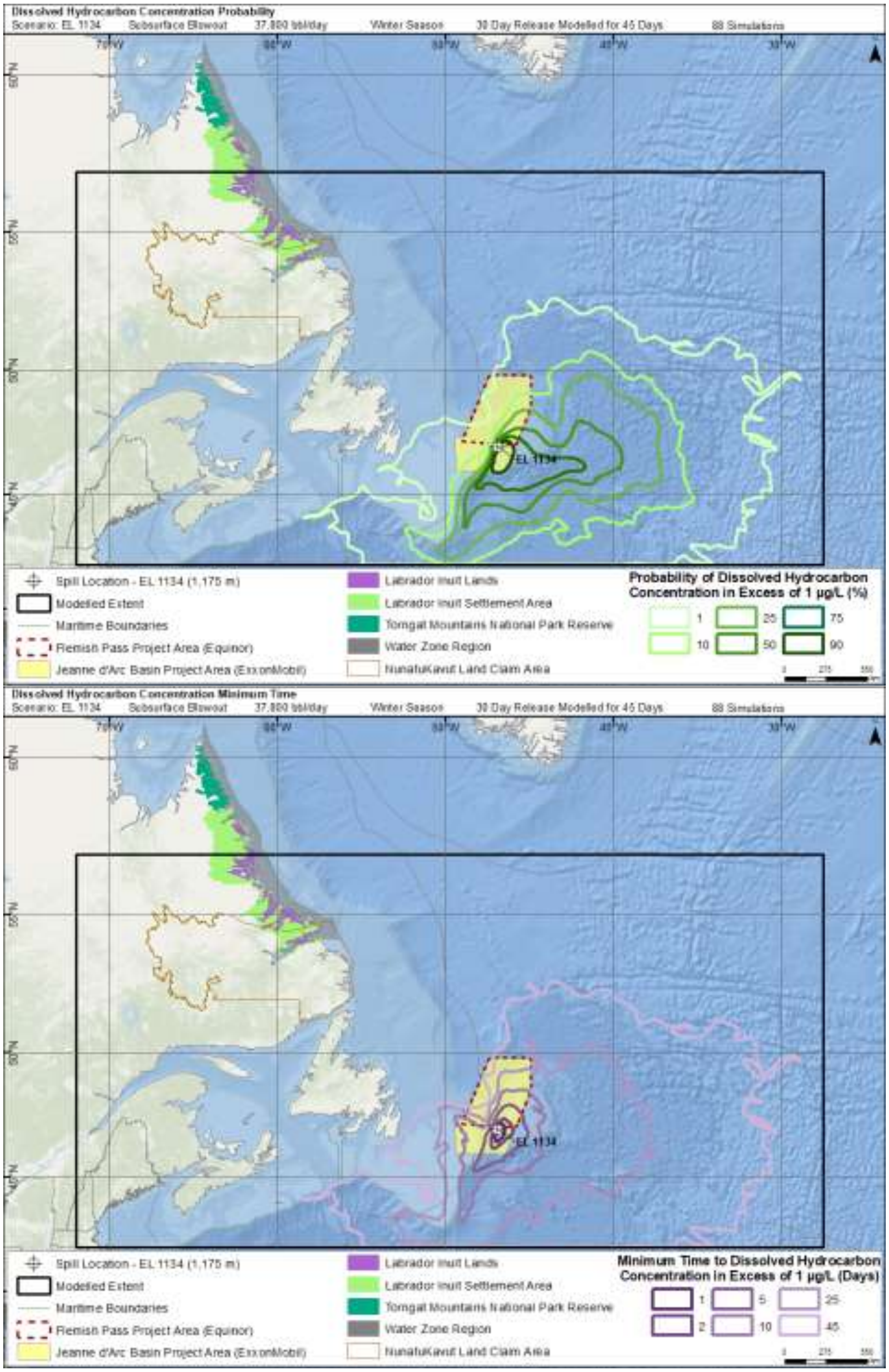


Figure 4-8. Winter probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 30-day subsurface blowout at the EL 1134 site.

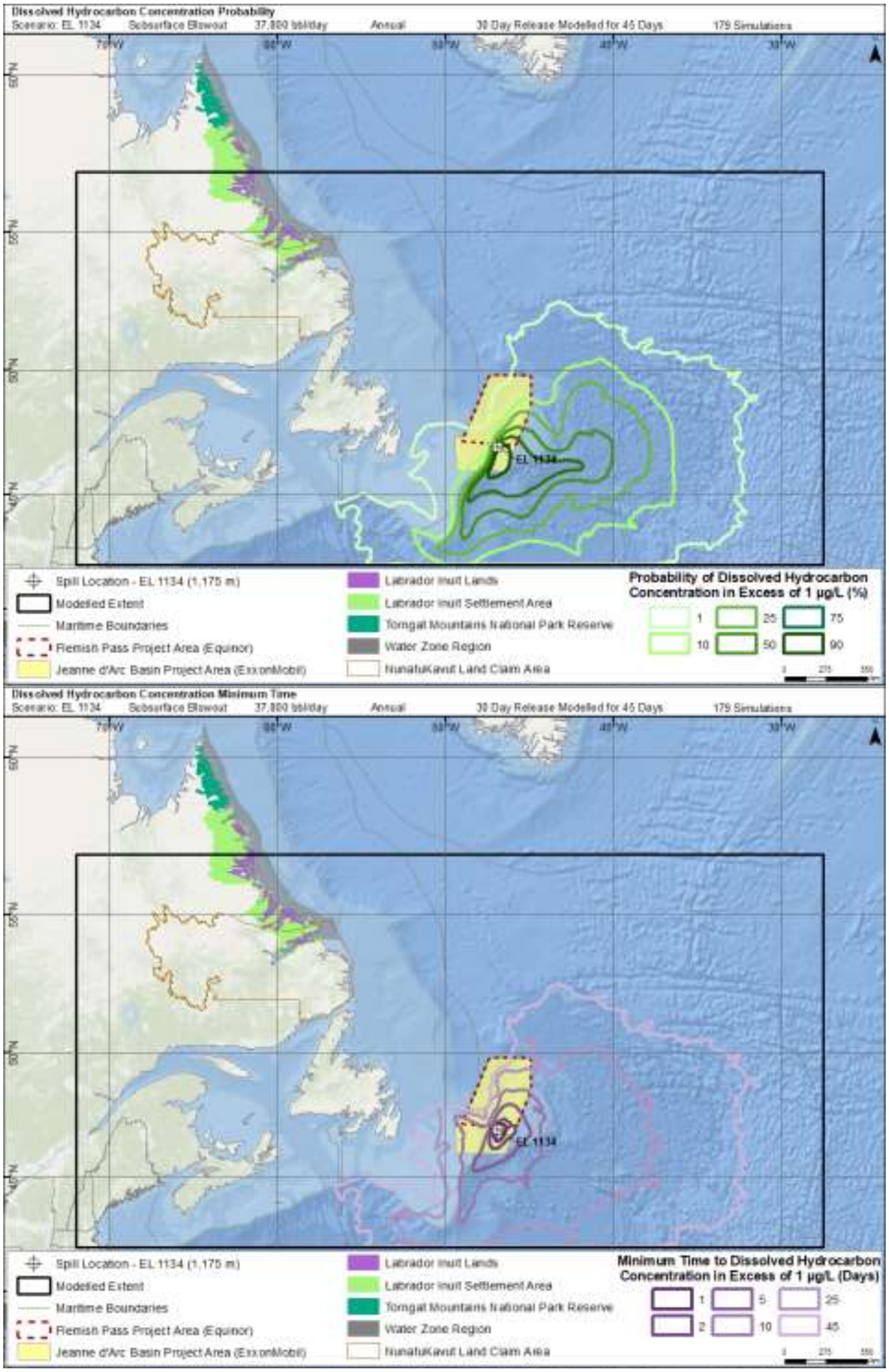


Figure 4-9. Annual probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 30-day subsurface blowout at the EL 1134 site.

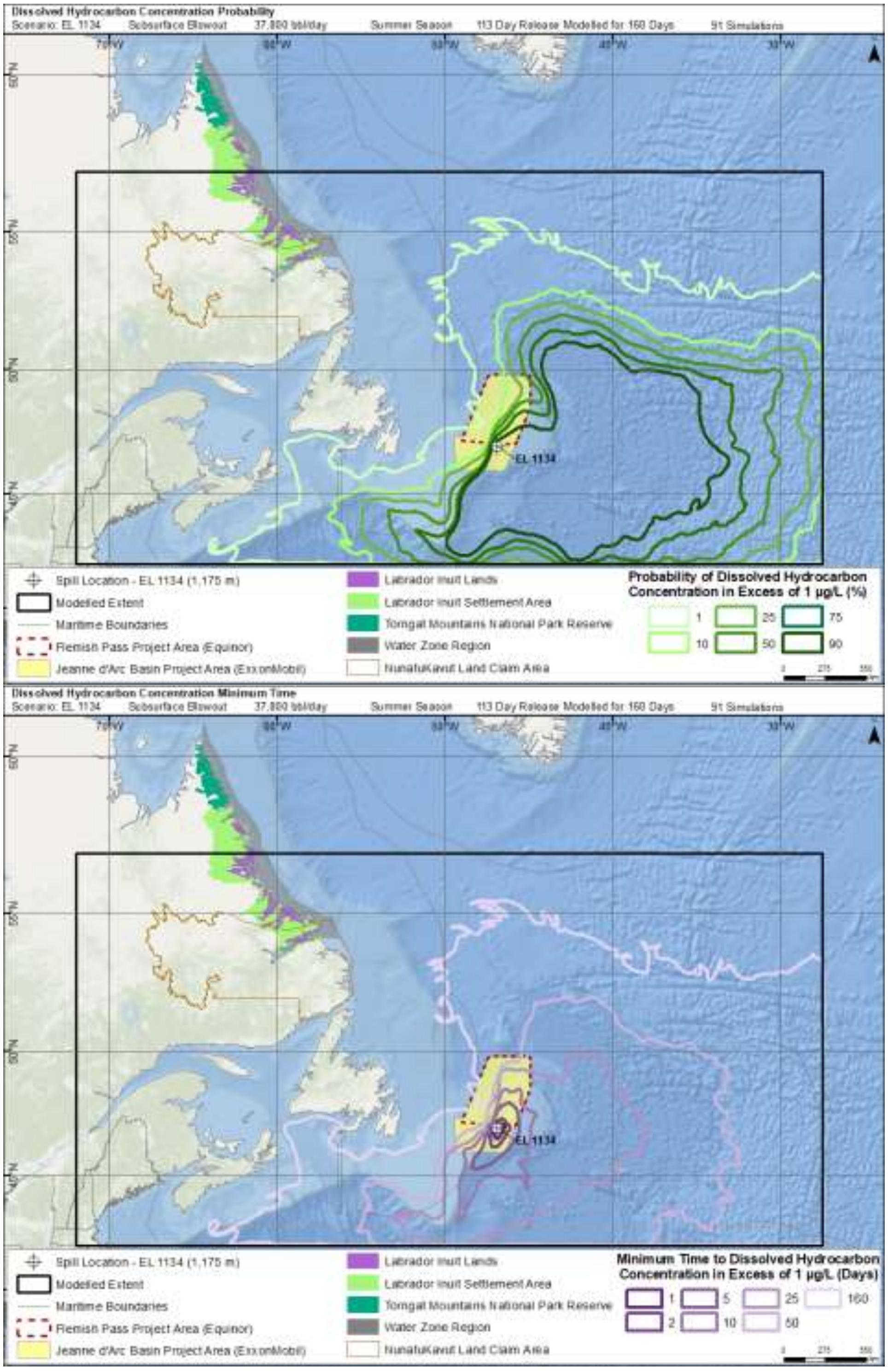


Figure 4-10. Summer probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 113-day subsurface blowout at the EL 1134 site.

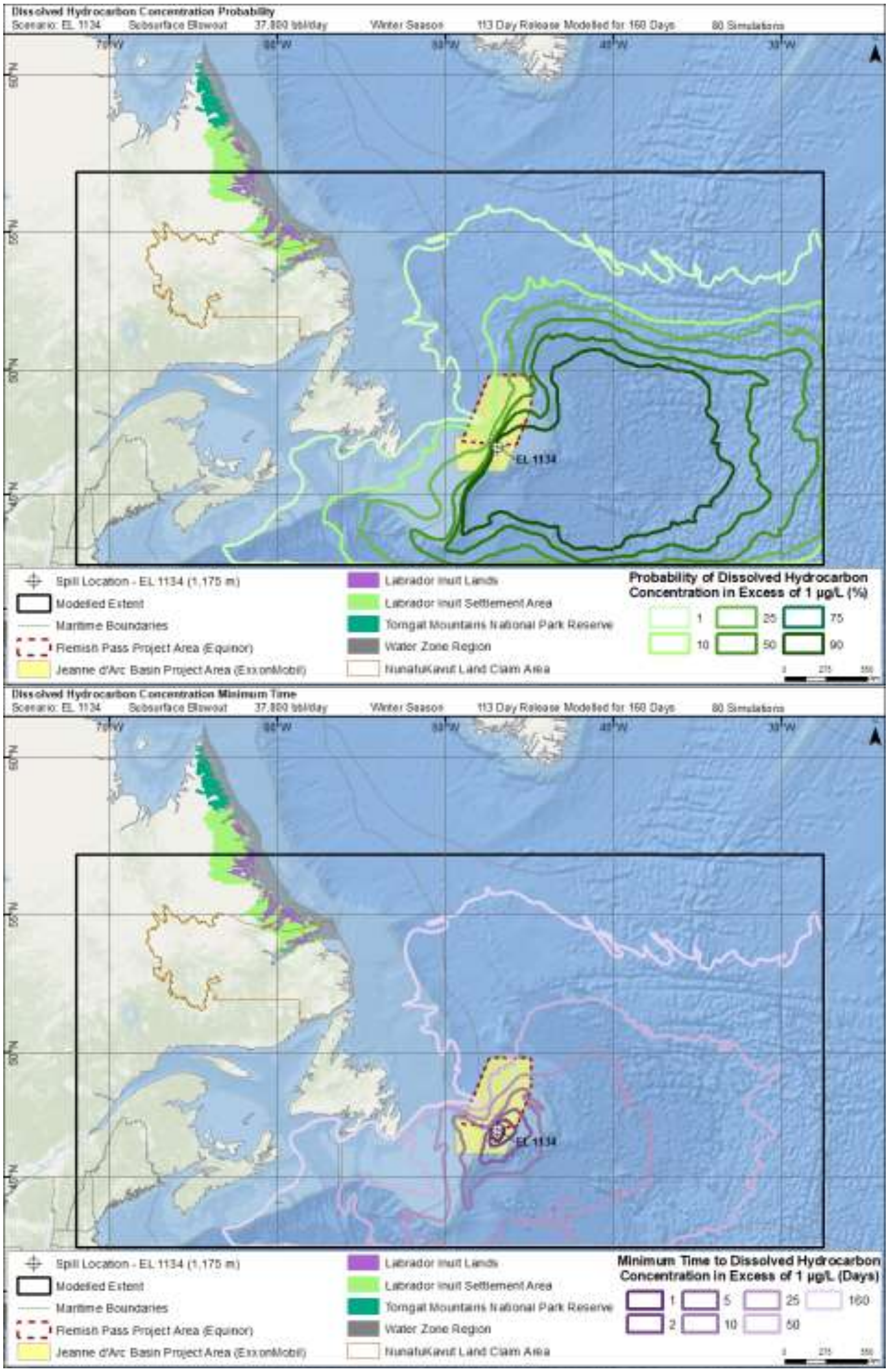


Figure 4-11. Winter probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 113-day subsurface blowout at the EL 1134 site.

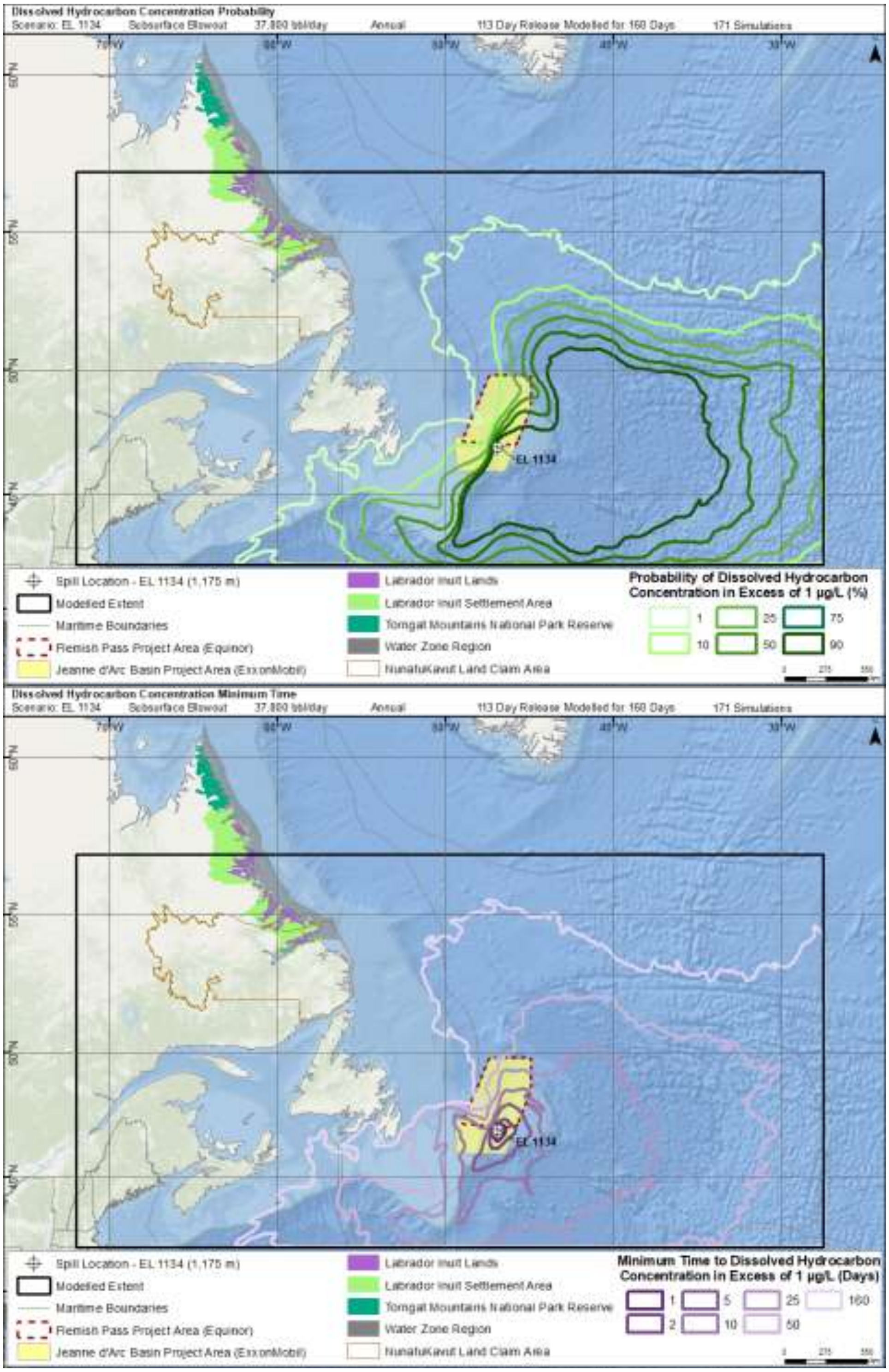


Figure 4-12. Annual probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 113-day subsurface blowout at the EL 1134 site.

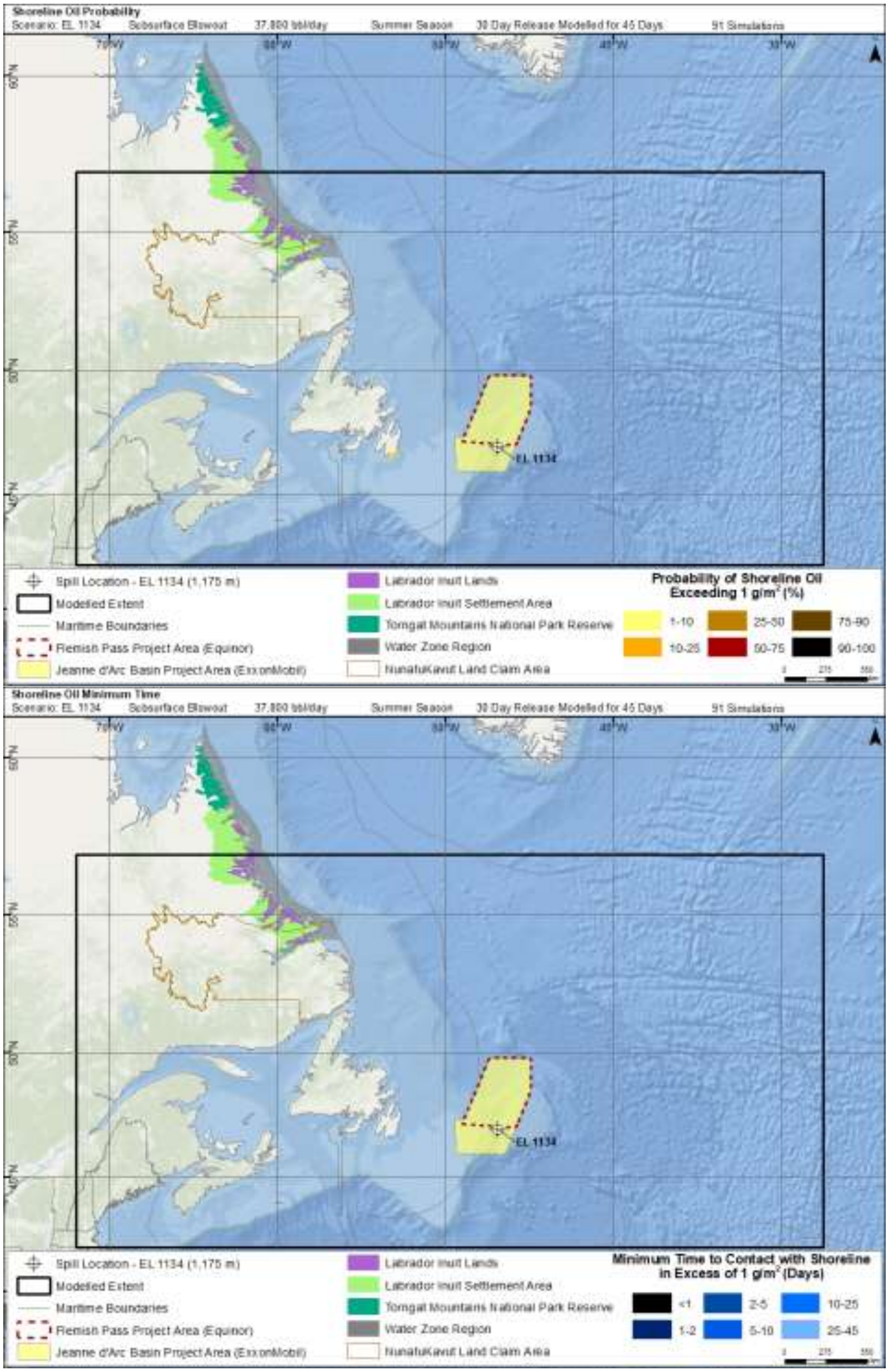


Figure 4-13. Summer probability of shoreline contact >1 g/m^2 (top) and minimum time to threshold exceedance (bottom) resulting from a 30-day subsurface blowout at the EL 1134 site. Only limited shoreline contact was predicted for this scenario on the Avalon Peninsula.

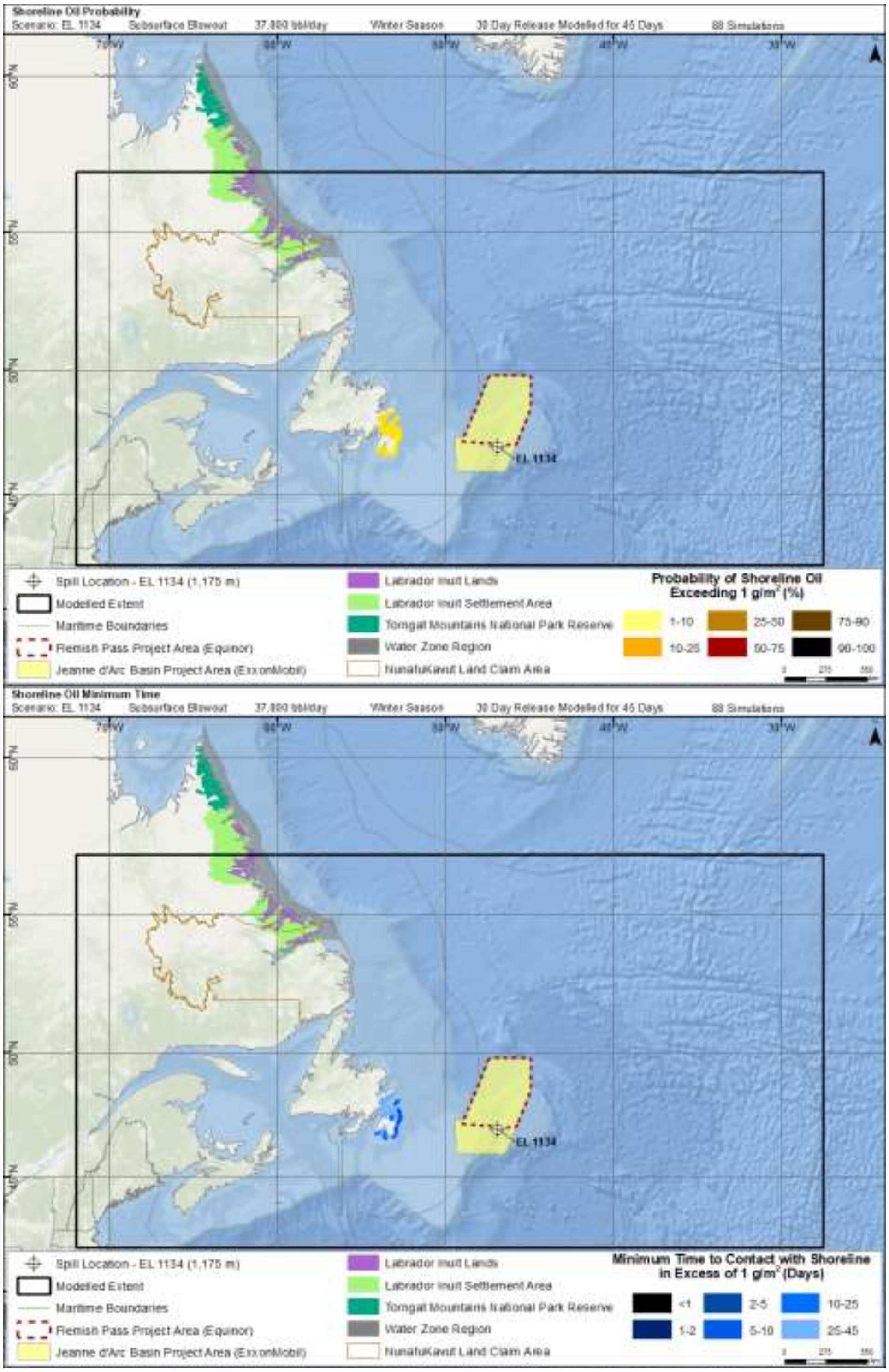


Figure 4-14. Winter probability of shoreline contact >1 g/m^2 (top) and minimum time to threshold exceedance (bottom) resulting from a 30-day subsurface blowout at the EL 1134 site.

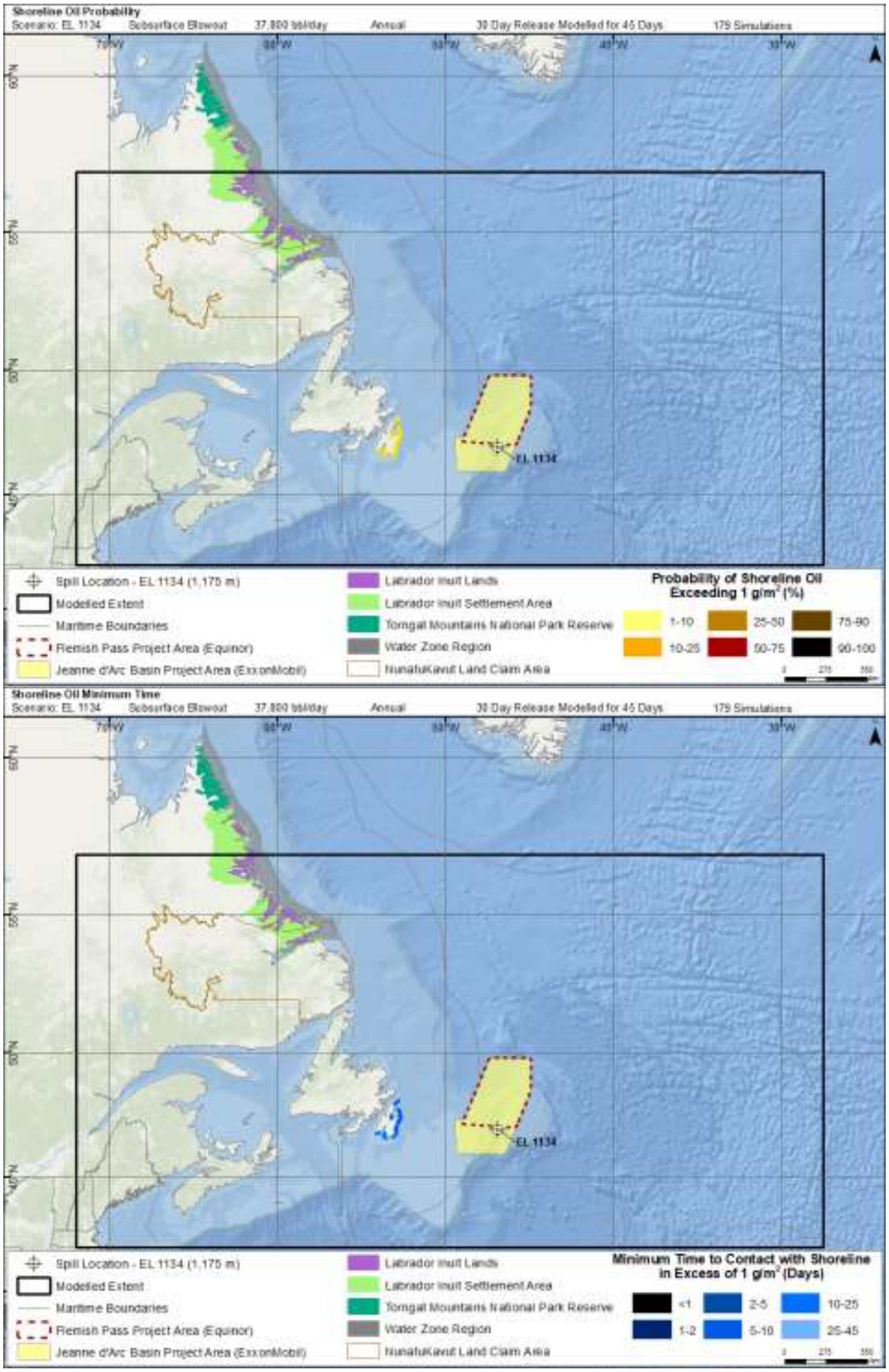


Figure 4-15: Annual probability of shoreline contact >1 g/m^2 (top) and minimum time to threshold exceedance (bottom) resulting from a 30-day subsurface blowout at the EL 1134 site.

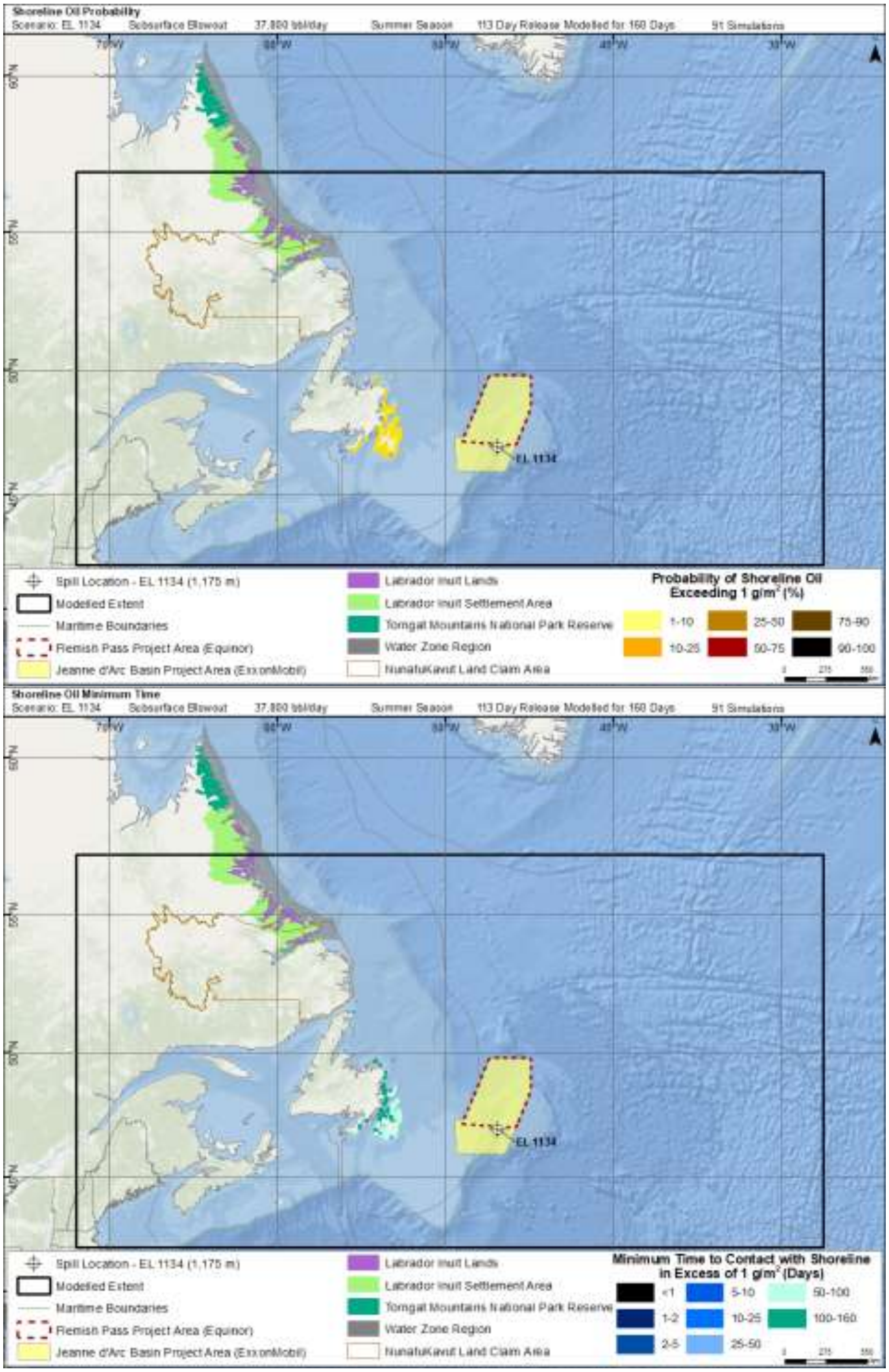


Figure 4-16. Summer probability of shoreline contact >1 g/m² (top) and minimum time to threshold exceedance (bottom) resulting from a 113-day subsurface blowout at the EL 1134 site.

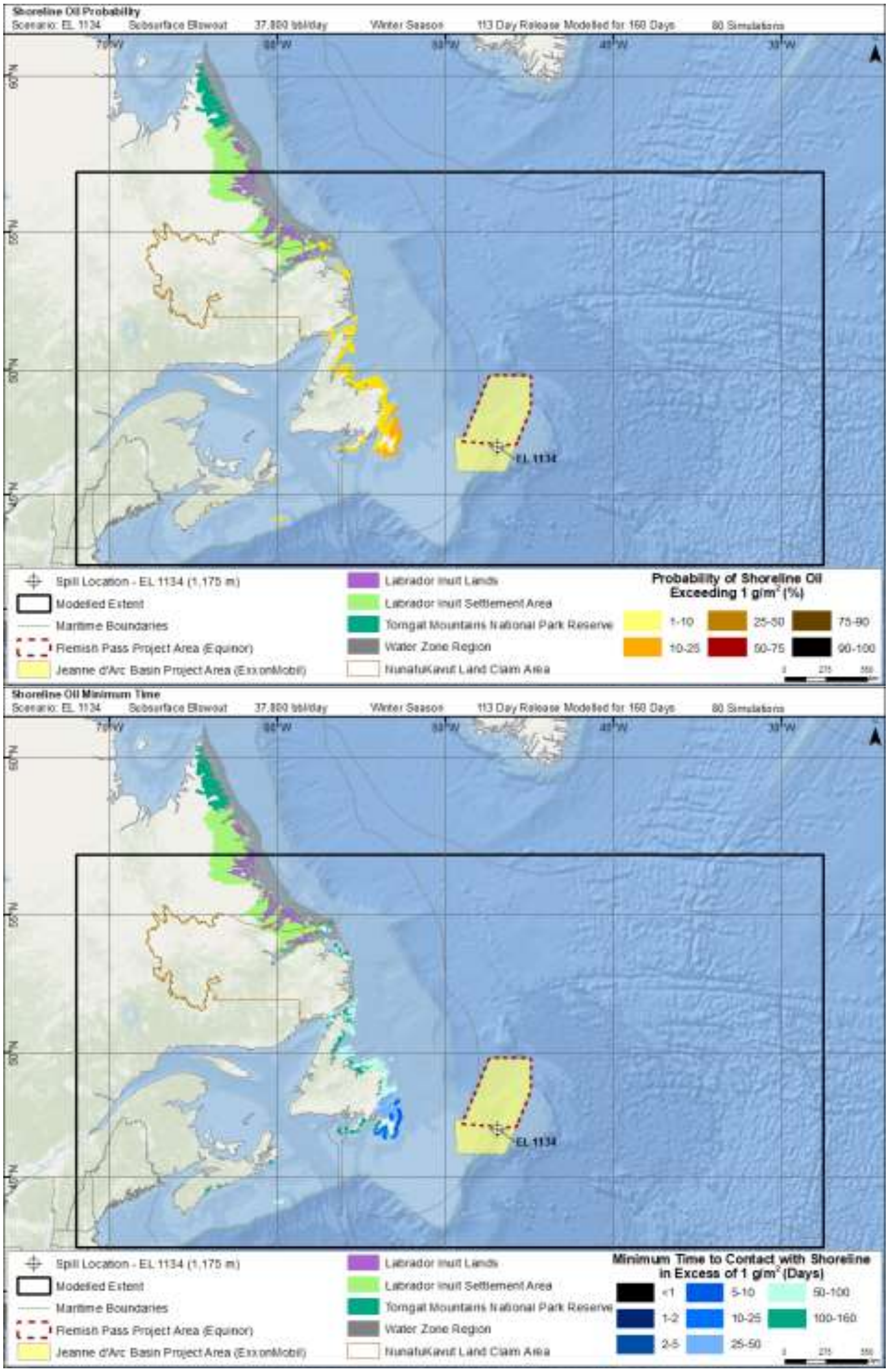


Figure 4-17. Winter probability of shoreline contact >1 g/m² (top) and minimum time to threshold exceedance (bottom) resulting from a 113-day subsurface blowout at the EL 1134 site.

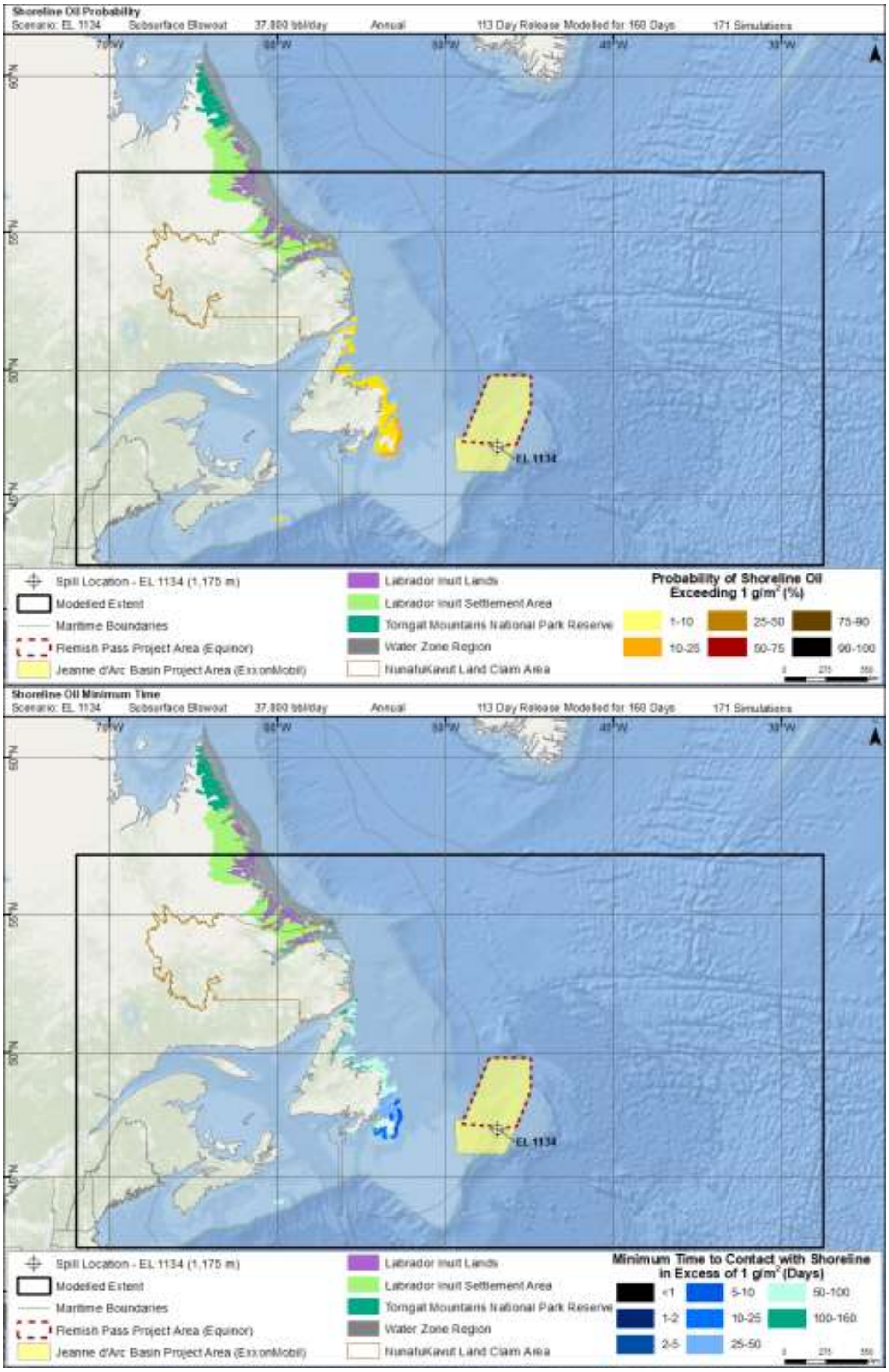


Figure 4-18. Annual probability of shoreline contact >1 g/m² (top) and minimum time to threshold exceedance (bottom) resulting from a 113-day subsurface blowout at the EL 1134 site.

4.1.2 Summary of Stochastic Results

A total of 179 (30-day) and 171 (113-day) individual model runs were conducted for the statistical analysis of the stochastic simulations at the EL 1134 site for a grand total of 350 individual model runs. Each simulation represents deep subsurface blowouts in the waters offshore of Newfoundland. A 30-day release was modelled at the EL 1134 (1,175 m) site to represent a cap-and-stack response scenario. Additionally, a 113-day release was modelled at the site to represent longer duration response associated with drilling a relief well. The 30-day release was modelled for 45 days and the 113-day release was modelled for 160 days.

Summaries of the stochastic analyses of potential surface oil exposure and water column contamination by dissolved hydrocarbons depict areas with the highest potential likelihood (>90%) to exceed thresholds to the east and south of the release sites. Much lower probabilities of threshold exceedance are predicted to the north and west (<25%) (Figure 4-1 through Figure 4-12). Releases are predicted to have potential effects on Canadian and International waters. In many cases, oil contamination above the identified threshold was predicted to extend beyond the extent of the model domain predominantly to the east and in some cases to the south. In these scenarios, the environmental forcing mechanisms (i.e., wind and currents) and long timeframe modelled (45 or 160 days) allowed for the transport of highly weathered oil at extremely conservative (low) thresholds outside of the model domain.

The hypothetical 113-day release of Ben Nevis at EL 1134 (see figures in Section 4.1.1) has nearly four times the release volume of the 30-day release (4,271,400 bbl vs. 1,134,000 bbl, respectively) and is predicted to lead to a larger probability footprint of surface oil exceeding the 0.04 µm thickness threshold in >1% (Table 4-1). This difference in release volume and ultimately the predicted area is the result of the longer model duration and release, which allows more oil to continue to be transported throughout the environment. The 90% probability footprint was predicted to be larger for summer scenarios, when compared to the winter, for both the 30- and 113-day release scenarios due to more variable winds and resulting transport (Table 4-1). Similarly, the predicted footprint of dissolved hydrocarbons within the water column, where there would be >1% probability of concentrations exceeding 1 µg/L at any depth, is larger in the summer than the winter for both the 30- and 113-day releases. Due to the volume of oil released and the duration modelled, the 113-day scenarios were predicted to have the potential to make contact with a longer length of shoreline, compared to that of the 30-day release (Table 4-1). The oil that is predicted to make contact with shorelines is expected to be weathered, as minimum time estimates for first shoreline oil exposure range from approximately 8-27 days, depending on the location and season (Table 4-2).

Table 4-1. Summary of predicted areas of threshold exceedance (km²) for surface and water column, and lengths (km) of shoreline oil predicted to have the potential to be affected. Areas are displayed by season (annual, winter, summer) and by the size of the regions within the modelled domain that had >1%, 10%, or 90% likelihood of exposure to oil.

Stochastic Scenario Parameters				Areas Exceeding Threshold (km^2)		
Component and Threshold	Scenario	Site	Probability Contour or Bin	Annual Results	Winter (ice cover)	Summer (ice-free)
Surface Oil >0.04 µm, on average	30-day release	EL 1134 (37,800 bbl/d)	1%	2,399,000	2,495,000	2,265,000
			10%	1,618,000	1,806,000	1,377,000
			90%	88,600	81,440	100,300
	113-day release	EL 1134 (37,800 bbl/d)	1%	3,422,000	3,528,000	3,402,000
			10%	2,723,000	2,885,000	2,488,000
			90%	1,314,000	1,286,000	1,394,000
Water Column Dissolved Hydrocarbons >1 µg/L at some depth within the water column	30-day release	El 1134 (37,800 bbl/d)	1%	1,401,000	1,579,000	1,400,000
			10%	646,000	681,800	604,300
			90%	9,961	9,953	19,410
	113-day release	EL 1134 (37,800 bbl/d)	1%	2,524,000	2,678,000	2,475,000
			10%	1,941,000	2,047,000	1,835,000
			90%	727,400	714,200	752,400
				Lengths Exceeding Threshold (km)		
Shoreline Oil >1 g/m^2, on average	30-day release	EL 1134 (37,800 bbl/d)	1 - 5%	384	1,245	18
			5 - 15%	-	-	-
			15 - 25%	-	-	-
	113-day release	EL 1134 (37,800 bbl/d)	1 - 5%	1,877	1,859	847
			5 - 15%	1,068	1,678	761
			15 - 25%	37	107	-

Table 4-2. Shoreline contamination predicted probabilities and minimum time for oil exposure exceeding 1 g/m².

Scenario	Release Site	Scenario Timeframe	Average Probability of Shoreline Oil Contamination (%)	Maximum Probability of Shoreline Oil Contamination (%)	Minimum Time to Shore (days)	Maximum Time to Shore (days)
30-day release	EL 1134 (37,800 bbl/d)	Annual	2	3	8	36
		Winter	2	5	8	44
		Summer	1	2	27	42
113-day release		Annual	5	16	8	151
		Winter	6	25	8	160
		Summer	4	14	27	160

As stated previously, stochastic figures do not imply that the entire contoured area would be covered with oil in the event of a single release, nor do they provide any information on the quantity of oil in each area. The large threshold exceedance footprints in annual results are not the expected exposure from any single release of oil, but rather areas where there is >1% probability that exposure above the threshold could occur, based on the combination of either 179/171 (annual), 91/91 (summer), or 88/80 (winter) individual releases analyzed together.

4.2 Deterministic Analysis Results

Four individual trajectories of interest were selected from the stochastic ensemble of results for the deterministic analysis (Table 2-5). The deterministic trajectory and fate simulations provided an estimate of the oil's transport through the environment over time as well as its physical and chemical behavior for the specific set of environmental conditions modelled. The representative worst case scenarios for shoreline length contact were identified from the two stochastic model scenarios. In addition, two cases representing 100 L and 1,000 L batch releases of marine diesel from surface vessels were modelled.

The following sections contain figures corresponding to each identified representative case and tables summarizing the areas exceeding specified thresholds. During modelling, components of oil were tracked as entrained droplets of oil, dissolved hydrocarbon constituents, floating surface oil, and stranded shoreline oil. The figures display the cumulative footprint of all oil experienced by a region over the entire duration of modelling. Therefore, the footprints are much larger than the amount of oil predicted to be present in a region at any given time. This concept is illustrated in Figure 4-19, which portrays average surface oil thickness in each cell at five specific time steps (days 2, 5, 10, 25, and 45) during the representative worst case shoreline oil area case, and in Figure 4-20, which portrays a much larger cumulative footprint of average surface oil thickness from an entire model run than was experienced during any of the individual time steps. The remaining figures in this report will display the cumulative footprints of oil exposure over the entire model duration, as in the latter figure.

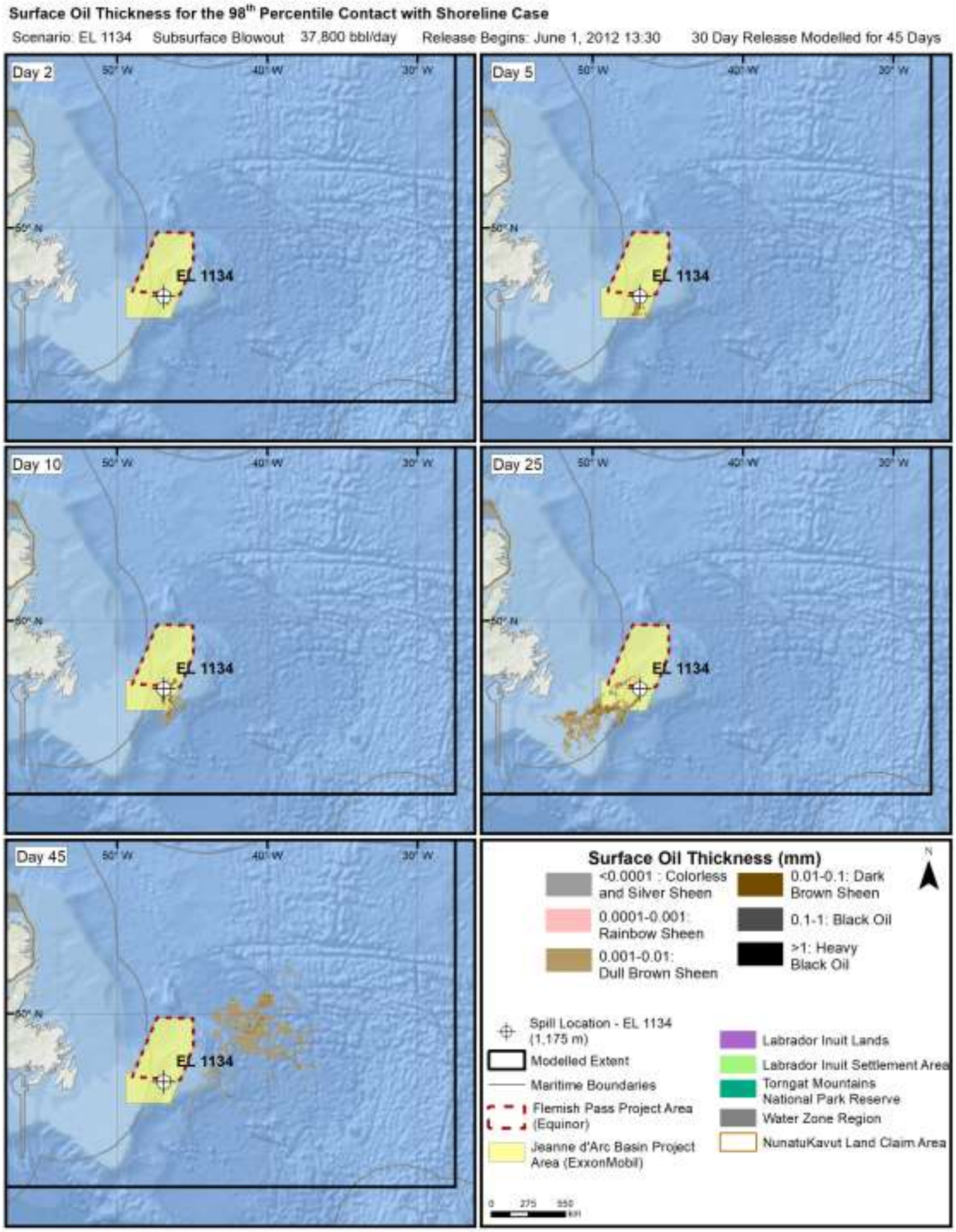


Figure 4-19. Average surface oil thickness for the representative 30-day blowout 98th percentile shoreline oil exposure case at days 2, 5, 10, 25, and 45 to illustrate the variation in size, continuity (i.e., patchy), and spatial extent of the surface oil footprint over the course of a single model run.

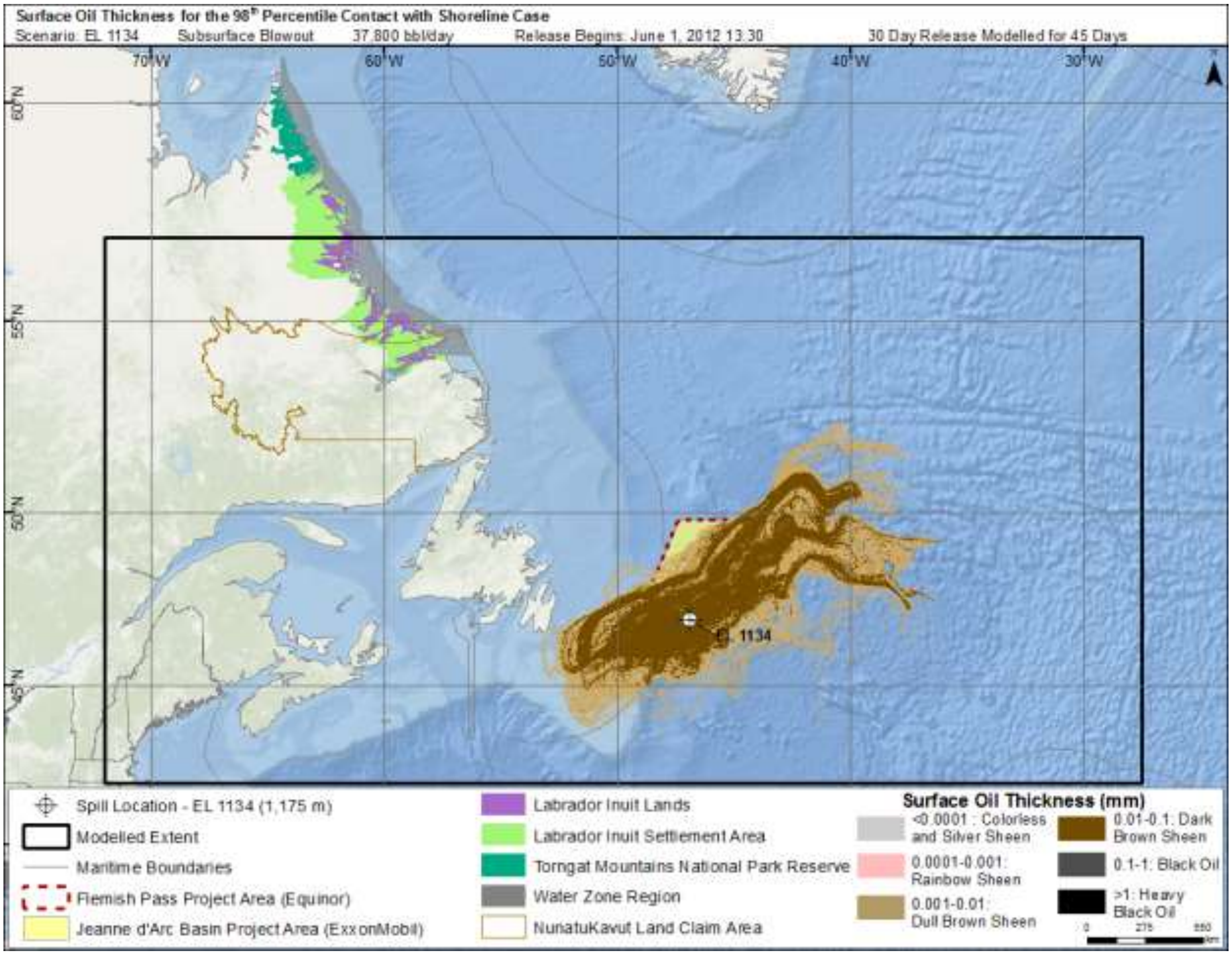


Figure 4-20. Cumulative maximum surface oil thickness for the 98th percentile shoreline exposure case of a 30-day blowout at EL 1134 to illustrate the much larger size of the cumulative surface oil footprint over the entire model duration, compared to the size of the surface oil footprint on any one day or time step (Figure 4-19).

The types of figures (cumulative maximum) that were used to summarize modelling results are provided, along with brief descriptions of the information that they portray.

1. **Mass Balance Plots**: Illustrate the predicted weathering and fate of oil for a specific run over the entire model duration as a fraction of the oil released up to that point. Components of the oil tracked over time include the amount of oil on the sea surface, the total entrained hydrocarbons in the water column, amount of oil in contact with the shore, oil evaporated into the atmosphere, and that which has degraded (accounts for both photo-oxidation and biodegradation).
2. **Surface Oil Thickness Maps:** Depict the predicted footprint of maximum floating surface oil and the associated oil thicknesses (mm) over all modelled time steps for an individual release simulation.
3. **Water Column Dissolved Hydrocarbon Concentration Maps**: Depict the predicted footprint of the vertical maximum water column concentration of dissolved hydrocarbons over all modelled time steps for an individual release simulation. Dissolved hydrocarbons are the constituents of the oil with the greatest potential to affect water column biota. Only concentrations above 1 µg/L for the representative cases are displayed (see Table 2-2). For the marine diesel batch spills, the volumes released were insufficient to produce dissolved hydrocarbon footprints at the gridded resolution used (the dissolved hydrocarbons comprise roughly 1% of total hydrocarbons released). Therefore, total hydrocarbon concentrations in the water column are displayed instead of the dissolved hydrocarbons.
4. **Water Column Total Hydrocarbon Concentration Maps:** Depict the predicted footprint of the vertical maximum water column concentration of total hydrocarbons over all modelled time steps for an individual release simulation. Only concentrations above 1 µg/L for the representative cases are displayed (Table 2-2).
5. **Shoreline and Sediment Total Hydrocarbon Concentration Maps:** Depict the predicted total mass of oil (per unit area as g/m^2) deposited onto the shoreline and on sediments.

4.2.1 Shoreline Exposure Case

Results for the identified representative worst case shoreline exposure cases for the releases at EL 1134 are provided below (Figure 4-21 through Figure 4-25). Note that the modelled release dates for the representative scenarios at each site differed. The 30-day release at EL 1134 spanned early June through mid-July 2012, while the 113-day release at EL 1134 spanned mid-April through mid-September 2011 (Table 2-5). The predicted contact with shoreline from the 30-day release at EL 1134 occurred on the south-eastern portion of the Avalon Peninsula, whereas the predicted contact from the 113-day release occurred on the entire eastern portion of the Avalon Peninsula and extended further to the south and north reaching the main island of Newfoundland (Figure 4-25). However, even in the representative worst case scenarios for shoreline oiling, only a very small portion of the released oil (<0.2% of the total release volume) was predicted to make contact with the shoreline (Table 4-4). Contact with the shoreline from the 30- and 113-day releases at EL 1134 was predicted to occur 28 and 58 days into the simulations, respectively. This difference in timing is due to the specific weather conditions during the modelled timeframe within each simulation (Table 2-5).

Shoreline oil exposure was more likely to occur from the 113-day release due to the total volume of oil released (4,271,400 bbl) and the longer period of time modelled. The surface currents and winds are variable (Figure 3-7 and Figure 3-8) and do not continuously transport oil in any one specific direction for significant periods of time. In addition, the EL 1134 release site is located approximately 400 km offshore. Therefore, there would be a large amount of time required to pass before any oil from EL 1134 made its way to shore, at which point evaporation and degradation would have weathered the oil.

The combination of wind and current conditions resulted in a very small portion of the release (<0.02%) making contact with the shoreline for both the 98th (30-day) and the 95th (113-day) percentile cases. The total hydrocarbon concentration on shore from the 30-day release ranged from 100-500 g/m^2, which was above the socioeconomic (1 g/m^2) and ecological (100 g/m^2) thresholds (Table 4-3). The total hydrocarbon concentration on shore from the 113-day releases at both EL 1134 was predicted to range from 100 to greater than 500 g/m^2.

At the end of the 45-day simulation, 47% of the released volume was predicted to remain floating on the water surface, 26% evaporated into the atmosphere, 7% remained entrained in the water column, <0.01% adhered to suspended sediment, 0.01% contacted the shore, 19% degraded, and <0.03% was transported outside the modelled domain (Figure 4-21and Table 4-4). At the end of the 160-day simulation, 10% of the released volume was predicted to remain floating on the water surface, 30% evaporated into the atmosphere, 3% remained entrained in the water column, <0.01% adhered to suspended sediment, <0.2% contacted the shore, 39% degraded, and 18% was transported outside the modelled domain (Figure 4-21 and Table 4-4).

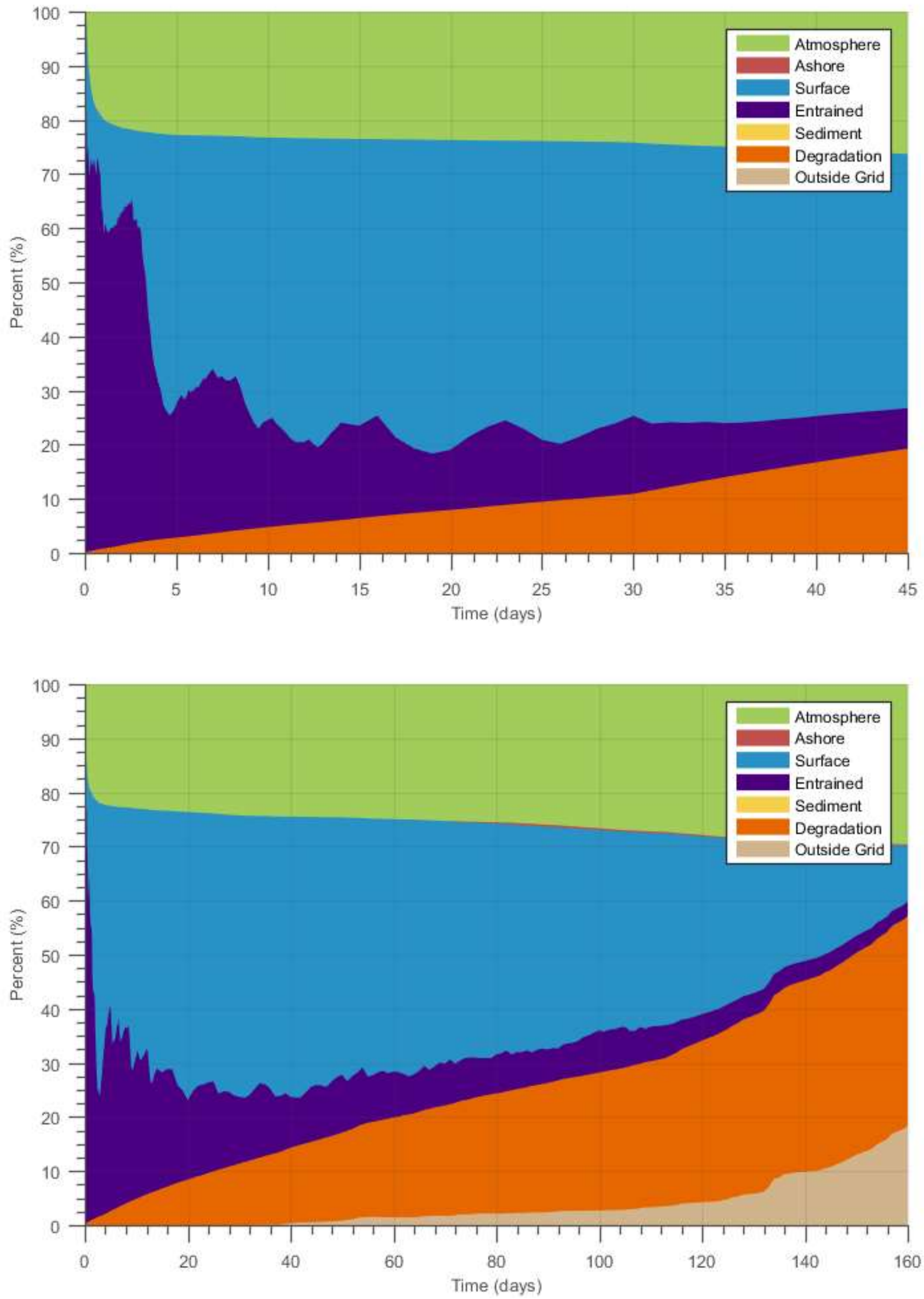


Figure 4-21. Mass balance plots of the representative worst case for shoreline contact resulting from 30-day (top) and 113-day (bottom) subsurface blowouts at EL 1134.

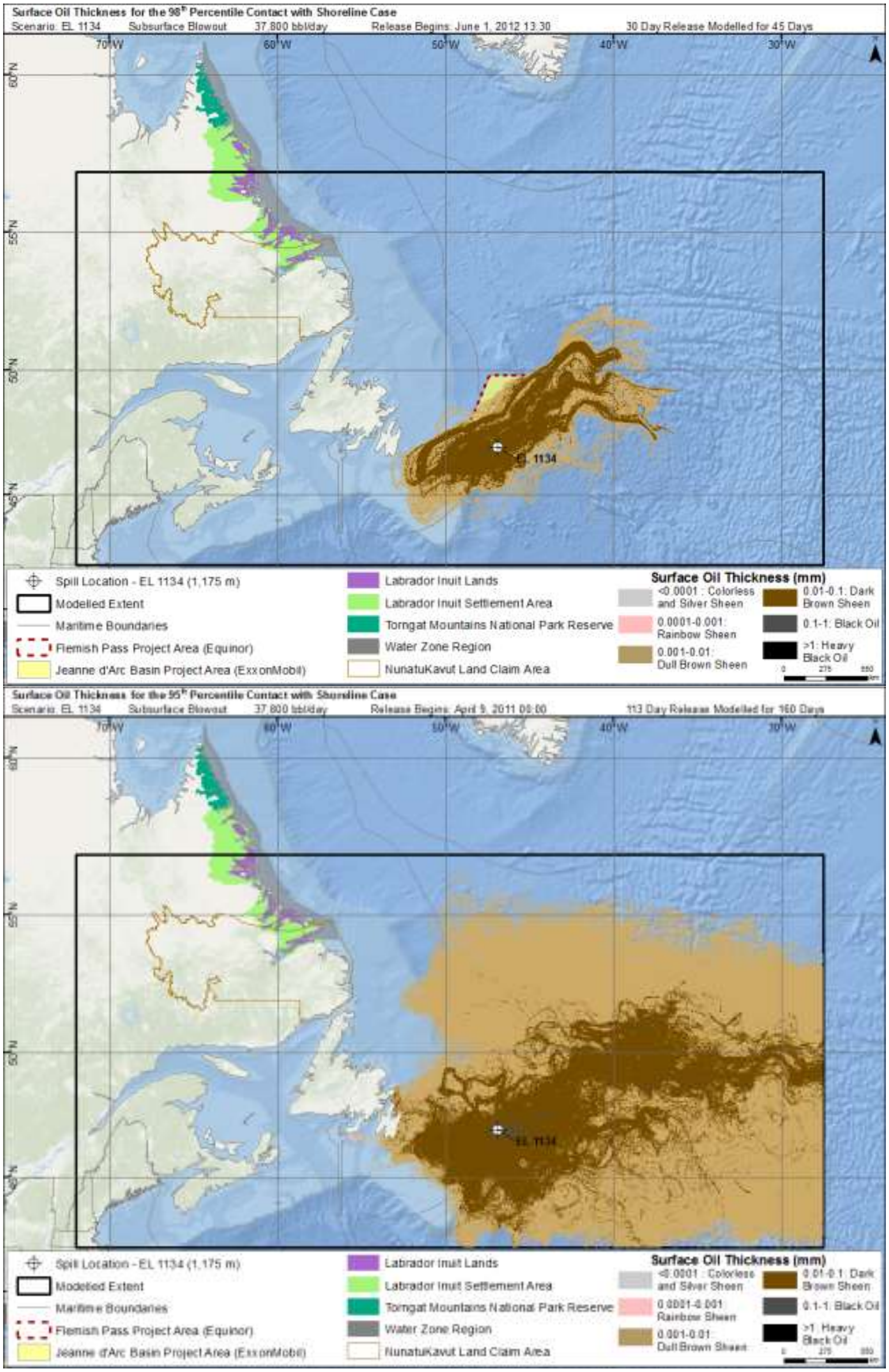


Figure 4-22. Surface oil thickness for the representative worst case for shoreline contact resulting from 30-day (top) and 113-day (bottom) subsurface blowouts at EL 1134.

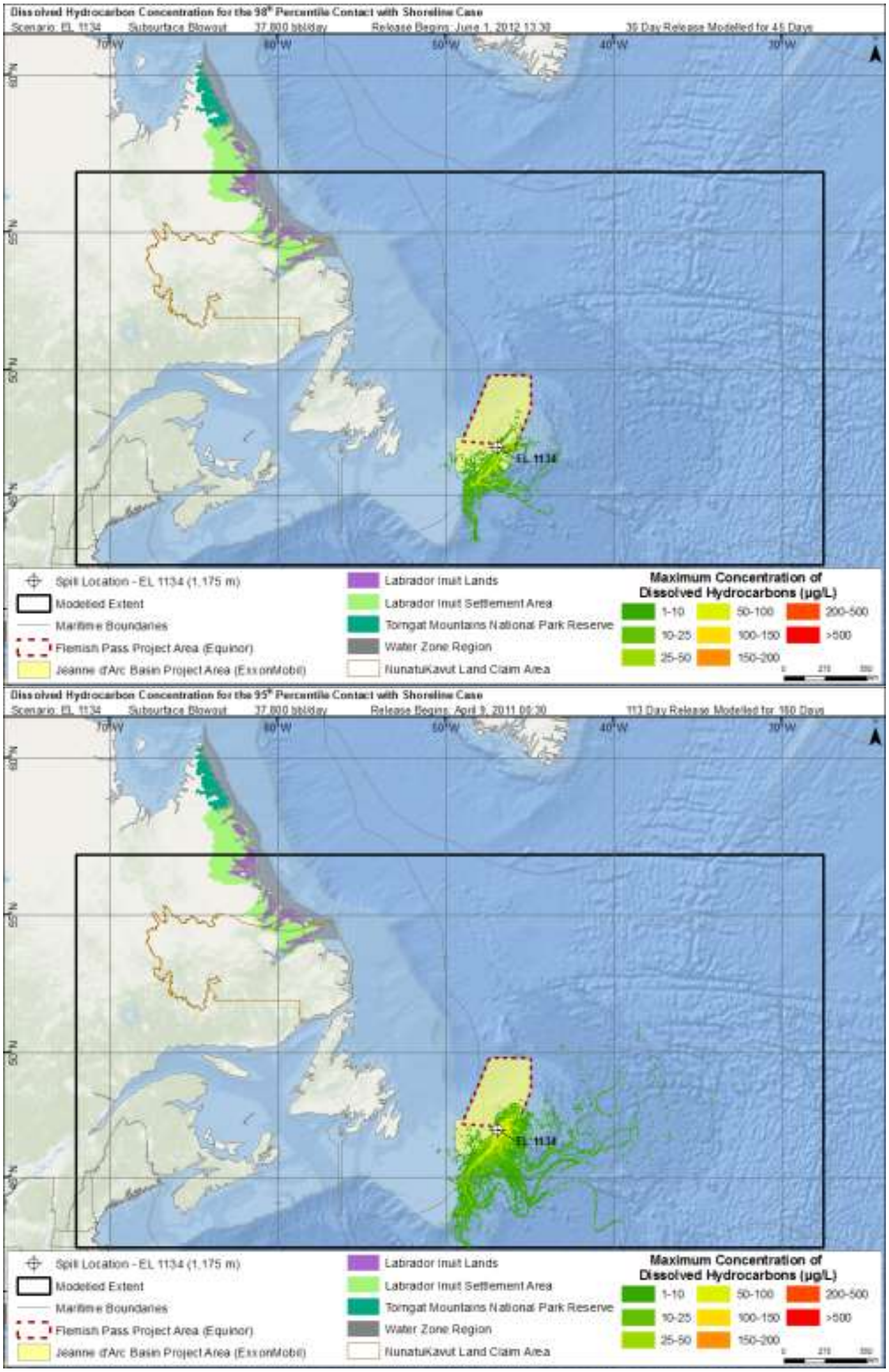


Figure 4-23. Maximum dissolved hydrocarbons at any depth in the water column for the representative worst case for shoreline contact resulting from 30-day (top) and 113-day (bottom) subsurface blowouts at EL 1134.

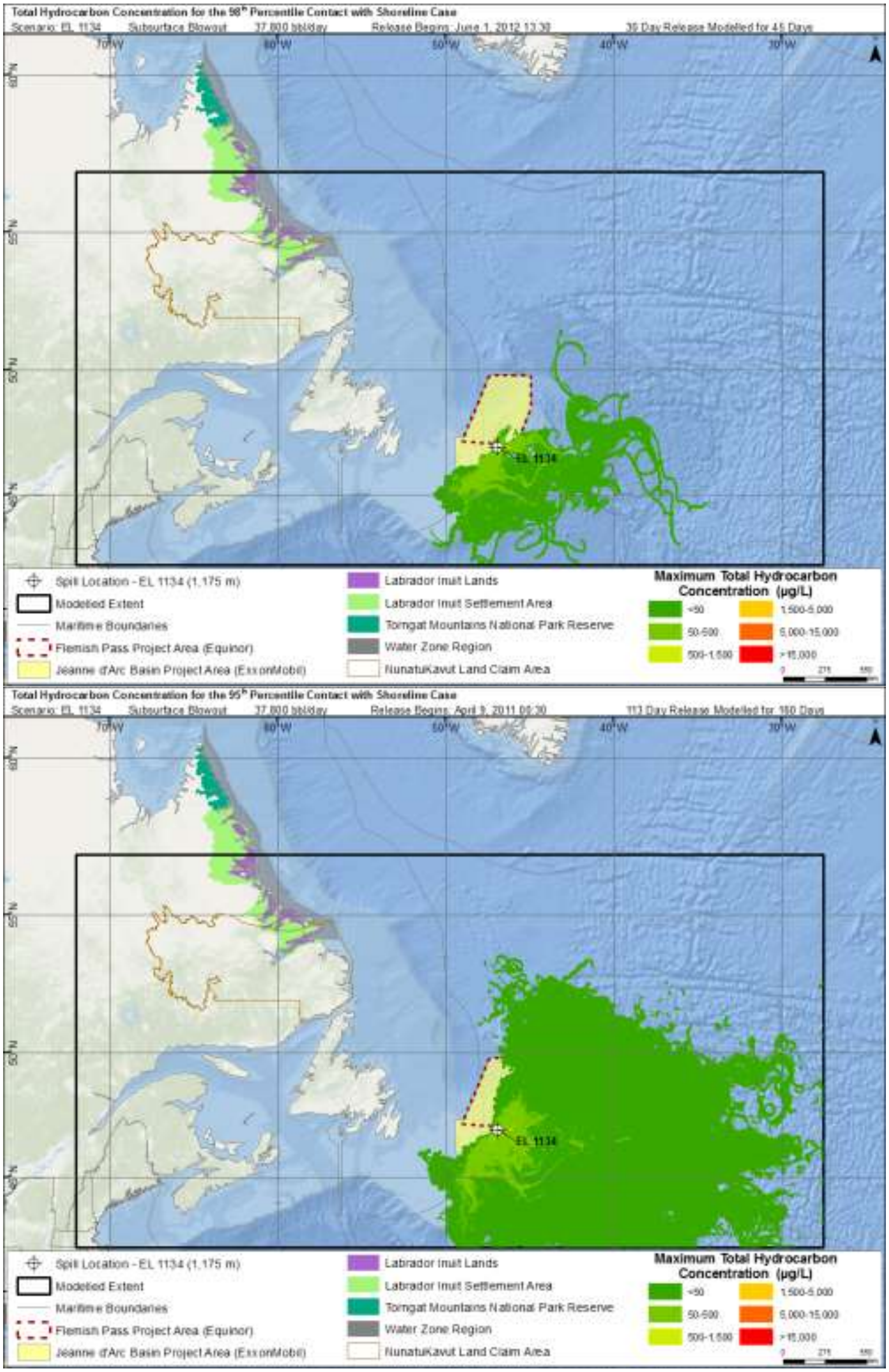


Figure 4-24. Maximum total hydrocarbon concentration (THC) at any depth in the water column for the representative worst case for shoreline contact resulting from 30-day (top) and 113-day (bottom) subsurface blowouts at EL 1134.

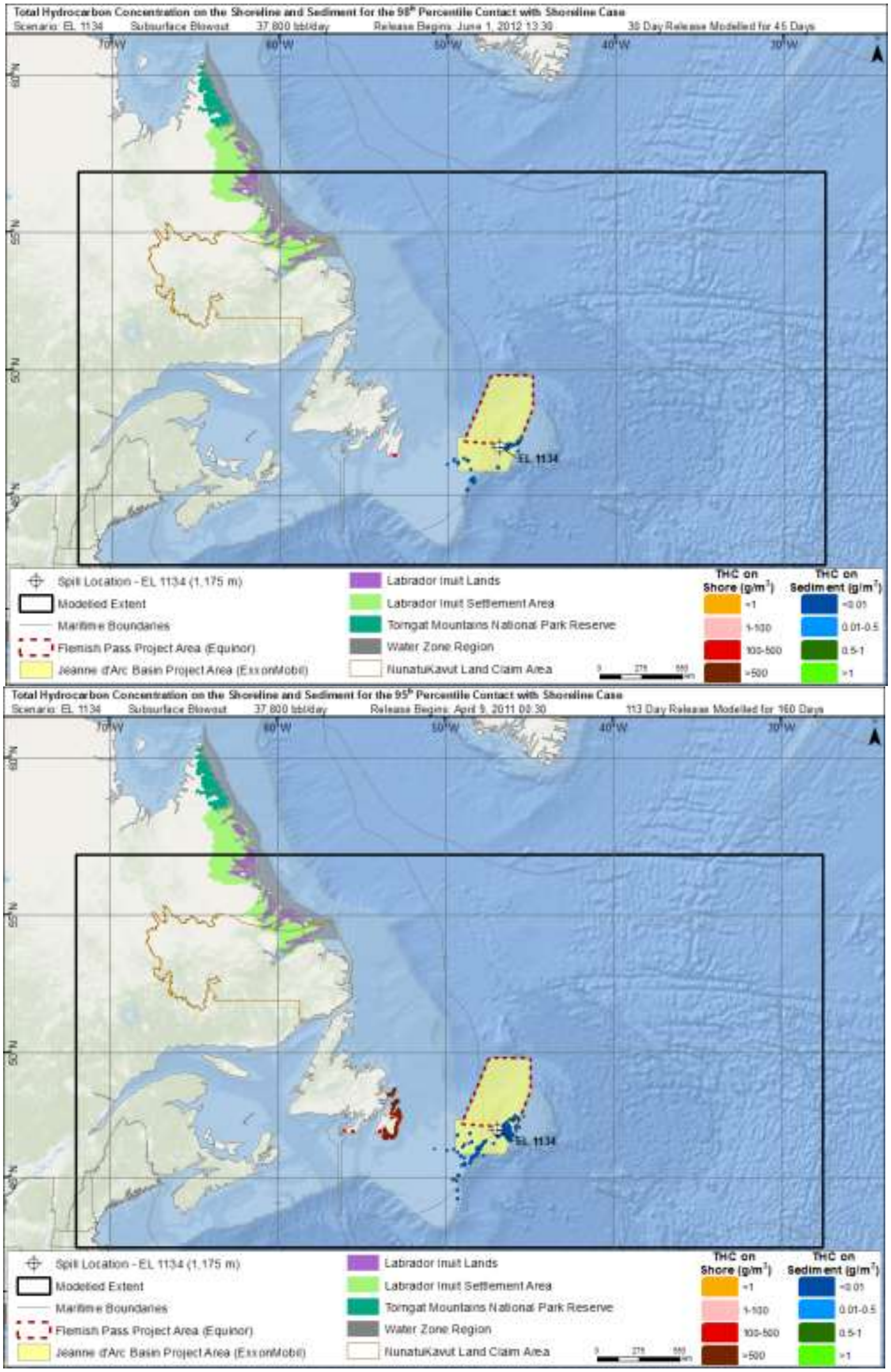


Figure 4-25. Total hydrocarbon concentration (THC) on the shore and sediment for the representative worst case for shoreline contact resulting from 30-day (top) and 113-day (bottom) subsurface blowouts at EL 1134. Only limited shoreline contact was predicted for the 30-day scenario on the Avalon Peninsula.

4.2.2 Batch Spills (100 L and 1,000 L)

Results for the batch spill scenarios (100 L and 1,000 L) at EL 1134 are provided in the figures below (Figure 4-26 through Figure 4-29). Small volume releases of marine diesel were modelled to be representative of spills that could occur during bunkering operations (i.e., transfer from a vessel). The scenarios were selected to occur during the calmest wind-speed period during the summer/ice-free conditions, which would result in the largest amount of oil on the water surface. The selected date for both the 100 and 1,000 L spills was June 15, 2009.

Due to the small release volume and the size of the concentration gridding (1,000 m by 1,000 m), predicted concentrations of dissolved hydrocarbons were not expected at either EL 1134 and thus figures have not been presented below. Furthermore, the predicted concentrations of total hydrocarbons were minimal and located in the immediate vicinity of the release site (Figure 4-28). The predicted THC concentrations were within tens of meters of the surface, as they are the result of entrained oil from wind-induced surface breaking waves within the surface mixed layer. For the smaller (100 L) batch spill, surface oil spread rapidly to a colorless or silver sheen with only 1 km^2 exceeding 0.04 µm on average (Figure 4-27). However, the larger volume release (1,000 L) resulted in predicted surface oil exposure area of 6 km^2 (Table 4-3). Neither of the batch spills were predicted to result in any oil contacting shorelines.

At the end of the 30-day batch spill simulations, <0.01% of the released volume was predicted to remain floating on the water surface, 59-73% evaporated into the atmosphere, 10-12% remained entrained in the water column, <0.01% adhered to suspended sediment, 0% contacted the shore, and 17-28% degraded (Figure 4-26 and Table 4-4).

4.2.2.1 EL 1134 Release Site

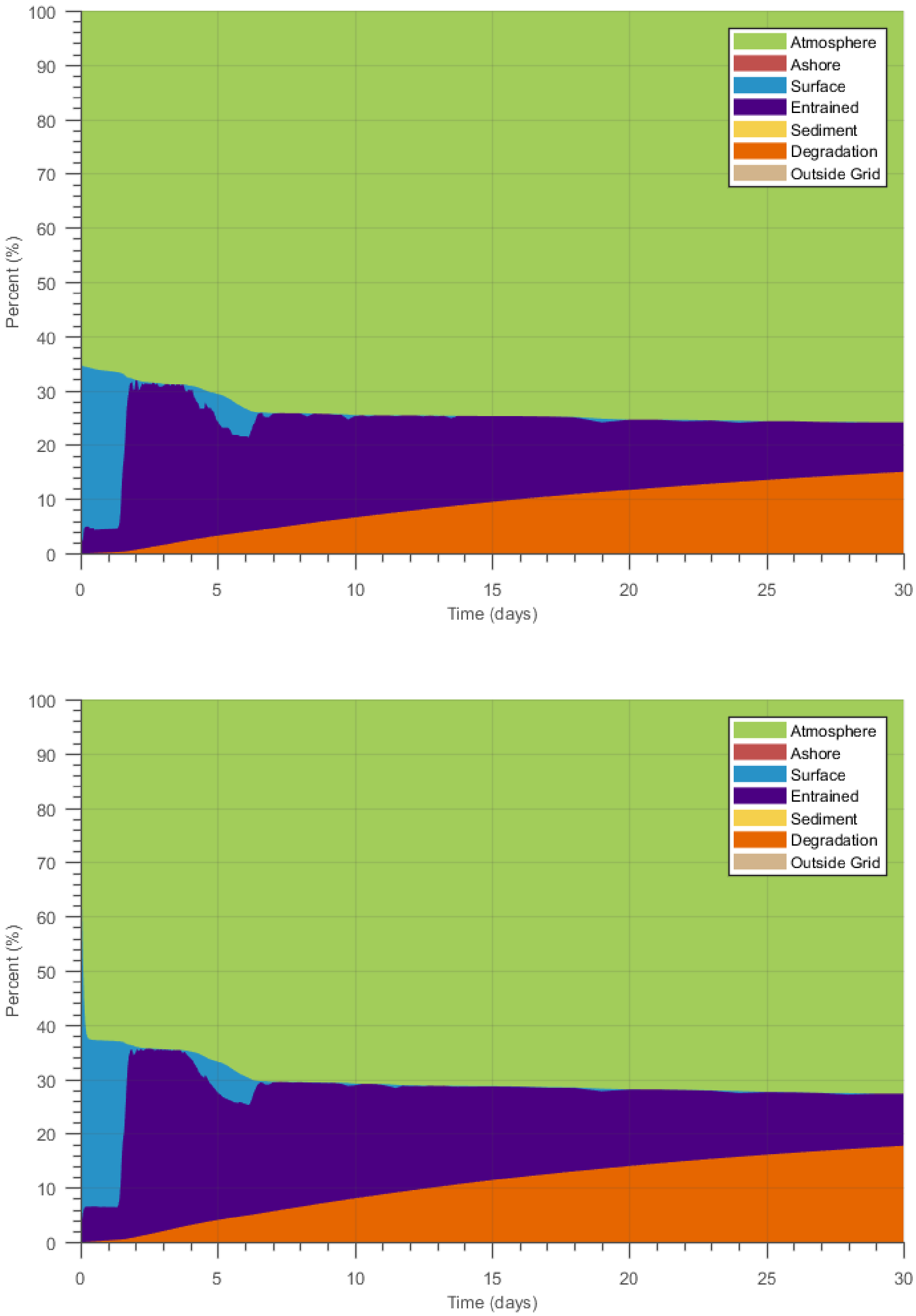


Figure 4-26. Mass balance plots of the EL 1134 release site marine diesel batch spills of 100 L (top) and 1,000 L (bottom).

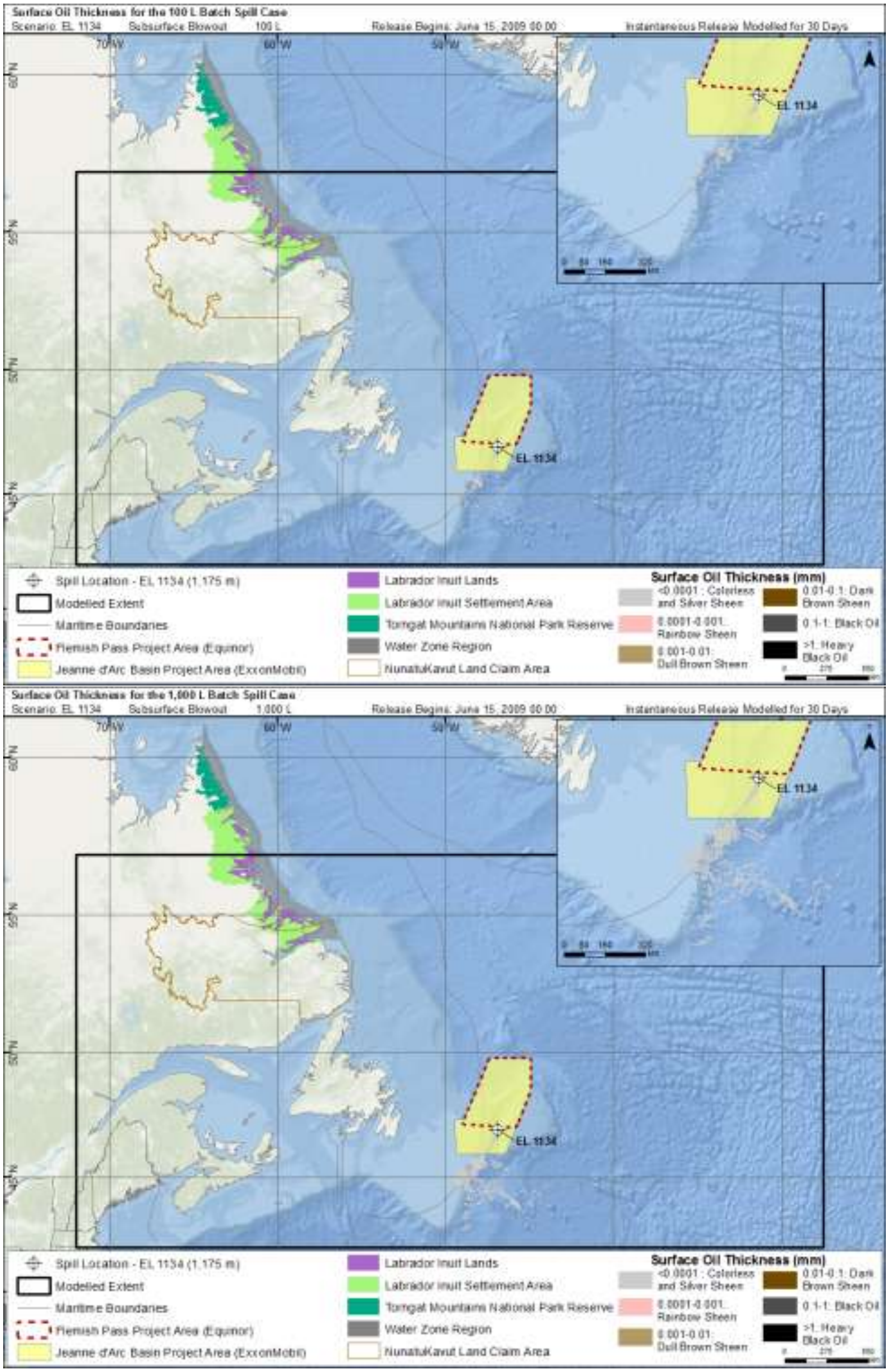


Figure 4-27. Surface oil thickness resulting from the EL 1134 marine diesel batch spills of 100 L (top) and 1,000 L (bottom).

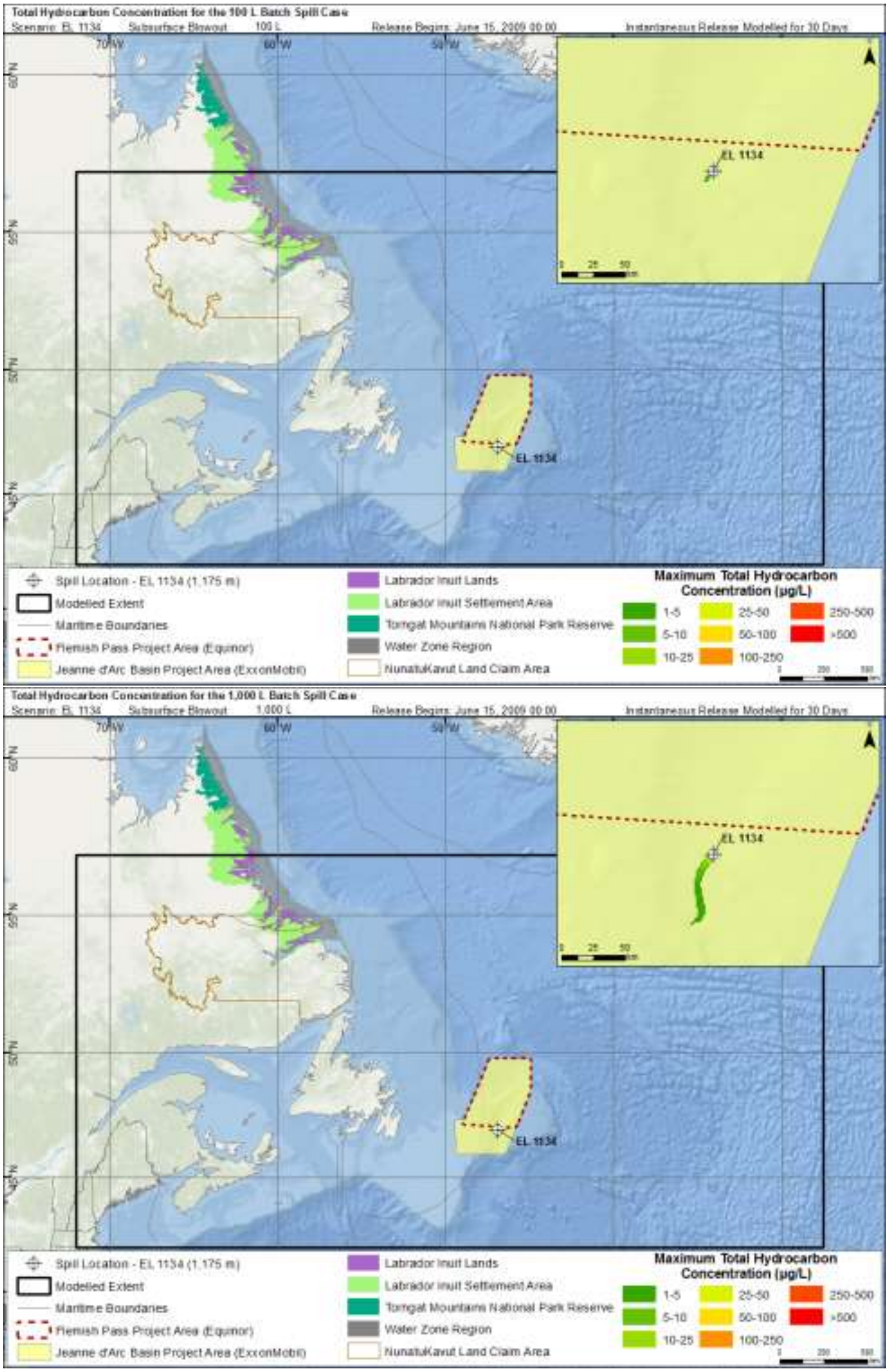


Figure 4-28. Maximum total hydrocarbon concentration (THC) at any depth in the water column resulting from EL 1134 marine diesel batch spills of 100 L (top) and 1,000 L (bottom).

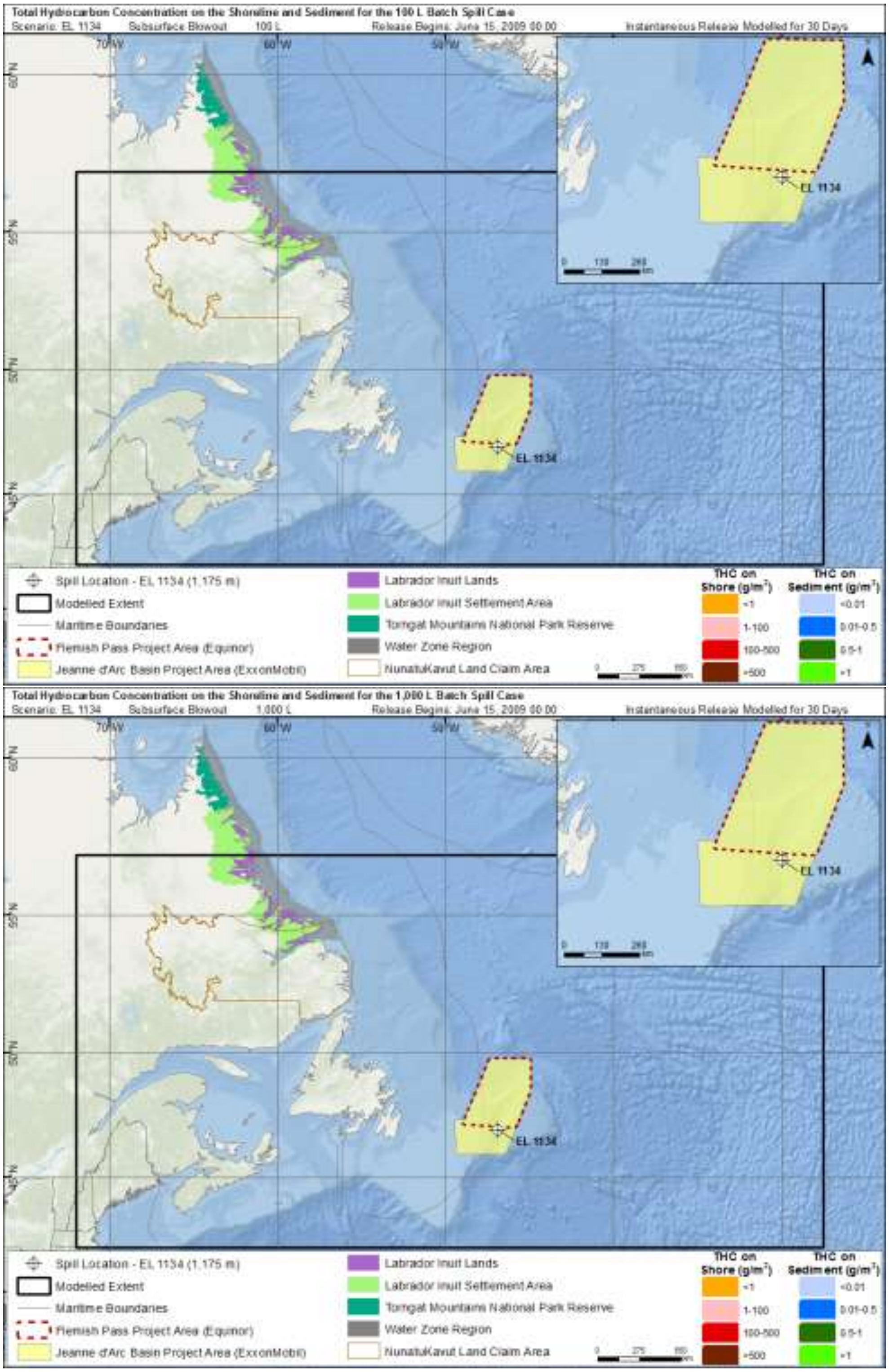


Figure 4-29. Total hydrocarbon concentration (THC) on the shore and sediment resulting from the EL 1134 marine diesel batch spills of 100 L (top) and 1,000 L (bottom).

4.2.3 Summary of Deterministic Results

4.2.3.1 Representative Shoreline Oil

For all representative deterministic scenarios, the amount of oil remaining in surface waters at the end of the simulation was less than 47% for the 30-day release and less than 10% for the 113-day release at EL 1134 (Table 4-4). Entrainment into the water column ranged between 3-8%. Shoreline contact was also limited for these simulations, where even the representative worst care shoreline contact cases were predicted to have less than 0.2% of the total volume of released oil reaching shore. In both simulations, some portions of the oil mass were predicted to travel outside of the model domain. In the 113-day release, up to 18% of the oil left the domain to the south and east, further out to sea.

The longer duration and larger volume release of Ben Nevis at EL 1134 was predicted to result in larger areas of dull brown oil (0.001 – 0.01 mm) and thick dark brown oil (0.01 – 0.1 mm) compared to the shorter, smaller volume release which was predicted to result in a smaller region of both the thinner dull brown sheens and dark brown oil (Figure 4-22). The area of surface oil exposure (>0.04 µm) for the 113-day representative worst case (~2,000,000 km^2) is about five times larger than that of the 30-day representative worst case (~500,000 km^2) (Table 4-3).

In both cases, a large proportion of the surface oil was predicted to either entrain, evaporate, or degrade by the end of the simulation (Table 4-4). The representative worst case scenarios represent what may be anticipated from a 'worst case' blowout, where the environmental conditions happen to be such that potential exposure is maximized. Note that all scenarios assume a completely unmitigated full bore release, which is an unlikely situation. Response efforts would likely be implemented within hours to days following a release. For surface oil, both the 30-day 98th percentile release (no shoreline oil occurred in the 95th percentile case) and 113-day 95th percentile release cases at EL 1134 occurred during the summer season (defined as ice-free for more than half the days of the model run).

The maximum subsurface water volume exposed to THC concentrations (cells are approximately 2 km by 2 km by 50 m) for the 113-day 95th percentile shoreline case is nearly four times larger than the volume exposed for the 30-day 98th percentile case (Table 4-3). A region of >100 µg/L dissolved hydrocarbon concentration was predicted to be transported primarily to the south-southwest a distance of roughly 200 km from the release site in both the 30- and 113-day representative worst cases (Figure 4-23).

The predicted shoreline contact from the 30-day release occurred in a localized region on the south eastern tip of the Avalon Peninsula, whereas the contact from the 113-day release was predicted to extend along the entire eastern portion of the Avalon Peninsula and to the north and south onto the main island of Newfoundland (Figure 4-25). The length of shore where shoreline contact exceeds the 1 g/m^2 threshold from the 30- and 113-day shoreline exposure scenarios was predicted to span approximately 15 km and 807 km, respectively (Table 4-3). In contrast, shoreline oil comprises an extremely small portion of the total mass of released oil (<0.2%) (Table 4-4).

4.2.3.2 Marine Diesel Batch Releases

To simulate accidental discharges from operational vessels, two batch releases of marine diesel were modelled as instantaneous surface releases. Releases of 100 L and 1,000 L were modelled for thirty days at the EL 1134 site. The marine diesel is a standard diesel that has a low viscosity and a high aromatic content and is predicted to evaporate quickly during the summertime releases.

The predicted cumulative area of average surface oil thickness >0.04 µm threshold extended primarily southwest of the release site, in a patchy distribution of <0.0001 mm (0.1 µm) average thickness (Figure 4-27). For the 100 and 1,000 L release volumes, floating oil reached about 400 to 525 km, respectively, southwest of the release site (Figure 4-27). The relatively large distance traveled by the surface oil is likely due to the location of the site within the Flemish Pass, where the strong Labrador Current branches off around the Grand Banks, as well as the surface winds in the region. However, for the smaller volume release (100 L), the surface oil exposure exceeding 0.04 µm area was 1 km^2 while for the larger volume release (1,000 L), the surface oil exposure area was larger, at 6 km^2 (Table 4-3). The areas where the vertical maximum THC concentrations in the water column were predicted to exceed the 1 µg/L threshold extended directly southwest from the release site, approximately 8 and 40 km for the 100 L and 1,000 L spills, respectively (Figure 4-28). Vertical maximum concentrations for the larger volume release reached nearly 60 µg/L in the immediate vicinity of the release site. Note that for the marine batch release cases, the water column contamination was measured as THC, not as dissolved hydrocarbons as in the other deterministic and stochastic scenarios; this is because the release volumes were so small that the concentrations of dissolved hydrocarbons in the water column (which comprise a very small portion of THC) were too low to portray in figures due to the concentration grid resolution.

Based on the mass balance plots (Figure 4-26), oil was predicted to entrain quickly in the 100 L and 1,000 L cases at the EL 1134 site, with 54-66% evaporated and only 1-2% on the surface at 24 hours after the release. Some of the entrained oil was predicted to resurface a few days later, but after seven days nearly all of the surface oil was either evaporated, entrained, or degraded. For both cases, less than 0.01% of oil remains in the surface by the end of the 30-day simulation, with the majority evaporated (60-73%) and the rest degraded (17-28%). No oil from batch releases at the EL 1134 site was predicted to make contact with the shore or leave the model domain (Table 4-4).

Table 4-3. Representative deterministic scenarios and associated areas exceeding specified thresholds (km^2) for the representative worst case shoreline contamination trajectories and 100 L and 1,000 L batch spill trajectories.

Scenario Name	Site	Released Volume	Approximate Surface Area exceeding thickness thresholds (km^2)		Approximate Shore Length exceeding mass per unit area thresholds (km)		Approximate Subsurface Volume exceeding THC threshold (km^3)
			Socioeconomic (0.04 µm)	Ecologic (10 µm)	Socioeconomic (1 g/m^2)	Ecologic (100 g/m^2)	Socioeconomic (1 µg/L)
98th percentile shoreline contact case – 30 d	EL 1134	1,134,000 bbl	457,300	226,300	15	15	18,930
95th percentile shoreline contact case – 113 d		4,271,400 bbl	2,316,000	750,400	807	767	72,200
100 L marine diesel batch spill		100 L	1	-	-	-	<1
1,000 L marine diesel batch spill		1,000 L	6	-	-	-	5

Table 4-4. Summary of the mass balance information for all representative scenarios. All values represent a percentage of the total amount of released oil.

Summary of Mass Balance Information at the End of the Simulation (Percentage of Released Oil)									
Scenario Information			Surface (%)	Evaporated (%)	Water Column (%)	Sediment (%)	Ashore (%)	Degraded (%)	Outside Grid (%)
Site	Scenario	Product							
EL 1134	30-day 98th percentile shoreline contact case	Ben Nevis	46.94	26.30	7.48	<0.01	0.01	19.25	0.03
	113-day 95th percentile shoreline contact case		10.43	29.61	2.66	<0.01	0.19	38.78	18.33
	100 L Batch Spill	Marine Diesel	0.00	73.03	9.52	<0.01	0.00	17.45	0.00
	1,000 L Batch Spill		0.01	59.51	11.99	<0.01	0.00	28.45	0.00

5 Discussion and Conclusions

Generally, most surface oil from the hypothetical release locations was predicted to move eastward due to the prevailing westerly winds. Winds and currents in the Project Area are similar throughout the year, with most notable differences in wind intensity. The increased winds during wintertime conditions have the potential to enhance surface breaking waves and results in more entrainment of oil, which lowers the likelihood that oil will remain on the surface for extended periods of time. The maximum shoreline probability was 5% for the 30-day releases and 25% for the 113-day releases. Minimum time estimates for first shoreline oil exposure ranged from approximately 8-27 days for both the 30- and 113-day releases. For both releases, shoreline contact was predicted to be more likely to occur during winter scenarios, due to the increased wind speeds. The shoreline contact that did occur was predicted to be localized to regions of the Avalon Peninsula and portions of the island of Newfoundland to the south and north of the Avalon Peninsula.

The releases modelled in this study may be considered representative of other potential releases in the Project Area. The depth of release of the EL 1134 site (1,175 m) is within the range found in the Project Area.

The hypothetical releases modelled in this study are not intended to predict a specific future event, but rather to be used as a tool in environmental assessments and release contingency planning. The results presented in this document demonstrate that there are a range of potential trajectories and fates that could result if a release of crude oil or a batch spill of marine diesel were to occur, and those trajectories and fates vary based upon the environmental conditions occurring at the time. While each oil release is unique and therefore uncertainties exist, the results of this modelling study suggest that if oil were to be released in the Project Area, it has the highest likelihood of moving away from shore to the east.

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