SUNCOR ENERGY OFFSHORE EXPLORATION PARTNERSHIP TILT COVE EXPLORATION DRILLING PROJECT 2019-2028
19-P-204239

Oil Spill Trajectory and Fate Assessment

Oil Spill Risk Assessment

Suncor Energy

Tilt Cove Exploration Drilling Project 2019-2028

19-P-204239

January 20, 2020

www.rpsgroup.com

Document Status

Version	Purpose of document	Authored by	Reviewed by	Approved by	Review date
Draft Report	Oil Spill Trajectory and Fate Assessment: Technical Report	LM, PA, ST, KR, TT, MF, JD, PA, MH	MH	MH	January 20, 2020
Internal Draft	Oil Spill Trajectory and Fate Assessment: Technical Report	LM, PA, ST, KR, TT, MF, JD, PA, MH	LM	LM	January 17, 2020

Approval for issue

<Original signed by>

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EXECUTIVE SUMMARY

Study Summary

Oil spill trajectory and fate modelling was performed to support an Environmental Impact Statement (EIS) for the Suncor Energy Exploration Drilling Project 2019-2028 in the Jeanne d'Arc Basin area. Hypothetical releases were modelled at one location approximately 325 km east-southeast of St. John's, Newfoundland, immediately west of the Terra Nova oil and gas field. Two hypothetical subsurface blowout scenarios were developed within the Project Area, which contains the block of interest; Exploration License (EL) 1161. Hypothetical releases were modelled as unmitigated subsurface blowouts of Terra Nova crude oil. The subsurface blowouts were simulated as continuous 30- and 120-day releases, with a total simulation duration of 160 days. The 120-day releases conservatively represent the anticipated time to kill the well (effectively stopping the subsurface release) by mobilizing a drilling platform and drilling a relief well, while the 30-day release represents the successful mobilization and implementation of a capping stack to contain the release. The estimated release rates of hydrocarbons simulated in the subsurface blowout scenarios were conservative (i.e., high) based on the current knowledge of the reservoir and other subsurface properties associated with the blowout scenario. An additional near-instantaneous, 1,000 L release of marine diesel was modelled as a batch spill for 30 days at EL 1161.

Study Goals

There were several goals of the modelling study. A stochastic assessment was used to provide an understanding of the probability and minimum time to exposure from unmitigated releases of oil. Separate highly conservative thresholds were investigated for oil on the water surface, concentrations of hydrocarbons in the water column, and oil on shorelines. The goal was to identify the areas that may be susceptible to contamination as well as the associated minimum time to exposure based upon variable environmental conditions (i.e., seasonal and interannual variability was assessed using >100 simulated releases). To conservatively determine the approximate magnitude of potential contamination from a single credible "worst-case" scenario (i.e., with spatially- and temporally-varying concentrations, rather than simply the knowledge of a threshold exceedance), three individual deterministic scenarios were selected from each stochastic simulation to represent 95th percentile maximum potential effects within each of three environmental compartments. These highly conservative 95th percentile scenarios were identified from the area of surface oil, volume of oil in the water column, and the length of shoreline oiled.

Models

In order to reproduce the dynamic and complex processes associated with deep subsea blowout releases, two models developed and maintained by RPS 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 within OILMAPDeep was used to characterize the size and distribution of oil droplets, including the associated mass of oil being released at specific water depths, where the oil jet and buoyant plume traps as an intrusion and the droplets rise by buoyancy alone. The output data from OILMAPDeep was then used to initialize the SIMAP model, which simulated the far-field trajectory, fate, and potential exposure of various environmental compartments within the marine environment following a release.

Geographical Data

Geographical data including habitat mapping and shoreline identification and classification were obtained from multiple data sources. For Canadian areas, province-specific data from the New Brunswick Department of Natural Resources and Nova Scotia Department of Natural Resources were used, as well as high-resolution data covering Canadian shorelines from Environment and Climate Change Canada. 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).

Wind and Currents

Wind data for this study were obtained from the U.S. National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) and Climate Forecast System Version 2 (CFSv2) models. Currents for the North Atlantic region were acquired from the U.S. Navy Global HYCOM (HYbrid Coordinate Ocean Model) circulation model. All data were acquired and used for the period between January 2006 and December 2012. This corresponded with the most recent long term (7 year) reanalysis period, meaning the same code-base (which is updated regularly) was used to drive a hind-cast of the coupled hydrodynamic and wind model. In essence, variability within this dataset would be associated with natural environmental variability and not any changes to the way the met-ocean modelling was conducted.

Stochastic Analysis

A stochastic analysis was conducted for each hypothetical unmitigated subsurface blowout, consisting of 171 individual modelled simulations within each stochastic scenario. Stochastic simulations included continuous unmitigated 30- and 120-day Terra Nova crude blowouts at EL 1161. Each simulation 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 each 14-day interval spanning the entire seven years of data. Results of the stochastic analysis included probability footprints above specified highly conservative, socio-economic thresholds for surface, water column, and shoreline contact and minimum time to oil exposure that may result in potential effects (i.e., acute mortality) within each environmental compartment.

Socio-economic thresholds:

- Surface oil average thickness >0.04 µm,
- Subsurface (within the water column) dissolved hydrocarbon concentrations >1.0 µg/L,
- Shore oil average concentration >1.0 g/m^2.

Because each set of stochastic simulations spanned seven full years and included the associated seasonal variability, the complete set was referred to as annual summaries. To investigate seasonality, results from stochastic analyses were broken into two seasons depending on the majority of modelled days falling within either ice free conditions (i.e., summer) from May through October or periods with ice-cover (i.e., winter) from November through April.

It is important to note that although large footprints of oil 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 specific threshold passing through each grid cell location in the model domain at any point over the entire model duration (i.e., 160 days for the subsurface blowouts), based on the entire ensemble of simulations (171 individual releases). Only probabilities of 1% or greater were included in the map output, as lesser probabilities represent random variability in the set of 171 trajectories. Stochastic maps of water column exposure depict the likelihood that dissolved and total hydrocarbon concentrations are predicted to exceed the identified threshold at any depth within the water column (i.e., vertical maximum). However, these figures do not specify the depth at which this threshold exceedance occurs and do not imply that the entire water column (i.e., from surface to bottom) will experience a concentration above the identified threshold.

Deterministic Analysis

Representative deterministic scenarios (i.e., single trajectory) were identified from each set of stochastic results of subsurface blowouts. Individual scenarios were selected based upon the size of the surface oil footprint, the concentration of dissolved hydrocarbons in the water column, and the length of shoreline contacted with oil, contingent upon the set of highly conservative socio-economic thresholds mentioned above.

The selected cases for deterministic analysis included the identified 95th percentile scenarios for surface oil footprint (by area), water column concentration (by volume), and shoreline oil length predicted to be affected by the subsurface releases. Additionally, the mass balance and surface oil footprint for the batch release of marine diesel are provided.

Results

Stochastic results are useful in planning for oil spill response as well as environmental assessments, as they characterize the probability that regions may experience oil exposure above specified thresholds, taking into account the environmental variability that is expected. Many release scenarios were simulated over multiple years to capture the different environmental forcing (e.g., variable wind and current speed and direction) that may be possible. Stochastic analyses were used to demonstrate that the highest potential likelihood (>90%) to exceed thresholds of potential surface oil exposure and water column contamination by dissolved hydrocarbons primarily occurred to the east, up to 1,500 km from the release site. In essence, prevailing winds and currents were most likely to force released oil to the east, away from Canadian shorelines. Water column probability footprints were smaller than surface oil footprints, where the probability of threshold exceedance decreased as distance from the release site increased. In nearly all stochastic scenarios, lower probabilities of threshold exceedance are predicted for surface and water column oil contamination to the north and south. The predicted high probability contours for surface oil thickness were much greater during winter months, when the temperature was lower than the pour point of the Terra Nova crude oil and surface oil remained thick, as it did not spread.

Due to the predominantly eastward transport of oil and the distance of EL 1161 to Canadian shorelines, the average probability of shoreline oiling above the identified threshold was low, with a maximum average probability of 4 to 9% (depending on the season and release duration) for a single shoreline grid cell from the 30- and 120-day releases, respectively. However, maximum probabilities of shoreline oil contamination ranged from 18-45% depending on the release scenario and season, focused on the Avalon Peninsula. The Azores had a <10% chance of shoreline oiling predicted. The currents in the region were predicted to further reduce the potential for Canadian shoreline exposure to oil, due primarily to the bathymetric steering along the continental shelf. As the Labrador Current flows southward along the continental shelf, it would be predicted to transport entrained oil parallel to the coast. However, this trend was generally absent in the surface oil predictions, as wind forcing typically transported oil to the east, further out to sea. Oil that does make its way to Canadian shorelines would likely be patchy and discontinuous due to the considerable weathering that would take place over the span of weeks to months. Predicted minimum time to shoreline threshold exceedance was 9-28 days along southeastern Newfoundland.

For most representative credible “worst-case” deterministic scenarios at EL 1161, natural degradation processes (evaporation and biological degradation) weathered the majority of oil over the 160-day model simulations. The highly volatile nature and large proportion of lower molecular weight compounds in the Terra Nova crude oil resulted in large percentages of evaporated (25-29%) and degraded (51-59%) oil, accounting for up to 87% of each modelled release over each 160-day simulation. The amount of oil predicted to remain on the water surface or within the water column after 160 days totaled less than 3%, understanding that entrainment and resurfacing can result in surface and entrained oil “see-sawing” between the two environmental compartments based upon wind/wave conditions on hourly time-scales. Less than 3.4% of oil (predominantly persistent surface oil) was predicted to be transported by winds outside the model domain (primarily to the east) over the 160-day simulation. As noted above, the shoreline oiling was predicted to be 4-9% on average, with a maximum of ~45% for the Avalon Peninsula. The maximum amount of oil predicted to strand on shorelines was 0.4% of the total release for the 95th percentile shoreline oil exposure case. For the 30- and 120-day representative shoreline oil exposure cases, shoreline oil contamination was predicted to range from approximately 1,461 to 1,493 km, respectively. Oil transported to the sediment was not a major fate pathway for these completely unmitigated offshore subsurface blowouts with <0.01% of the total release predicted to settle on sediments. Note that all scenarios assumed a completely unmitigated release, which is an unlikely situation, as emergency response tactics would typically be employed in the event of a spill within hours to days of the release.

The batch spill release of 1,000 L marine diesel was predicted to result in oil floating on the water surface with the visual appearance of silver or colorless sheens (<0.0001 mm). Based upon the environmental conditions modelled, marine diesel was predicted to be transported south and west (within 175 km) of the release location. However, this small amount of oil was at thicknesses below the socio-economic threshold.

The hypothetical releases modelled in this study are not intended to predict a specific future event, but rather are intended to be used as a tool in environmental assessments and spill 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 at any point throughout the year. The specific trajectories and fates vary greatly for each release based upon the environmental conditions occurring at the time of the release. While each oil release is unique, and uncertainties exist, the results of this modelling study suggest that, if oil were to be released in EL 1161, it has a high likelihood of moving away from shore to the east with less likelihood of shoreline oil exposure. Furthermore, this modelling assumes completely unmitigated releases, which is an unlikely situation because emergency response measures would typically be employed in the event of a spill.

Document Summary

This report includes an introduction describing the region, the modelling approach, the methodology, and finally the predicted modelling results of the study. The model results are summarized in figures and tables in the main body of this document, describing the potential for oil exposure on the water surface, within the water column, and along shorelines. This document is broken down into several sections.

- Section 1 – Introduction
- Section 2 – Background and Scenarios, including description of Regional Area and Project Area, modelling approach with the OILMAPDeep and SIMAP models, scenarios, and uncertainty
- Section 3 – Model Input Data
- Section 4 – Model Results, including both stochastic and deterministic oil trajectory and fate simulations
- Section 5 – Discussion and Conclusions
- Section 6 – References

Appendix A – additional information including a detailed description of the OILMAPDeep and SIMAP models, fate processes, and algorithms used.

Contents

Tables

Figures

1 INTRODUCTION

RPS conducted trajectory and fate modelling to support an Environmental Impact Statement (EIS) for the Suncor Energy Tilt Cove Exploration Drilling Project 2019-2028. Hypothetical blowout releases were modelled at one location in the Jeanne D'Arc Basin, located immediately west of Suncor's Terra Nova oil field. The Project Area is located approximately 325 km east-southeast of St. John's, Newfoundland on the eastern edge of the Grand Banks and approximately 100 km west of the Flemish Pass. Modelling was performed within the Exploration License (EL) 1161 at the Tilt Cove Project Area with drilling and production activities in waters that are roughly 100 m deep. 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 in the Jeanne D'Arc Basin within EL 1161. Modelling included large-scale, long-duration, shallow-water blowouts of a Terra Nova light crude oil from the wellhead at the seafloor and a smaller scale surface batch spill of marine diesel. All releases were modelled as completely unmitigated, implying that no response efforts (e.g., subsurface dispersant injection, aerial dispersant application, burning, etc.) were undertaken during the modelled time period. 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, with the goal to predict the magnitude and extent of potential for surface oil, subsurface contamination, and shoreline oiling. The nearfield OILMAPDeep blowout model and the far-field Spill Impact Model Application Package (SIMAP) oil trajectory, fate, and potential effects model were used. These state-of-the-art models were developed and are maintained by RPS. This report provides a description of the Project Area, modelled hypothetical release scenarios, an overview of the modelling approach, details about the model input data that were used, and a presentation and discussion of the predicted model 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 Tilt Cove Project Area is located within Exploration License (EL) 1161, approximately 325 km east-southeast of St. John's, Newfoundland on the eastern edge of the Grand Banks immediately west of Suncor's Terra Nova oil field (Figure 2-1). This biologically productive region sits atop substantial petroleum resources, with the Hibernia and White Rose fields in close proximity. Bathymetry is consistently approximately 100 m within the area, as it is over much of the Grand Banks. Therefore, the water depth at the proposed site selected for modelling was 100 m. The model domain extends as from 35°N to 60°N and 72°W to 15°W, encompassing Canadian, U.S., and International waters, including the Azores. This modelled extent is much larger than the Project Area, as hypothetical releases of oil were to be tracked for long periods of time (160 days).

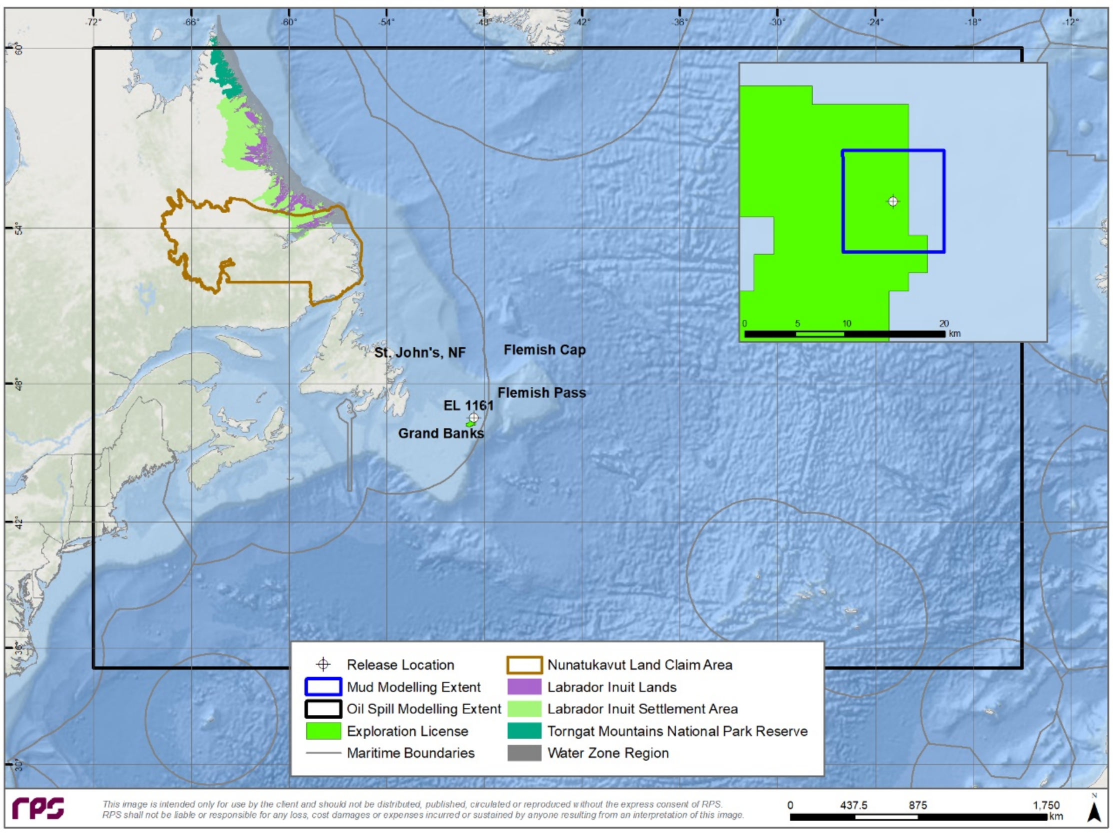


Figure 2-1. Project Area, including the hypothetical release location for the subsurface blowouts (EL 1161).

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 a site east of Newfoundland (Table 2-1 and Table 2-2). Stochastic modelling provides a probabilistic view of the likelihood that a given region might be exposed to released hydrocarbons over specified thresholds as well as the minimum time it may take for those threshold exceedances. Because stochastic analyses include >100 simulated releases with different start dates throughout a year and over multiple years, they provide a range of possible trajectories based upon variable environmental conditions. Deterministic analyses provide views of the time-history of individual releases including the spatially- and temporally-varying movement and behavior of released oil from specified individual releases (i.e., representative credible "worst cases"). Deterministic scenarios provide an understanding of the predicted spatial and temporal variability in thicknesses, concentrations, and mass within each environmental compartment. Together, these methods provide a more complete view of the likelihood, timing, and degree or magnitude of potential exposure.

Two hypothetical blowout release scenarios were modelled for 160-day periods to simulate short (30-day) and long (120-day) duration blowouts. The 120-day release represents the anticipated time to kill the well (effectively stopping the subsurface release) by mobilizing a drilling platform and drilling a relief well, while the 30-day release represents the successful mobilization and implementation of a capping stack to contain the release. The total model duration of 160 days was used to track the trajectory and fate of spilled product as it continued to weather after the releases had stopped.

Predicted surface oil thickness, dispersed oil in the water column, and shoreline oil mass exceeding specified thresholds for the full year (i.e., annual) are provided along with seasonal breakdowns associated with variable ice-cover conditions (i.e., summer/ice-free and winter/ice-covered). Individual deterministic trajectories that characterize single release scenarios are also presented and are associated with representative credible "worst-case" scenarios from each stochastic simulation (i.e., 95th percentile "worst-case" for surface oil, subsurface contamination, and shoreline oiling) (Table 2-2). Stochastic analysis of hypothetical blowouts were modelled using the physical-chemical properties of a crude oil and seven years of variable environmental data, which are discussed further in Section 3. The hypothetical release location is located within the Jeanne D'Arc Basin (Figure 2-1). A total of 171 individual oil spill trajectories were modelled for each scenario as unmitigated subsurface releases with randomized start dates/times within each two-week time period making up the seven-years (2006-2012) modelled here (Table 2-1). Each stochastic scenario included 82 winter and 89 summer simulations. The duration of each simulation within the stochastic scenarios was 160 days.

Additionally, a diesel deterministic release (1,000 L) was analyzed to evaluate a potential discharge of marine diesel on the surface associated with a batch spill that could occur.

In total, 343 individual releases were simulated within this assessment with a goal of capturing environmental variability and resulting differences in the movement and behavior of oil following unmitigated subsurface short- and long-duration releases within each exploration lease as well as a marine diesel release offshore.

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

Hypothetical Release Location	Release Location (Lat, Lon)	Release Type	Water Depth (m)	Release Duration	Model Duration	Number of Model Runs	Released Product	Release Volume
EL 1161	46.546252 ºN 48.618508 ºW	Subsurface Blowout	100 m	30 days	160 days	171	Terra Nova Crude	555,012 m^3 Day 1: 20,000 m^3/day Day 30: 17,000 m^3/day
				120 days	160 days	171	Terra Nova Crude	1,661,574 m^3 Day 1: 20,000 m^3/day Day 120: 7,693 m^3/day

Table 2-2. Site and release information used for the deterministic scenarios.

Scenario Parameter	Release Parameters for Representative Deterministic Scenarios			
	Identified from Stochastic Results 95th Percentile*			Batch Spill
Representative Scenario	Surface Oil (area)	Water Column (volume)	Shoreline (length)	Bunkering Accident
Release Site	EL 1161			EL 1161
Release Type	Subsurface Blowout			Batch Spill
Depth of Release	100 m			Surface Release
Released Product	Terra Nova Crude			Marine Diesel
Release Rate	Day 1: 20,000 m^3/day Day 120: 7,693 m^3/day			1,000 L
Release Duration (Model Duration)	120 Days (160 Days) & 30 Days (160 Days)			Instantaneous (30 Days)
Total Release Volume	1,661,574 m^3			1,000 L

*The 95th percentile "worst-case" scenarios for surface, water column, and shoreline were identified from each of the two stochastic scenarios and modelled as three separate deterministic simulations per stochastic scenario. In total, six deterministic scenarios were run for the subsurface blowouts at EL 1161.

2.2.1 Modelling Tools

Hypothetical release scenarios were simulated using the OILMAPDeep blowout model and the SIMAP oil trajectory, fate, and effects model, both developed and maintained 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 near-field plume dynamics are modelled to predict the mass, location, and droplet size distribution of the subsurface oil droplets at the termination (i.e., trap) height, where the oil jet and buoyant oil and gas plume are “trapped” and form an intrusion. The depth of the trap height is dependent upon the environmental conditions, the specific chemical and physical properties of the oil, and other release parameters. Typically, the near-field model considers timescales of seconds and length scales of hundreds of meters, whereas the far-field model considers many days and months (at 30-minute time steps) and length scales of tens, hundreds, and even thousands 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, a plume model and a droplet size model. The plume model predicts the evolution of the plume position, geometry, centerline velocity, and oil and gas concentrations until the plume either surfaces or reaches a terminal height (i.e., trap height). During a subsea blowout in deep water, an oil jet and buoyant plume carries oil and gas upwards to a water depth (or depths) where, due to the ambient density gradient in the ocean, the buoyant plume is arrested, or “trapped” and forms an intrusion (Socolofsky et al. 2011, 2015). Oil droplets are released from the intrusion to the water column above, where they subsequently rise (buoyancy) and are transported by ambient currents. The trap height is typically a few hundred meters above the release depth (Socolofsky et al. 2015). 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, the hydrate formation, and the 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 fate processes, such as oil rise velocity and dissolution.

For oil discharged during a deep-water blowout, the oil droplet size distribution profoundly effects how oil is transported and behaves after the initial release as a buoyant plume. The size of the individual droplets dictates buoyancy, which controls rise rate and the associated 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 (due to less buoyancy and increased drag) and are subjected to subsurface advection-diffusion processes. The small droplets are therefore transported within the water column for a longer period of time. As oil is transported by subsurface currents away from the release location, natural dispersion and degradation of the oil droplets will reduce 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. The surface area to volume ratio of smaller droplets is much larger than that of larger droplets. Therefore, with such a large exchange interface, a larger portion of the soluble fraction of hydrocarbons within the smaller droplets will dissolve into the water column and at a higher rate than that of larger oil droplets. Details of the OILMAPDeep model background theory, inputs, algorithms, and outputs can be found in Appendix A.

SIMAP Model

The SIMAP model is a state-of-the-art oil trajectory, fate, and effects model that was developed by RPS and is constantly being updated/maintained based upon the growing body of field and laboratory data associated with releases of oil in many different environments. 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 (previously Applied Science Associates) 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 fate processes. Oil fate processes included in SIMAP are 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 (>100) 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 (2006-2012) to ensure that the data was adequately sampled. This stochastic approach allowed 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.

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. Seven years of environmental data were used for this modelling study, including 2006-2012. Using wind and current data from throughout this period, a sufficient number of model simulations will adequately sample the variability in wind and current speeds and directions in the region over time and will result in a prediction of the probable oil pathways for releases at the prescribed location.

Stochastic analyses provide two types of information: 1) the areas associated with the probability of oil exposure at some time during or after a release, and 2) the shortest time required for oil above a specified threshold to reach any point within the modelled areas. 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 different environmental conditions, and thus was transported in different directions. To compute the stochastic results in this study, 171 individual trajectories were overlaid upon one another, like the four depicted below. The number of times that each given location throughout the modelled domain (i.e., grid cell) was intersected by a trajectory that exceeded the specified threshold was then quantified and used to calculate the probability of oil exposure for each specific location. This process is illustrated by the stacked simulations in the right panel of Figure 2-2. The predicted footprint is the cumulative oil-exposed area for all the 171 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 likely be much smaller than the cumulative footprint of all the simulations 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.

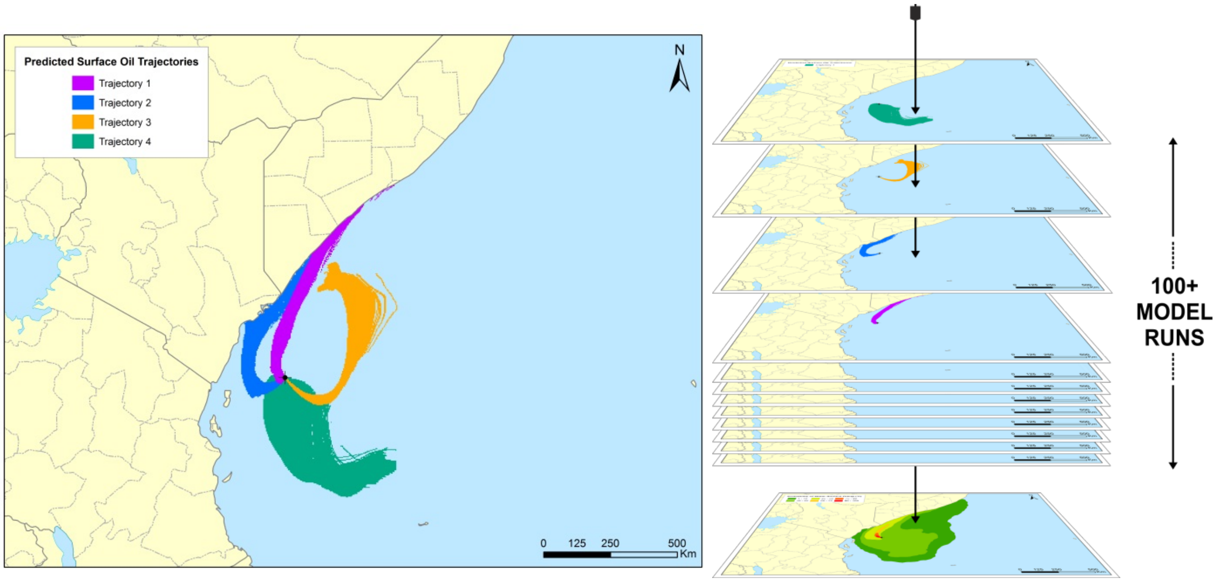


Figure 2-2. Example of four individual release trajectories predicted by SIMAP for a generic release scenario at a generic location simulated with different start dates and therefore environmental conditions. In a stochastic analysis, over one hundred individual trajectories are overlaid (shown as the stacked simulations on the right) and the frequency of threshold exceedance at each location is used to calculate the predicted probability following 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 simulations 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 increase. However, there is a “law of diminishing returns” and thousands of scenarios are not necessary to capture the environmental variability within the system. Annual stochastic model simulations resulted 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 (i.e., 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 simulations (over one hundred 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 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 concentrations were required (Table 2-3). Above these conservative socio-economic thresholds, previous studies identified that there is the potential for negative effects to occur. The first set of figures and further analyses for each scenario in this study include the more conservative lower socio-economic thresholds of concern calculated from stochastic results. The use of such conservative thresholds serves as more of a binary “yes/no” question of whether any oil passed through each identified area, as opposed to an ecological threshold that may indicate the potential for acute mortality.

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) 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, 2016b; Table 2-4). 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 1 mm 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 patchy and discontinuous with a range of visual appearances including silver sheen, rainbow sheen, and metallic areas simultaneously, as a combination of thicknesses may be present (Table 2-4). 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 2-3. 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 (0.04 µm on average over grid cell)	**Socio-economic:** A conservative threshold used in several risk assessments to determine effects on socio-economic 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 threshold 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 (10 µm on average over grid cell)	**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 threshold 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 (1 µm on average over grid cell)	**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 (100 µm on average over grid cell)	**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 **socio-economic** (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 2-4. Oil Appearances based on NOAA JobAid (2016b) 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

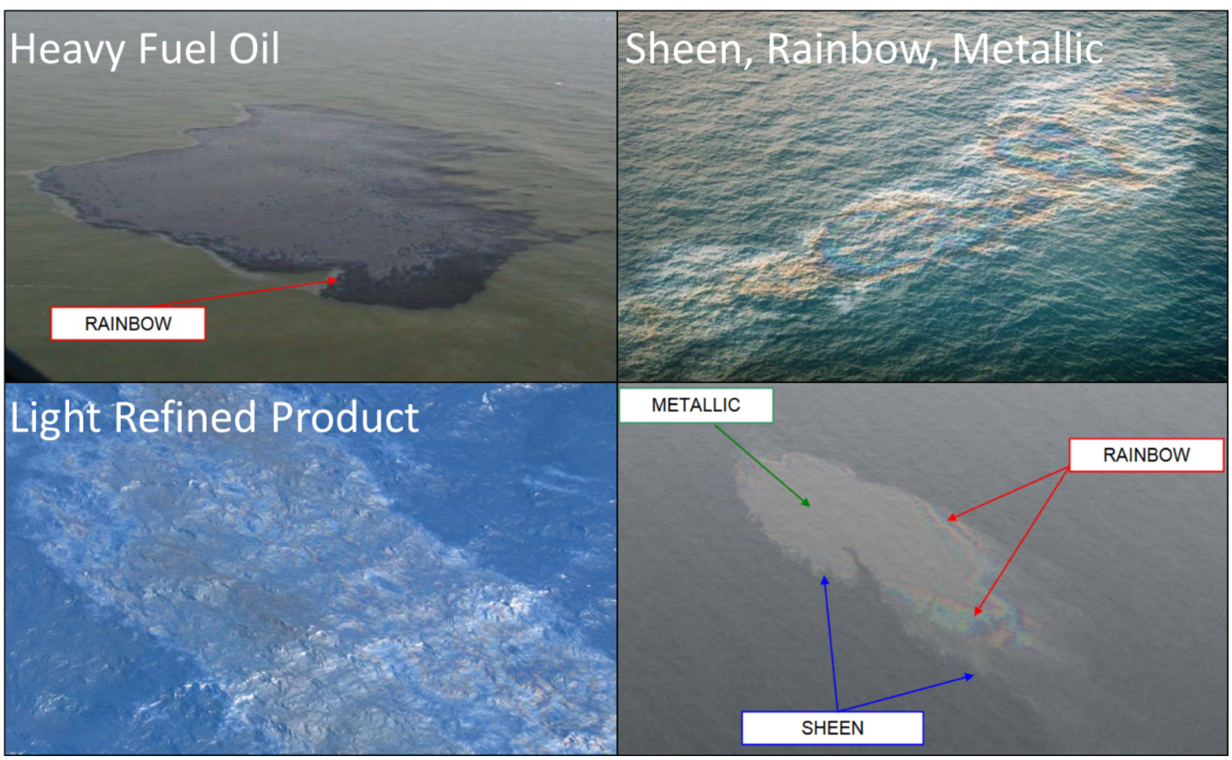


Figure 2-3. Aerial surveillance images of released oil in the environment as examples of different visual appearances based on surface oil thickness and product type (Bonn Agreement, 2011).

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 transport and fate 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 of oil contamination, mass balance, and other information related to a single release at a given location and time.

Each single deterministic simulation within a stochastic analysis represents a specific set of wind and current conditions for the modelled time period. When analyzed together, over one hundred simulations within a stochastic scenario provide a range of expected exposures. The exposures between cases may differ as the trajectory and fate of each individual modelled release is unique. Therefore, the movement and behavior, as well as the resulting areas and magnitudes of predicted contamination for surface, water column, and shoreline oil will be different for each modelled simulation. The 95th percentile "worst-case" exposure for surface, in-water concentration, and shoreline were identified based upon the area, volume, or length of oil that was predicted in each environmental compartment of interest (i.e., water surface area, volume in the water column, or shoreline length).

In addition, a deterministic analysis of a single batch spill release of 1,000 L of marine diesel was modelled within EL 1161. The scenario was assumed to occur during the calmest wind-speed period during the summer/ice-free conditions, as it would result in the largest amount of oil on the surface. The simulation includes its own spatially and temporally variable trajectory, mass balance, surface oil thickness, in-water concentration of dissolved hydrocarbons, etc. reported individually.

The results of each deterministic simulation provides 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, as well as the portion that was transported outside of the model domain. 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, the mass of oil on shorelines, and the maximum concentrations of dissolved hydrocarbons in the water column at any instant in time. These results are a way to simplify the 4-dimensional nature of 3D model predictions through time, with spatially and temporally variable magnitudes and are presented in figures in Section 4.2.

2.3 Modelled Scenarios

One hypothetical release location was used for subsurface blowout modelling, representative of EL 1161 in the Jeanne D'Arc Basin (Table 2-5). A surface batch spill of 1,000 L of marine diesel was also modelled within EL 1161. Scenarios were each modelled separately in a stochastic analysis that included 171 individual model simulations per scenario. This analysis investigated the influence of environmental variability throughout the year over multiple years, on the trajectory and fate of released oil (Table 2-5).

The estimated volume of hydrocarbons released in the subsurface blowout scenarios represent the best technical estimate of the release rates from the wells. In essence, these blowout rates represent credible "worst-case" release volumes given realistic inputs and hypothetical releases.

Table 2-5. Hypothetical subsurface release location, parameters, and stochastic scenario information.

Scenario Parameter	Release Locations of Stochastic Scenarios	
Block/Release Location	EL 1161	
Latitude	46.546252 N	
Longitude	48.618508 W	
Water Depth of Release	100 m	
Released Product	Terra Nova Crude	
Gas to Oil Ratio	153 m^3/m^3	
Pipe Diameter	27.31 cm (10.75 in.)	
Oil Discharge Temperature	118°C	
Release Duration	30 Days	120 days
Release Rate	Day 1: 20,000 m^3/day Day 30: 17,000 m^3/day	Day 1: 20,000 m^3/day Day 120: 7,693 m^3/day
Total Released Volume	555,012 m^3	1,661,574 m^3
Model Duration	160 Days	
Number of Simulations within Stochastic Analysis*	171 annual (82 winter & 89 summer) for each scenario	

*A total of 342 individual subsurface releases were modelled within the stochastic analyses.

Table 2-6. Selected representative deterministic scenarios.

Scenario Parameter	Release Parameters for Representative Deterministic Scenarios						
	30-day Subsurface Release			120-day Subsurface Release			Surface Batch Spill
Representative Scenario	Surface Oil Exposure Area	Water Column Oil Volume	Shoreline Contact Length	Surface Oil Exposure Area	Water Column Oil Volume	Shoreline Contact Length	Surface Batch Spill
Block Release Site	EL 1161						
Release Type	Subsurface Blowout						Surface Batch Spill
Water Depth of Release	100 m						Surface
Released Product	Terra Nova Crude						Marine Diesel
Release Duration	30 Days			120 Days			Near Instantaneous
Release Rate	Day 1: 20,000 m³/day Day 30: 17,000 m³/day			Day 1: 20,000 m³/day Day 120: 7,693 m³/day			-
Total Released Volume	555,012 m³			1,661,574 m³			1,000 L
Model Duration	160 Days						30 Days
Modelled Start Date and Season	10/7/2010 Winter	3/11/2008 Summer r	4/24/2011 Summer	7/14/2007 Summer	4/4/2007 Summer	4/24/2011 Summer	6/15/2009 Summer

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 are:

- 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 fate 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.
- 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.

SIMAP has been validated against many real-world releases including the Deepwater Horizon oil spill, where it was used in the US Government's Natural Resource Damage Assessment. In this specific example, a small portion of the released oil may have sunk as a result of the interaction of released oil with sediments, drilling muds, and other material used in response efforts such as procedures used to seal a leaking well. These are currently areas of active research. While there are additional fate processes that may result in slight differences in the ultimate fate of oil, these processes are known to have relatively lower effects on the total volume of oil in each environmental compartment (on the order of single percentages different, depending on the release and receiving environment) as compared to the fate processes such as entrainment, which are already being modelled. The science and algorithms that may be used to model these processes have not been developed in the scientific community to the point of a consensus or use in modelling. Ongoing research topics currently underway include the formation of marine oil snow (MOS), photo-degradation, droplet size distributions, and other research areas. These and other multi-year research projects are considered for incorporation in modelling nearly constantly. Due to these topics being in the research phase, without scientific consensus, they have not been included in this analysis.

In the unlikely event of an actual release of oil, the trajectory and fate will be strongly determined by the specific environmental conditions, the precise location, 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 release scenarios.

3 MODEL INPUT DATA

3.1 Oil Characterization

Two hydrocarbon products (Terra Nova Crude and Marine Diesel) were modelled for this hypothetical release study. Terra Nova is a light crude oil that has a low viscosity and a high volatile content (Table 3-1 and Table 3-2). The marine diesel modelled is a standard diesel that also has a low viscosity and high content of soluble hydrocarbons. The low viscosity and high soluble content of these oil products provides 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.

The Terra Nova Crude oil is a light crude oil that has a high pour point (+10°C), relative to other light crudes. The pour point is the temperature below which the liquid loses its flow characteristics. This high pour point typically occurs in crudes derived from a larger proportion of plant material that has a high paraffin (i.e. wax) content, which solidifies before the hydrocarbons. Therefore, when the temperature of the environment is less than the pour point, the oil will essentially "freeze." This will reduce spreading and can inhibit or prevent entrainment and evaporation. The marine diesel is expected to weather (i.e., evaporate) rapidly and be nearly completely on the water surface (Table 3-2). The physical and chemical data used to characterize these oils was provided by Suncor Energy, with additional information taken from Environment Canada's oil database (ECCC, 2001).

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

Physical Property	Terra Nova Crude Oil	Marine Diesel
Density (g/cm^3)	0.852 @25°C	0.83100 @25°C
Viscosity (cP)	2.04 @25°C	2.76 @15°
API Gravity	34.58	38.8
Pour Point (°C)	10	-50
Interface Tension (dyne/cm)	25.45	27.5
Emulsion Maximum Water Content (%)	10	0

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

Distillation Cut[1]	Boiling Point (°C)	Description	Terra Nova Crude (% composition)	Marine Diesel (% composition)
AR1	<180	highly volatile and soluble monoaromatic hydrocarbons (BTEX[2] and MAHs C6-C9)	4.6000	1.93
AR2	180 - 264	semi-volatile and soluble 2-ring aromatics (MAHs and PAHs C10-C12)	1.7194	1.14
AR3	265 - 380	low volatility and solubility 3-ring aromatics (PAHs C13-C18)	5.3397	1.56
AL1	<180	highly volatile aliphatics (C4-C8)	16.9066	14.46
AL2	180 - 280	semi-volatile aliphatics (C9-C16)	12.0310	47.86
AL3	280 - 380	low volatility aliphatics (C17-C23)	37.3603	30.32
THC1	<180	total hydrocarbon fraction 1 (sum of AR1 and AL1)	21.5066	16.40
THC2	180 - 280	total hydrocarbon fraction 2 (sum of AR2 and AL2)	13.7500	49.01
THC3	280 - 380	total hydrocarbon fraction 3 (sum of AR3 and AL3)	42.7000	31.89
Residuals	>380	aromatics ≥ 4 rings and aliphatics >C20 that are neither volatile nor soluble	22.0000	2.70

Numerous data sources and dozens of analyses were used to classify the different chemical and physical characteristics of the oil. As an example, this would include but not be limited to physical testing, distillation studies, weathering studies, measurements of chemicals (e.g. GCMS, PAH, alkanes, saturates, aromatics,

[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 (by chemical definition) that are soluble. In the modelling context, "aliphatic" refers to insoluble and volatile hydrocarbons. Note that Σ(AR) + Σ(AL) + residuals = Σ(THC) + residual = total hydrocarbon composition

[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.

resins, asphaltenes, etc.), emulsification studies, degradation studies, etc. All available data was used to classify each oil. When advanced analyses were not available, surrogate oils with more information are used to fill in data gaps and professional judgement and previous experience are used to further refine the oil characterization model inputs.

The “pseudo-component” approach was used to simplify the tracking of thousands of chemicals comprising oil for modelling (Payne et al., 1984; 1987; French et al., 1996; 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.

Degradation rates for each component and compartment (surface, upper water column, lower water column, and sediments) were based on biodegradation rates obtained from literature reviews that included estimates for compounds and/or components of crude oil generally (French McCay et al., 2018a: Annex C to Appendix II). For the semi-volatile components, degradation in floating oil would be considerably slower than volatilization. The rates for residual oil are consistent with studies by Zahed et al. (2011) and Atlas and Bragg (2009).

Through the modelled processes, the density and viscosity of the oil tend to increase as the oil weathers. It is possible for the weathered oil, especially in the presence of suspended particulate matter in the water column, to become denser than water and sink. In addition, the oil (including the residual fraction) does continue to degrade over time within the model. In addition, one must consider that the hypothetical long-term releases of oil (many months) continues to add fresh oil, which will increase the total amount of oil through time that will degrade. As time progresses, residual oil is all that remains of the early portions of the release while whole fresh oil continues to be released in later stages. In total, this may appear as though degradation rates are increasing, but it is rather a function of the static degradation rate and the increasing amount of oil (a portion fresh oil) through time.

A recent comprehensive model update with literature review of over a dozen of the most recent studies on oil degradation rates validating the use of modelled SIMAP degradation rates was conducted for work following the Deepwater Horizon Natural Resource Damage Assessment (French et al., 2015) as well as for the United States Bureau of Ocean Energy Management (BOEM) (French McCay et al., 2018b,c).

The long-term weathering and degradability of an oil (including microbial degradation, photo-oxidation, and other processes that may break down compounds or components of oil) may increase the tendency of an oil to sink. These processes are highly dependent upon the type of oil released and the environmental conditions of the receiving environment. A large amount of work is currently being undertaken to develop scientific consensus in this area; however, it is understood that compounds with a boiling temperature >380°C degrade slowly and that these compounds are difficult to measure. The modelled bulk disappearance is quite slow and would conservatively overestimate the effects following a release as oil would remain in the modelled system. The inclusion of compound-specific degradation would increase the degradation and reduce the amount of oil remaining in the model, therefore potentially skewing results towards less effects.

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. The cells were coded for depth and habitat type. Geographical data were obtained from multiple international sources to provide the geographic and environmental information 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.).

The SIMAP model used these grids to identify the location of the shoreline and amount of oil that may adhere once oil contacted the shoreline (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 4 km north-south by 5 km east-west (0.045° 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).

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 2016a
	Maine Environmental Vulnerability Index	United States - Maine	MDEP 2016
	New Brunswick Department of Natural Resources	New Brunswick	NBDNR 2013
	Nova Scotia Department of Natural Resources	Nova Scotia	NSDNR 2013
Bathymetry	General Bathymetric Chart of the Oceans Digital Atlas	Global	GEBCO 2003

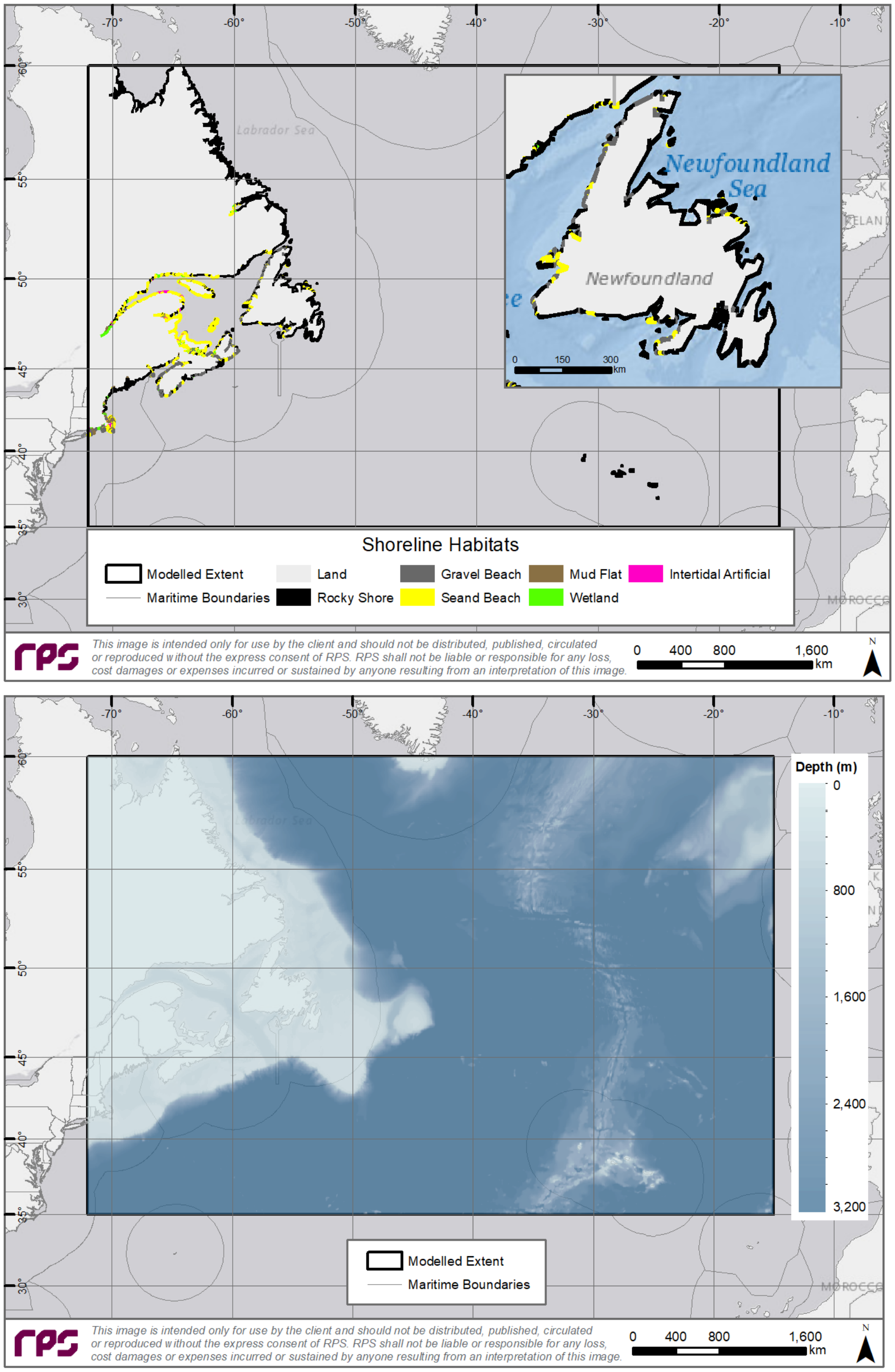


Figure 3-1. Shoreline habitat data (top) and depth (bottom) through modelled domain. The black box represents the modelled extent.

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 seawater with a salinity of 35 parts per thousand (PPT) is about -2°C (NOAA, 2014).

The movement and behavior of released oil is greatly affected by the presence of sea-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 (also commonly referred to as ice concentration) and an extensive review of the literature (French McCay et al., 2014, French McCay et al., 2016, French McCay et al., 2017a, French McCay et al., 2017b, French McCay et al., 2018a, Wilson et al., 2018). From 0 to ~30% coverage, the sea-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 sea-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% sea-ice coverage, surface oil moves with the sea-ice, and evaporation and entrainment cease.

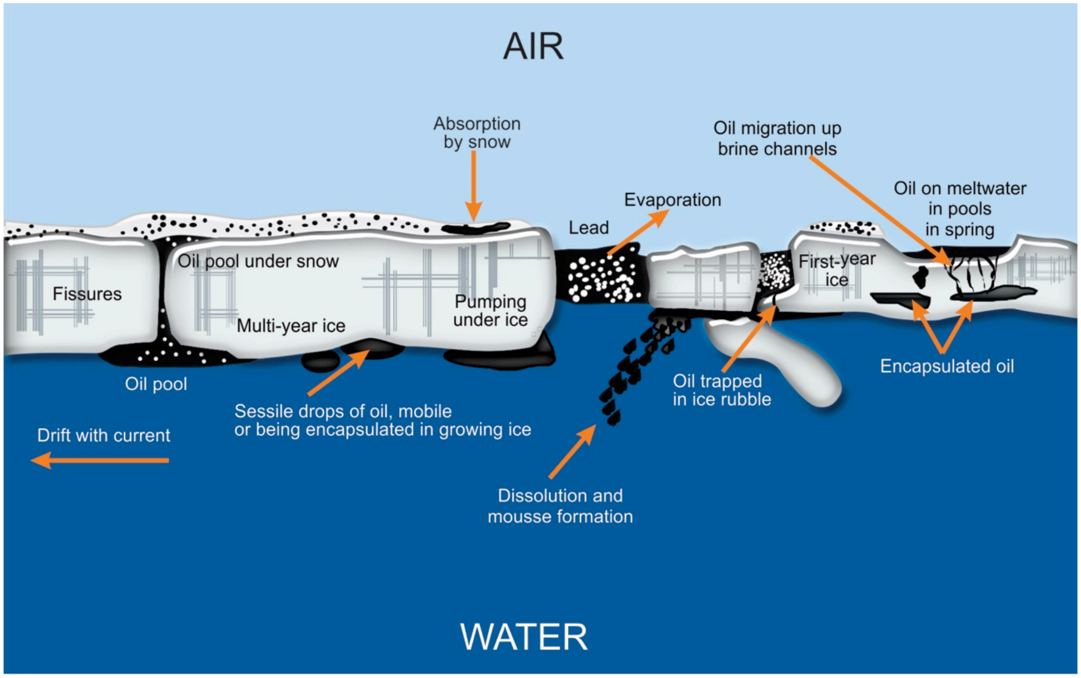


Figure 3-2. Oil and ice interactions at the water surface (RPS 2017, modified by Alan A. Allen from original, DF Dickins Associates Ltd, 2004).

The sea-ice thickness and concentration can vary greatly based upon prevailing weather conditions. If oil is released under sea-ice, water column exposures can be greater, due to the “capping” effect of the ice. Sea-ice cover limits or prevents evaporative losses and could result in substantially greater dissolution of hydrocarbons into the water column.

Sea-ice data used as modelling inputs were obtained from the Canadian Ice Service (CIS; ECCC, 2017) in weekly files spanning from January 2006 to December 2012. These data were in the form of polygon data, with information on total sea-ice concentration and stage of development. For each ice polygon, concentration codes were converted to concentration percentages. Average sea-ice thickness was calculated based on the proportional concentration of the various stages of sea-ice present for each week of the season over seven years. The CIS data provides a range of thicknesses for each sea-ice category and stage of development. In most cases, the mid-point of those ranges was used in the calculation of average sea-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 sea-ice data was gridded at a resolution matching the habitat grid (0.045°). A representative map depicting percentage of sea-ice coverage and thickness for the first week of February 2008 is presented as an example (Figure 3-3).

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

CIS Sea-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
Land fast Ice	100%	n/a	assumed full water depth
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.

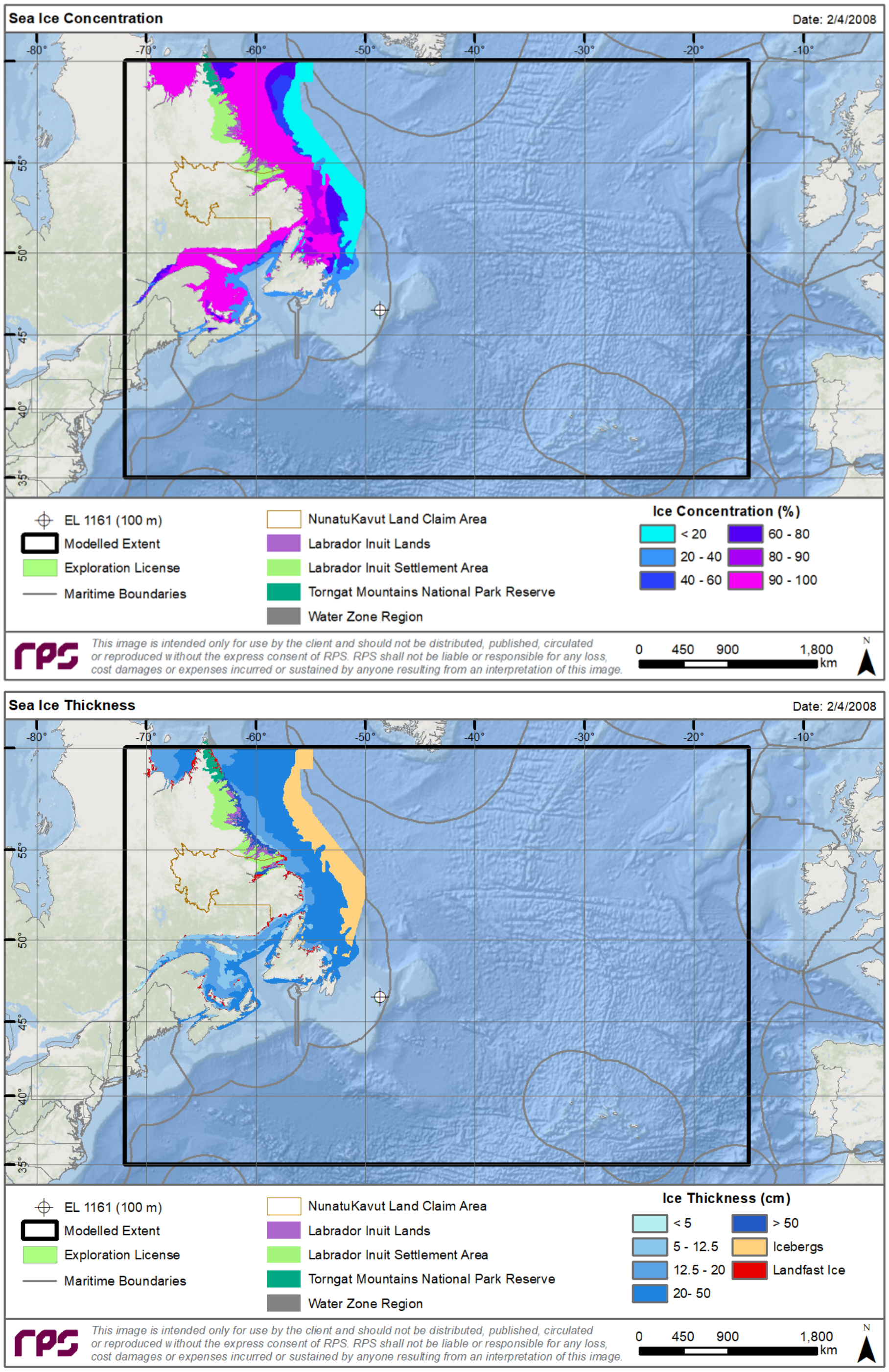


Figure 3-3. Representative percentage sea-ice coverage (top) and corresponding thickness (bottom) for the first week of February 2008.

3.4 Wind Data

Winds are one of the main physical forcing mechanisms of oil transport on the water surface, thus wind speed and direction at the water surface are driving factors of a transport simulation. To effectively model this phenomenon, the wind velocity components data must encompass a large geographic area in order to capture the spatial extent and any spatial variability in potential transport that may occur. The SIMAP model uses time-varying wind speeds and directions over the area for the period which each release was simulated. A multi-year dataset of wind velocity components was used to capture the variability that occurs over the model domain for the multiple years that were modelled (2006-2012). Simulated oil release trajectories using these long-term wind datasets are representative of possible wind conditions at each hypothetical release site. Oil released over long periods of time (e.g., the 120-day blowouts modelled here for 160 days) has the potential to be transported long distances by wind transport.

Wind data for this study were obtained for the entire model domain from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) product for 2006 through 2010 (Saha et al., 2010). Another two years (2011-2012) of wind data were added to the analysis from CFSv2, which uses the same model that was used to create CFSR and thus works as an extension of CFSR (Saha et al., 2014). The CFS 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 CFS includes coupling of atmosphere and ocean, as well as assimilation of satellite radiances. The CFS global atmospheric resolution is ~38 km, with 64 vertical levels extending from the surface to 0.26 hPa. CFS winds are one of the main driving forces in the HYCOM hydrodynamic dataset. The CFS dataset acquired for and used in this study has 0.5-degree horizontal resolution and 6-hourly intervals.

Averaged annual wind data at the EL 1161 site are frequently from the west-southwest direction (Figure 3-4) as part of prevailing Westerlies wind pattern. These winds would be expected to transport oil generally to the east, away from nearby shorelines and further into the open ocean. Winter season (November-March) winds are most frequently from the west and west-northwest with higher velocity than summer season (June-August) winds, which typically come from the southwest (Figure 3-5). The months of April and September are more dynamic transitional periods between 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. However, winds throughout the year predominantly come from the west, northwest, and southwest, which would force oil further into the open ocean. Monthly average wind speeds varied between 7 and 11 m/s while the 95th percentile wind speed ranged from 12 to 19 m/s throughout the year at EL 1161 (Figure 3-6). The highest wind speeds typically occurred during winter months (November-March) and lowest speeds during summer months (June-August). Resulting significant wave heights, induced by winds at the surface of the ocean, are typically highest from November – February, in regions with no ice (C-NLOPB, 2014).

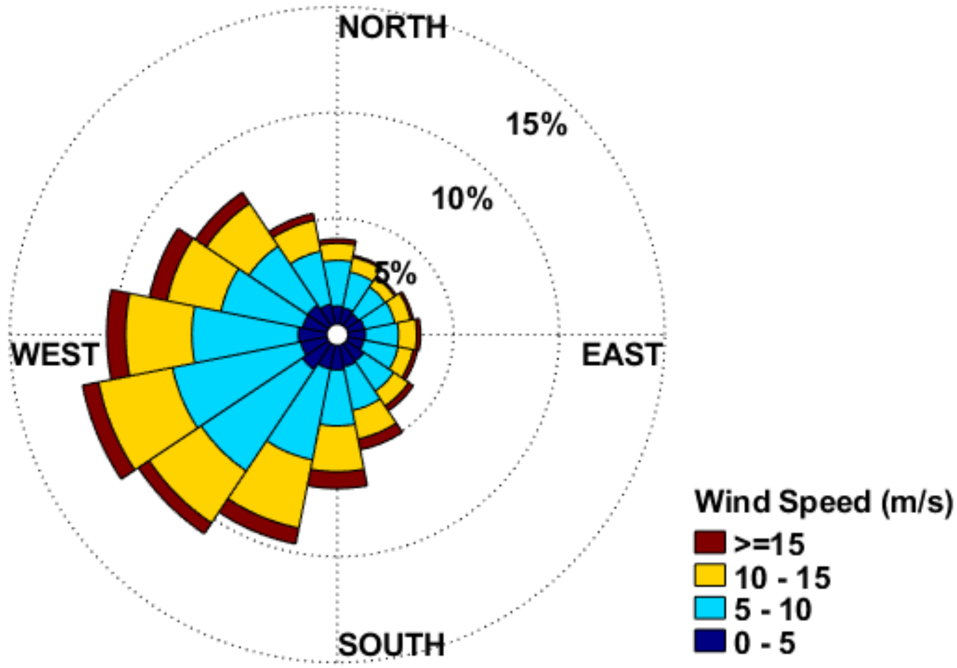


Figure 3-4. Annual CFS wind rose near EL 1161. Wind speeds are presented in m/s, using meteorological convention (i.e., direction wind is coming from).

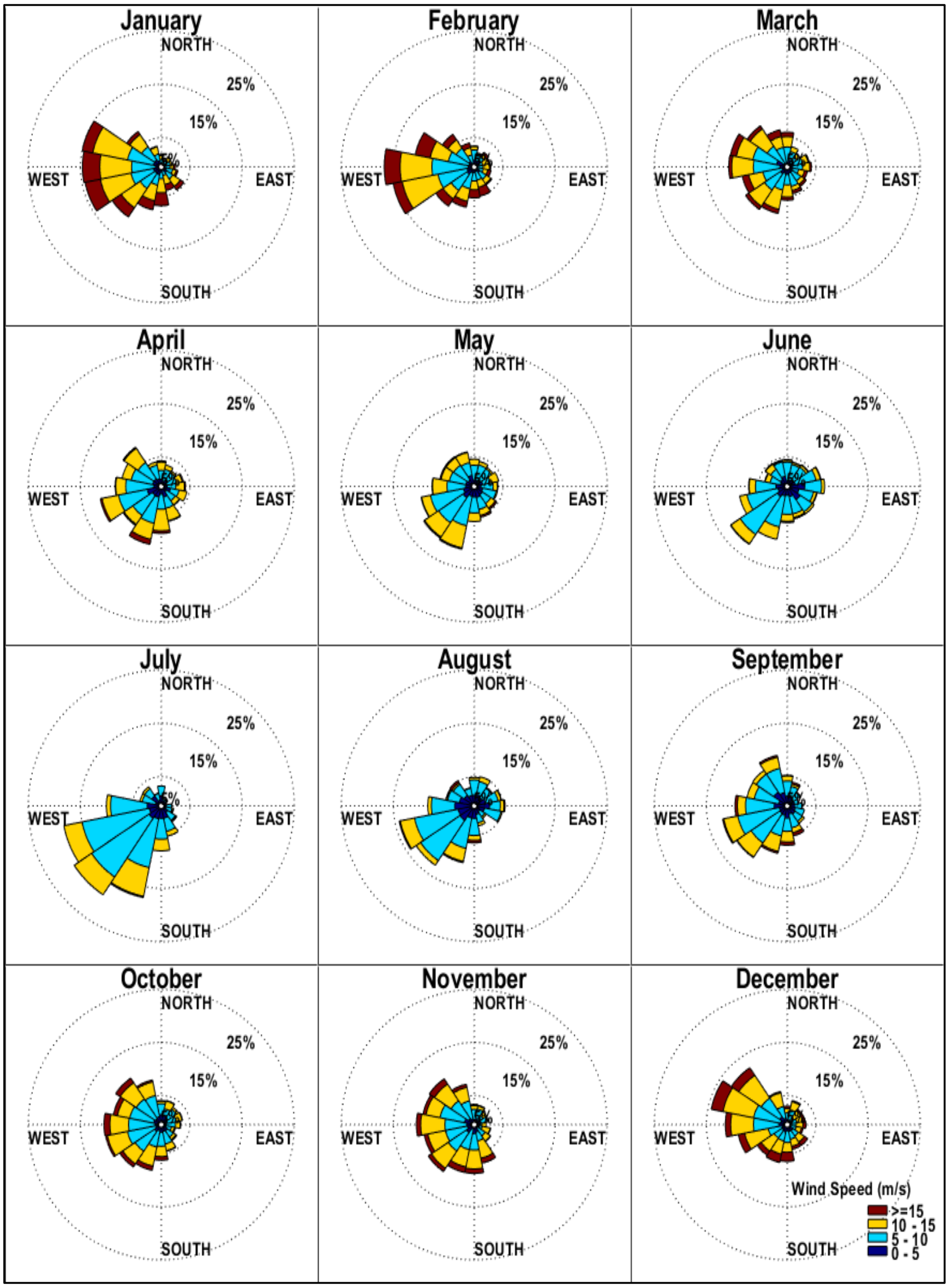


Figure 3-5. Monthly CFS wind rose near EL 1161. Wind speeds are presented in m/s, using meteorological convention (i.e., direction wind is coming from).

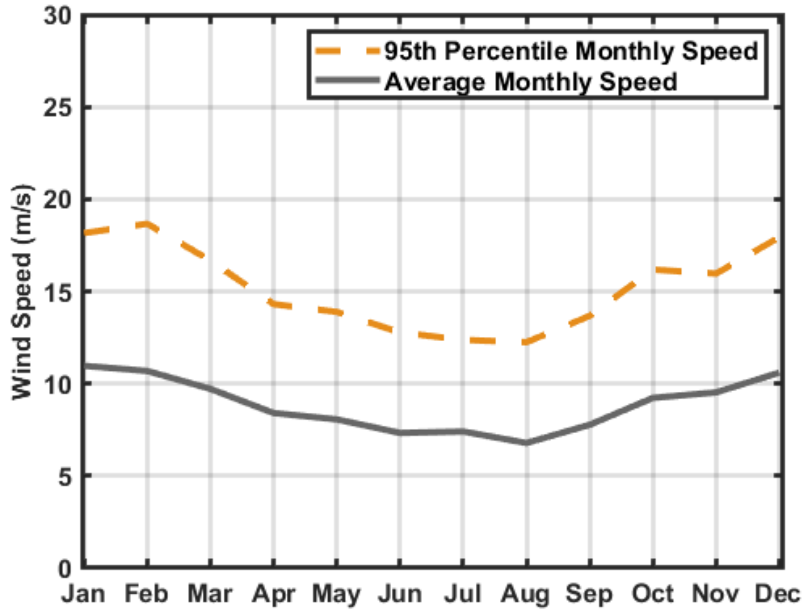


Figure 3-6. Average and 95th percentile monthly wind speeds near EL 1161.

3.5 Currents

The second main forcing factor on oil drift, in addition to winds, is 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 3-7 through Figure 3-9). This southerly current intensifies as waters funnel through the offshore branch, which follows the Flemish Pass along the 1,000 m contour depth 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 south (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 region where these two currents converge is one of the most dynamic oceanographic areas in the world, where extremely energetic and variable frontal systems and eddies are produced 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 and Anderson, 1983; Richardson, 1983) where they intersect with the North Atlantic Current.

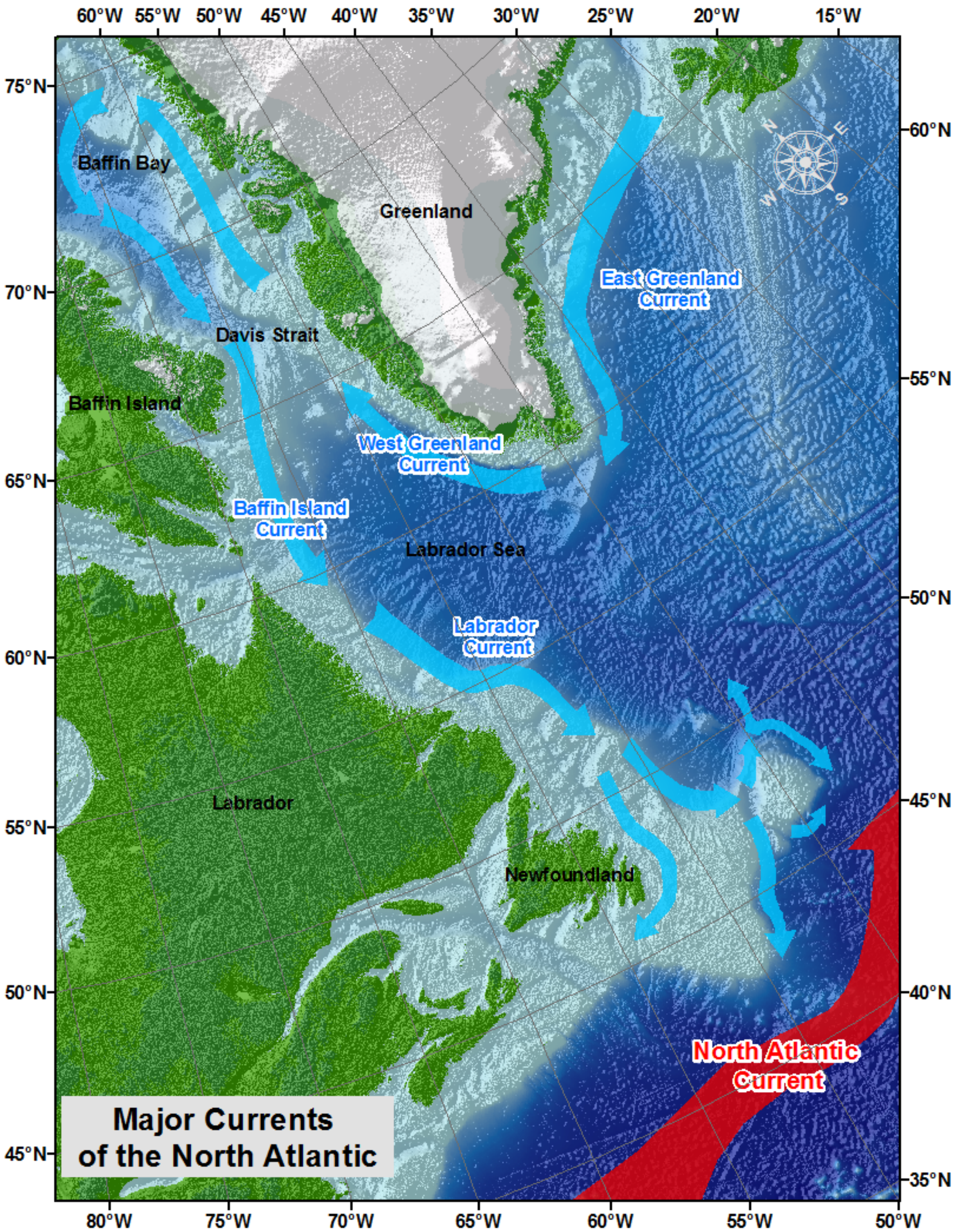


Figure 3-7. Large scale ocean currents in the Newfoundland region (USCG 2009).

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; Bleck, 2002; Halliwell et al., 2001, 1998). 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 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).

For the energetic eddies at the frontal systems that are of a smaller scale than ~7 km, the HYCOM model would not directly capture these features due to its low resolution (Volkov, 2005). However, from a broader-scale oil trajectory perspective, it is not required to capture these smaller scale features. The movement of water within an eddy is circular by nature, meaning that oil in the eddy would tend to be trapped, circulating within the grid cell. Therefore, while the rate of circulation (i.e., velocity of rotating water body) may be greater than the forward current speed of the eddy, it is irrelevant to the broader scale modelled transport processes. The general ocean circulation (i.e., forward movement of the eddy itself) would be resolved by the average current within the single grid cell, which captures the forward speed of the core of the eddies. In addition, the randomized advection and dispersion account for the variability in currents below the spatial and temporal resolution of each dataset. Because HYCOM does not resolve the trapping of oil in these small-scale features, results of the modelled simulations would tend to include a higher degree of dispersion and would therefore cover larger areas and may be considered more conservative. For eddies that are larger than approximately 14 km in diameter, the HYCOM gridding could capture the circular nature of the circulation in the multiple grid points.

In general, the resolution of underlying forcing data has the potential to influence the results of trajectory and fate simulations. If extremely coarse resolution forcing is used, intricate flow paths may be straightened, and velocities would tend to be closer to the mean. If extremely fine resolution gridding is used, smaller-scale features will be resolved. However, there is a balance and a "law of diminishing returns" when modelling these processes. When higher spatial and temporal resolutions are used, larger amounts of data are required, and the number of modelled time steps must increase. Shorter time steps are required with higher spatial resolution data to account for the distance travelled within each time step, to ensure the spatial scale is resolved (i.e., particles to not jump or skip adjacent grid cells). As the number of cells covering the same domain with higher resolution increases, the amount of time required to model will increase as will the amount of data storage for model outputs.

The HYCOM model leverages data assimilation techniques used in the Navy Coupled Ocean Data Assimilation (NCODA) system (Cummings, 2005). The NCODA system employs a Multi-Variate Optimal Interpolation scheme. This scheme 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). Its bathymetry is derived from the General Bathymetric Chart of the Oceans (GEBCO; Supporting Volume to the GEBCO Digital Atlas, 2003). Surface forcing is derived from the Navy Operational Global Atmospheric Prediction System (NOGAPS), which includes wind stress, wind speed, heat flux (using bulk formula), and precipitation.

For this study, daily HYCOM current data were obtained for the period of January 2006 through December 2012, for the North Atlantic region (Halliwell, 2002; Bleck, 2002; Halliwell et al., 2001, 1998). The data spanned seven years, which encompasses the variability in winds and currents in daily, weekly, seasonal, and inter-annual scales, including calm periods, seasonal variations, and the full range of environmental forcing over the entire period. Because of the bi-weekly randomized sampling within the seven-year modelled period and the 160-day duration of the oil spill models themselves, the range of calm to more energetic periods would be captured in each stochastic analysis. While this subset of hydrodynamic data is not the most recent seven years of data, currents and winds in the study area would be representative of environmental conditions that are likely to be present. Similarly, while there may be questions regarding general circulation during specific time periods, it is important to note that oil spill trajectories are influenced by day to day currents, as opposed to seasonal or annual averages. Average surface current speeds (Figure 3-8) and direction of offshore Newfoundland (Figure 3-9) for 2006-2012 in the model domain depict large scale features such as the Labrador Current and the North Atlantic Current as well as bathymetric steering of currents around the Grand Banks and Flemish Cap. In particular, the site is close to the inshore branch of the Labrador Current, which follows the Avalon Channel between Newfoundland and the Grand Banks (Figure 3-9).

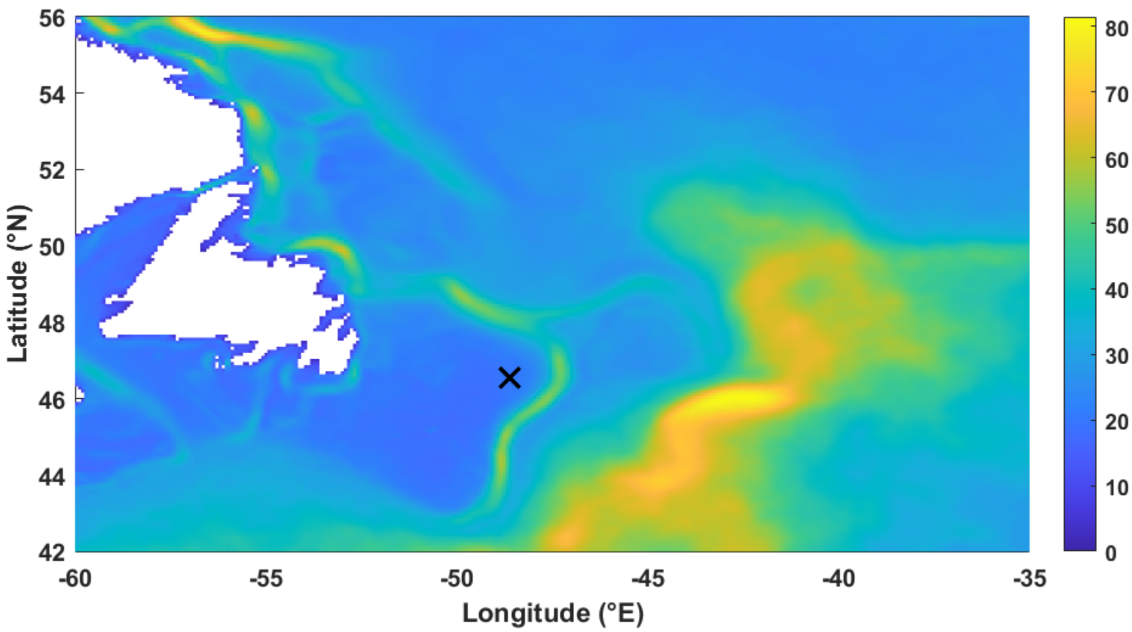


Figure 3-8. Average HYCOM surface current speeds (cm/s) off the coast of Newfoundland from 2006 – 2012. The black cross represents the EL 1161 well location.

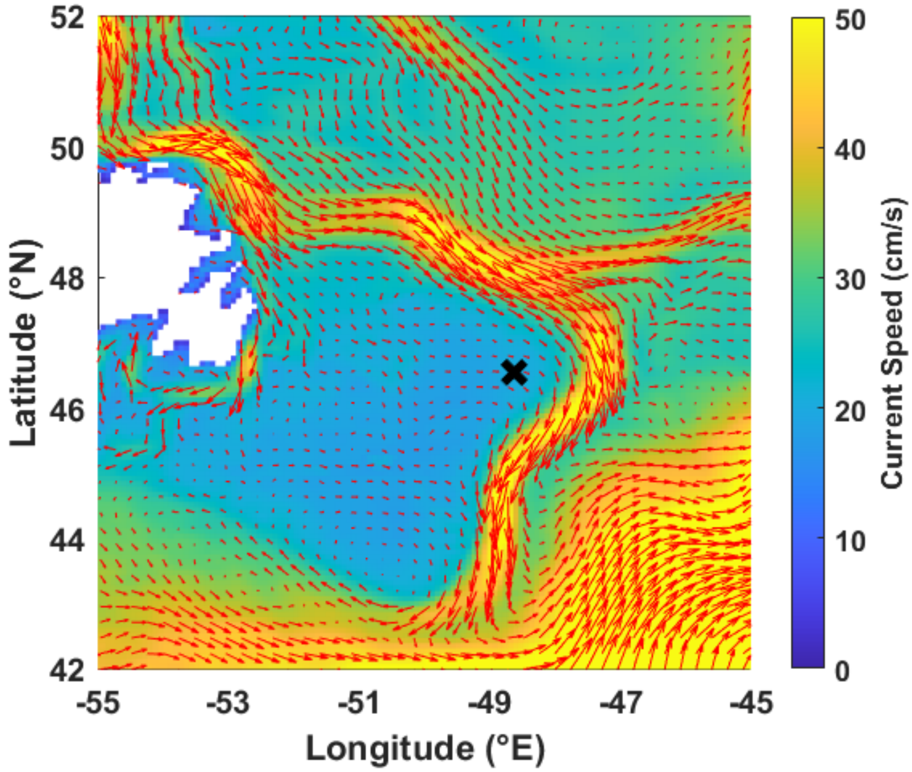


Figure 3-9. Averaged HYCOM surface current speed (cm/s) in color and arrow size, and direction presented as red vectors around the Newfoundland coast, including portions of Labrador (2006-2012). The black cross represents the EL 1161 well location.

3.6 Water Temperature & Salinity

Temperature and salinity values throughout the water column influence several oil transport and fate calculations including (but not limited to) density/buoyancy, viscosity, and evaporation (French McCay et al. 2018a). Temperature and salinity data were obtained from the World Ocean Atlas (WOA) 2018 high-resolution dataset, 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., 2002), 2013, and 2018. 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. At the site, the temperature sharply decreases as the depth increases, reaching the lowest value of roughly -2.0 °C at 90 m at the seabed (Figure 3-10). On the other hand, the salinity and density (represented by salinity and sigma-T plots respectively) of the seawater increase with depth and stabilizes below 60 m at roughly 33 psu for salinity and 26.5 kg/m^3 for density (Figure 3-10).

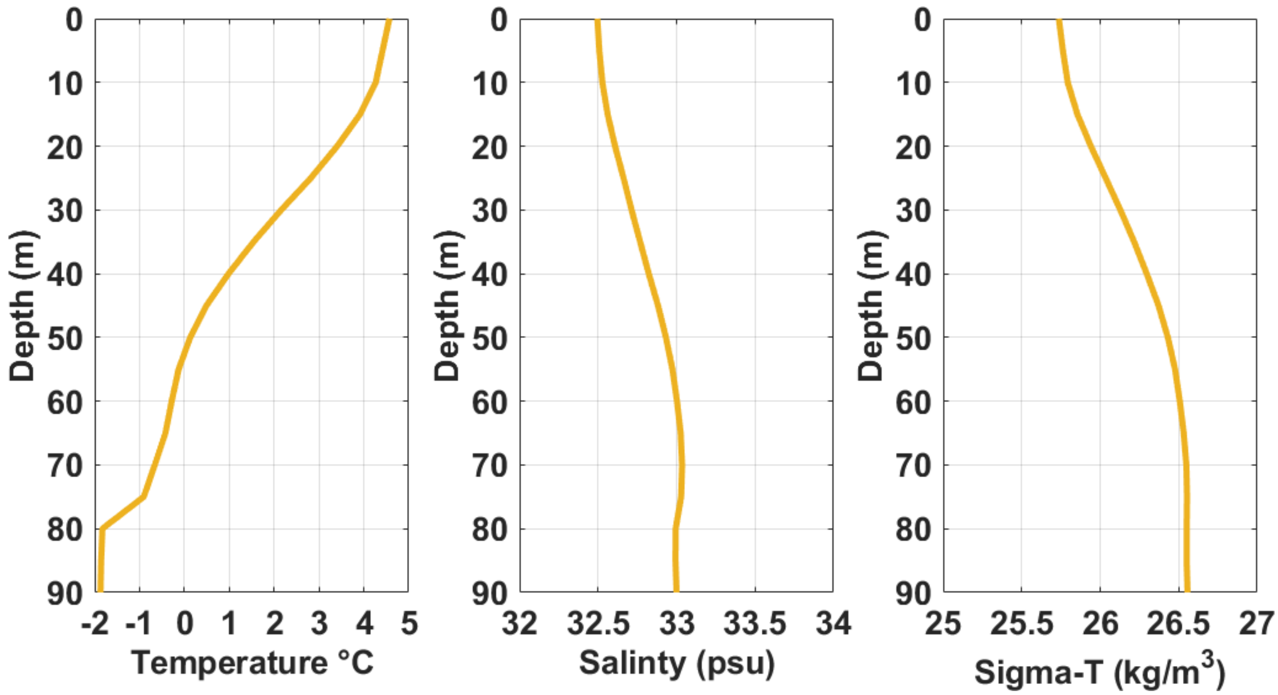


Figure 3-10. Profiles of annual water column temperature (left) and salinity (middle) from WOA18, and the corresponding calculated density (right) represented as sigma-t in the vicinity of the EL 1161 release site. The density profile was generated based on the temperature and salinity data using equations of state as published by UNESCO, 1981 (EOS – 80).

3.7 Blowout Model Scenario and Results

The nearfield model OILMAPDeep was used to predict the initial droplet size distribution associated with subsurface blowouts of Terra Nova crude oil. Two subsurface blowouts of Terra Nova crude oil were evaluated at EL 1161 as part of this study, capturing 30- and 120-day releases (Table 2-1). 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 orifice diameter was assumed to be 27.3 cm (10.75 inches) at the seafloor (Table 2-5). The releases modelled at EL 1161 are of a variable flow rate, meaning that the droplet size distribution modelled is predicted to change (increased droplet size) as the flow rate changes (decreased over time).

The droplet size model was used to predict 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 unmitigated scenarios simulated for this study, the oil was assumed to be untreated (i.e., no dispersant used). 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.

The predicted droplet size distribution was represented by seven discrete size bins for each modelled release scenario (Table 3-5). 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 daily, such that an equal proportion of the released oil by mass (14.29%) was within each bin. The releases modelled at EL 1161 are of a variable flow rate, meaning that the droplet size distributions modelled were predicted to change as the flow rate decreased. The initial flow rate was assumed to be the same for both the short (30-day) and long (120-day) releases. The flow rate was assumed to decrease (daily) with the same linearity for both releases. Therefore, the droplet size distributions for first 30 days of the two simulated releases were the same. As the flow rate of the well was predicted to decrease, the droplet size distribution was predicted to increase (Table 3-5).

Table 3-5. Summary of droplet size distribution results for each of two modelled subsurface blowouts at snapshots in time: Days 1, 30, and 120. The droplet size distributions were calculated daily, to account for the variable oil flow rate through time.

Median Droplet Size in Each of Seven Equal-Mass Bins, by Diameter (µm)		
EL 1161		
Day 1	**Day 30**	**Day 120**
31.8	38.5	86.5
72.7	87.9	197.5
90.5	109.5	245.9
109.0	131.8	295.9
131.4	158.9	356.8
164.6	199.0	446.9
216.1	261.5	586.8

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 3-10). The majority of oil rose to the water surface in minutes, while smaller droplets (less than roughly 100 µm) remained entrained in the water column indefinitely. 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.

4 MODEL RESULTS

4.1 Stochastic Analysis Results

Stochastic analyses characterize results from many tens to hundreds of individual modelled releases. This study included 171 individual subsurface releases modelled for 160 days for each blowout stochastic scenario. Modelled start times were distributed over a period of seven years of environmental data to capture the natural variability in the environment. In total, two stochastic analyses were completed, composed of 342 individual trajectories. Each stochastic analysis was defined by the release duration (30- or 120-days). These scenarios represent the time required to mobilize and implement a capping stack to contain the release (30-day) or mobilize a drilling platform, drill a relief well, and kill the well (120-day).

Because ice cover can affect the trajectory and fate of oil, individual model simulations within each stochastic scenario were broken into two groups based upon the specific modelled time period and associated presence or absence of ice cover. Statistics for all 171 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-year period. Sea-ice coverage in the region is present in specific regions from November through April, while May through October is mostly ice-free. Modelled releases with the majority of their simulated days (>80 of the 160-day modelled duration) experiencing mostly ice-free periods are referred to as “summer” simulations (89 modelled releases), while those releases with a majority of days experiencing periods with sea-ice coverage are referred to as “winter” simulations (82 modelled releases). Sea-ice coverage very rarely extended far enough offshore to reach within kilometers of the release locations, and when it did, <10% ice coverage was predicted. However, sea ice was present along most of the coastline in winter months, with February typically having the largest expanses of 90-100% sea-ice coverage (Figure 3-3).

The figures presented within this section illustrate the predicted spatial extent of surface floating oil, water column contamination, and shoreline contact above the specified socio-economic thresholds (Table 2-3). They include both the probabilities and associated minimum times to threshold exceedance for the four hypothetical release scenarios (Table 4-1 and Table 4-2). The probability maps define the area of potential exposure and the associated probability with which sea surface oil, water column contamination, or shoreline oil are expected to exceed the specified thresholds at any point in time throughout each of the 171 simulations with 160-day modelled duration. The colored contours in the stochastic maps specify the probability boundaries for areas that may experience oil at or above the specified thresholds for each release scenario. Darker color contours denote areas that are more likely to exceed the specified threshold, but do *not* denote higher concentrations. Lighter color contours depict regions that are less likely to exceed the specified threshold. Note that the lightest mint-green line represents areas where oil may exceed the specified threshold in only 1% of modelled simulations. In other words, the likelihood that any oil exceeding the identified threshold would leave the area bounded by the mint-green line is <1% out of 171 individual simulations. The area between the 1% contour and the next (10%) has between a 1-10% probability of exceeding the threshold, based upon the environmental variability and given that the modelled release 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 an unmitigated release occurred. 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 that contamination may exceed identified socio-economic thresholds at any modelled time step (over 160 days), for each point within the modelled domain, assuming a release were to occur at some point in time.

The 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 threshold may be exceeded at a specific depth (typically within a few meters from the surface) in the mapped location.

The minimum time footprints correspond with the associated probability of oil exposure maps. 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 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 Zones (EEZ) in the North Atlantic, 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 the 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 (82 or 89 modelled simulations), two scenarios would be required to exceed the same threshold in the annual analysis due to a greater number (171 modelled simulations) of modelled releases in the annual set of simulations 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 (Figure 4-1 to Figure 4-18).

4.1.1 EL 1161 30-day Subsurface Release

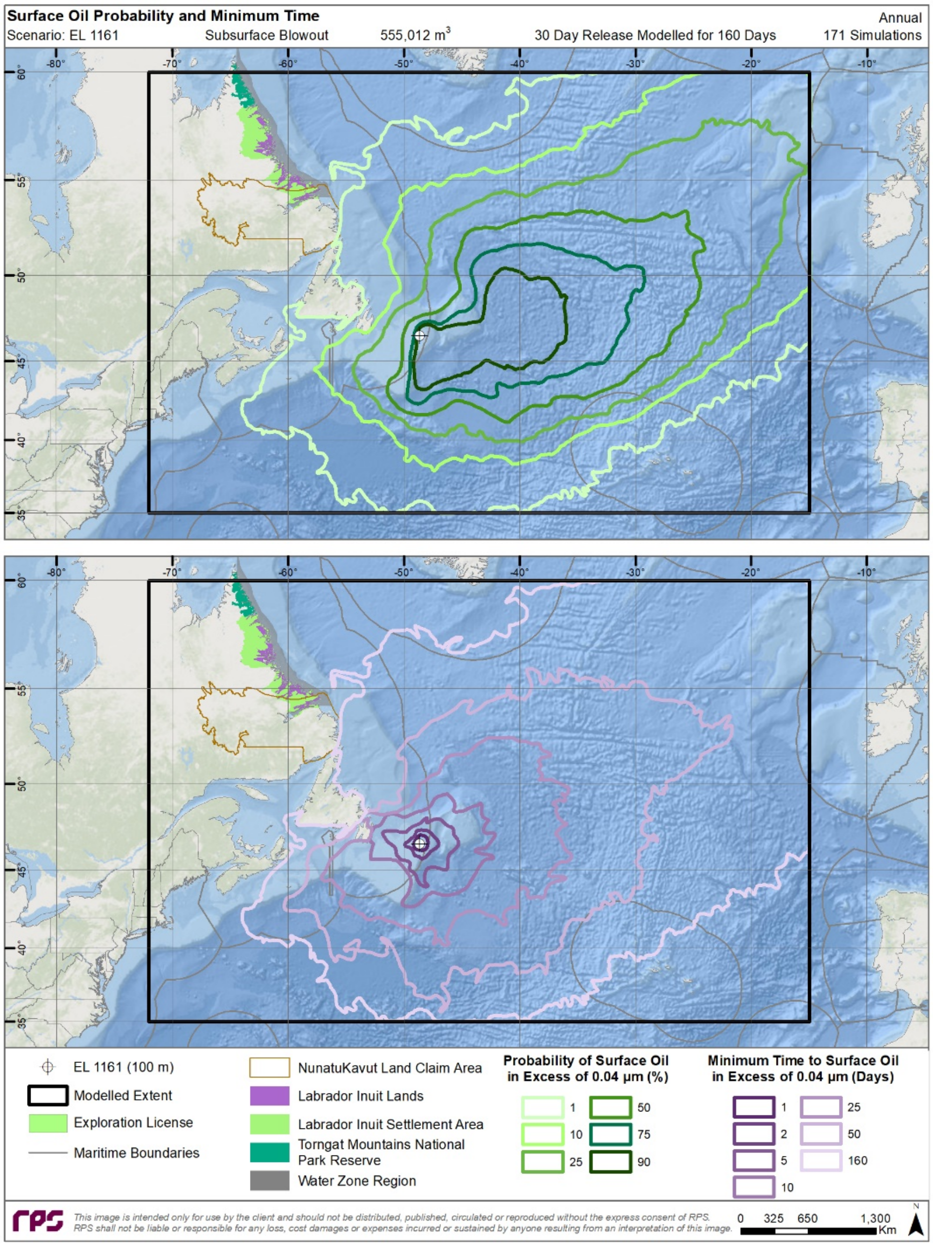


Figure 4-1. Annual probability of surface oil thickness >0.04 µm (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 30-day subsurface blowout at EL 1161.

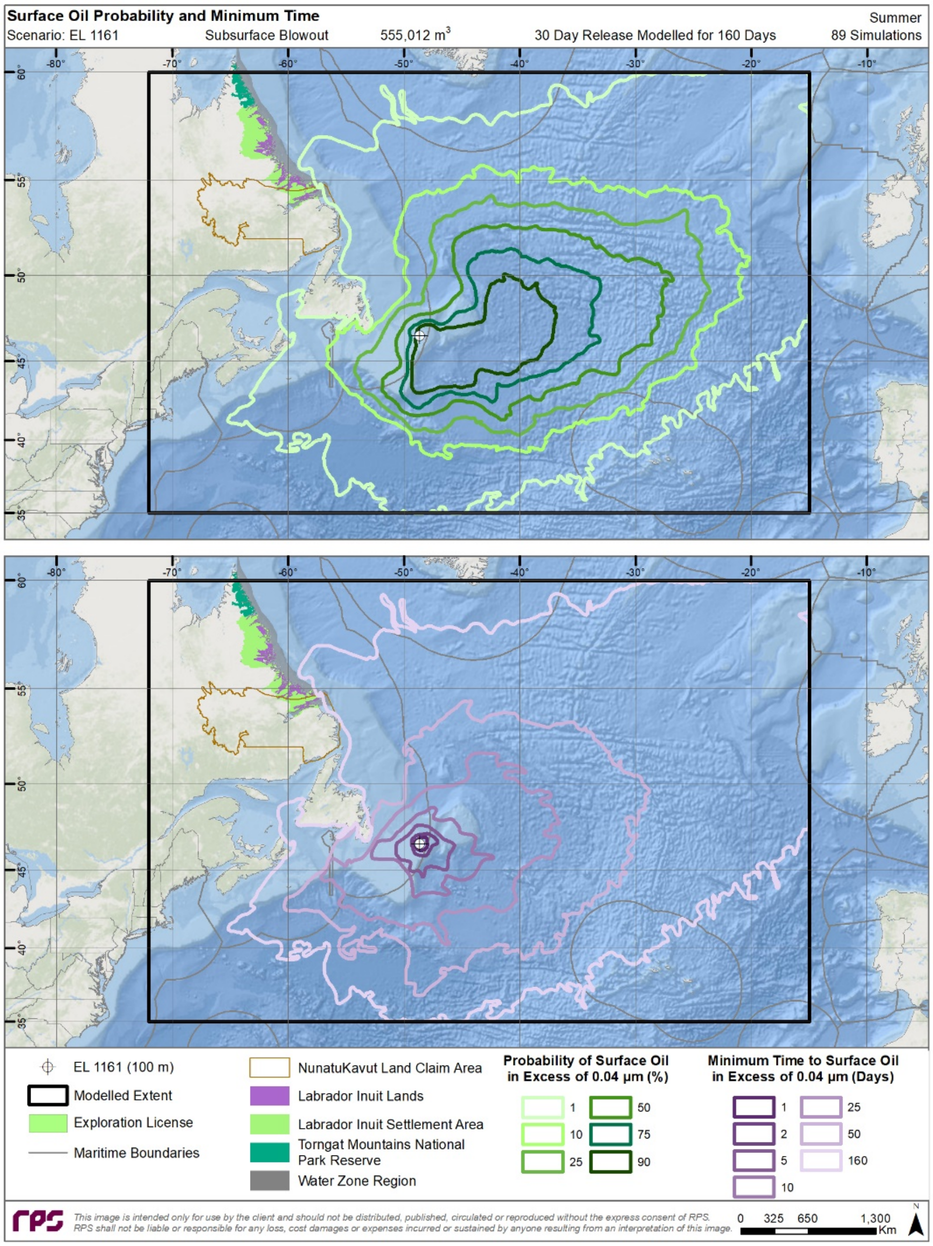


Figure 4-2. Summer probability of surface oil thickness >0.04 µm (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 30-day subsurface blowout at EL 1161.

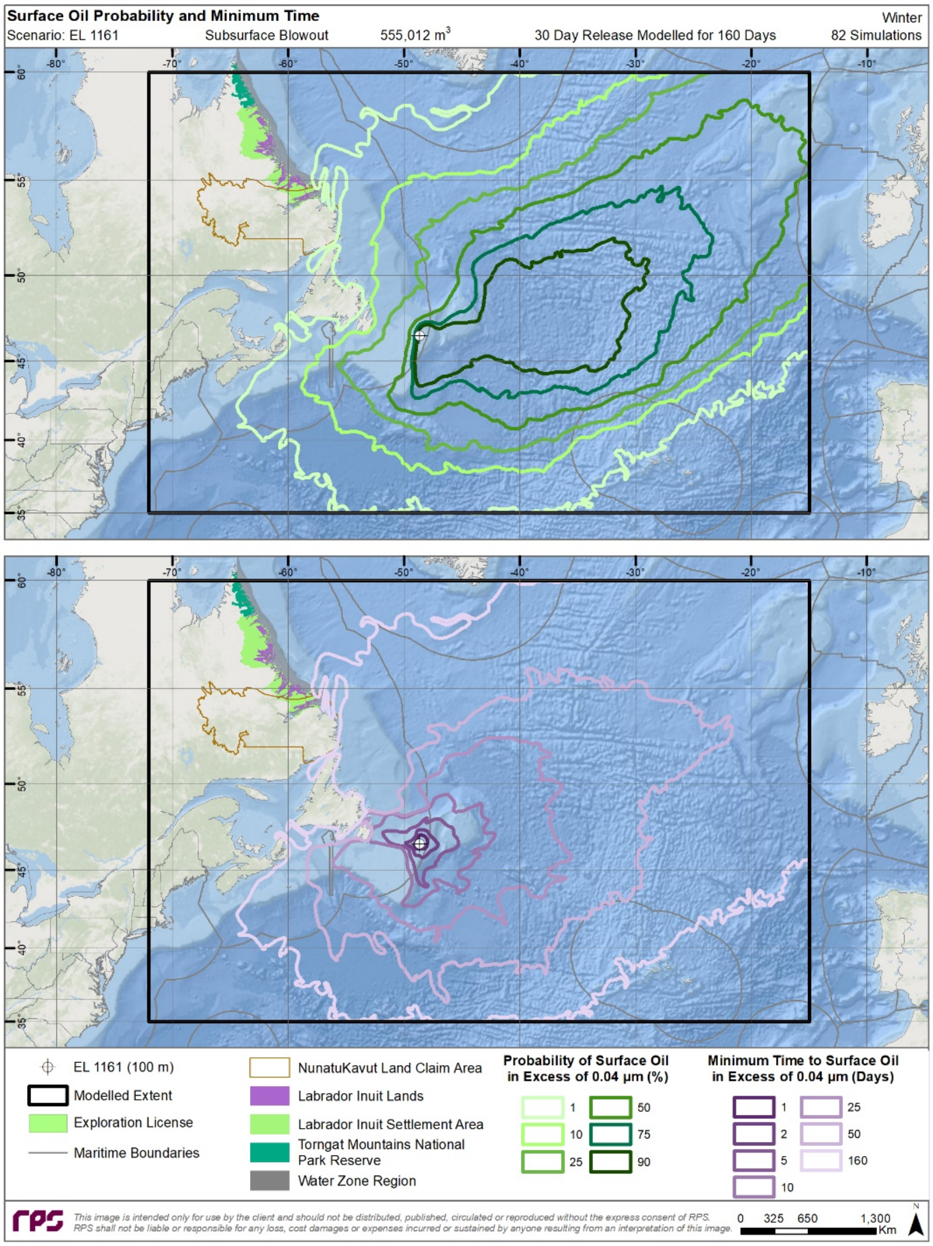


Figure 4-3. Winter probability of surface oil thickness >0.04 µm (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 30-day subsurface blowout at EL 1161.

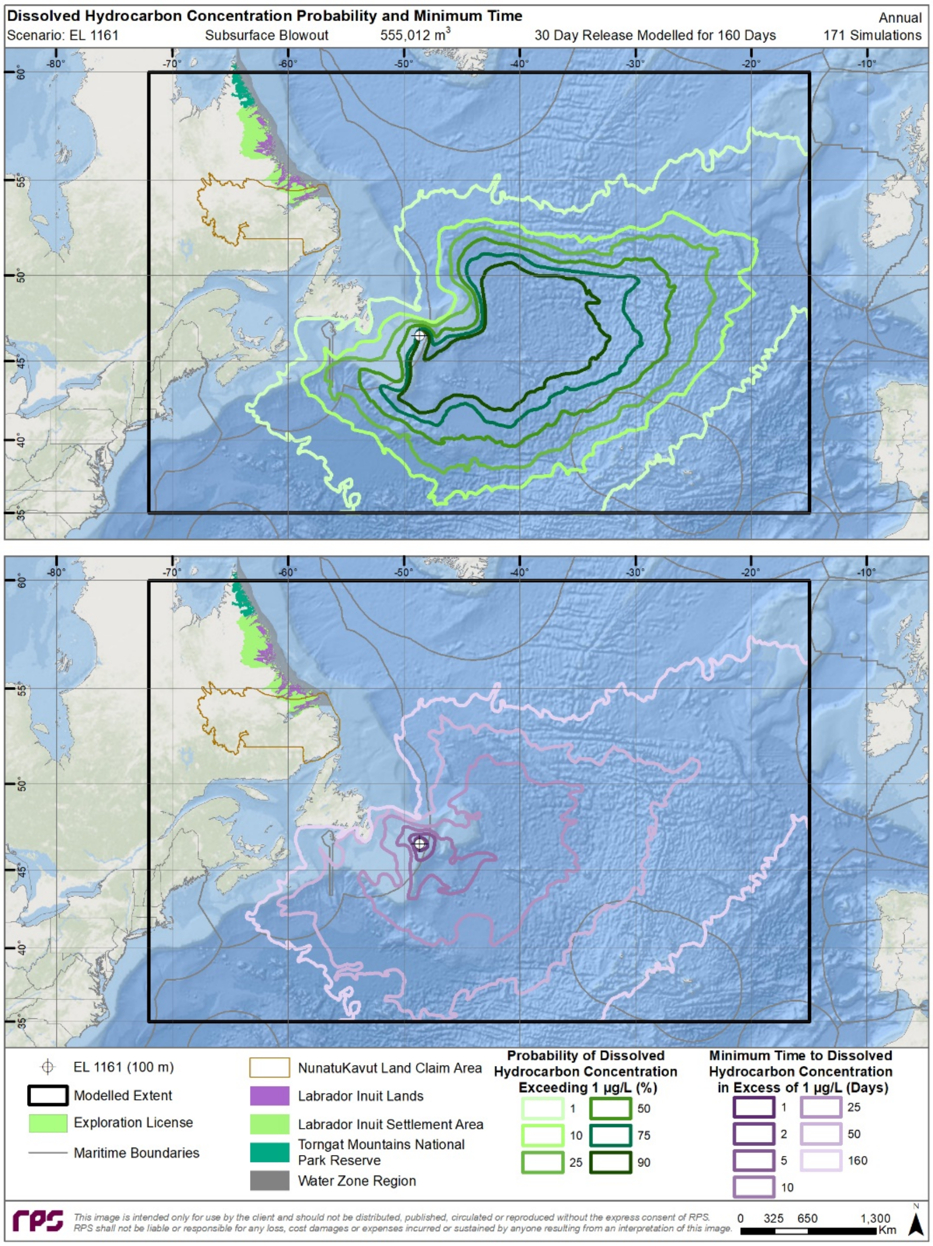


Figure 4-4. Annual probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 30-day subsurface blowout at EL 1161.

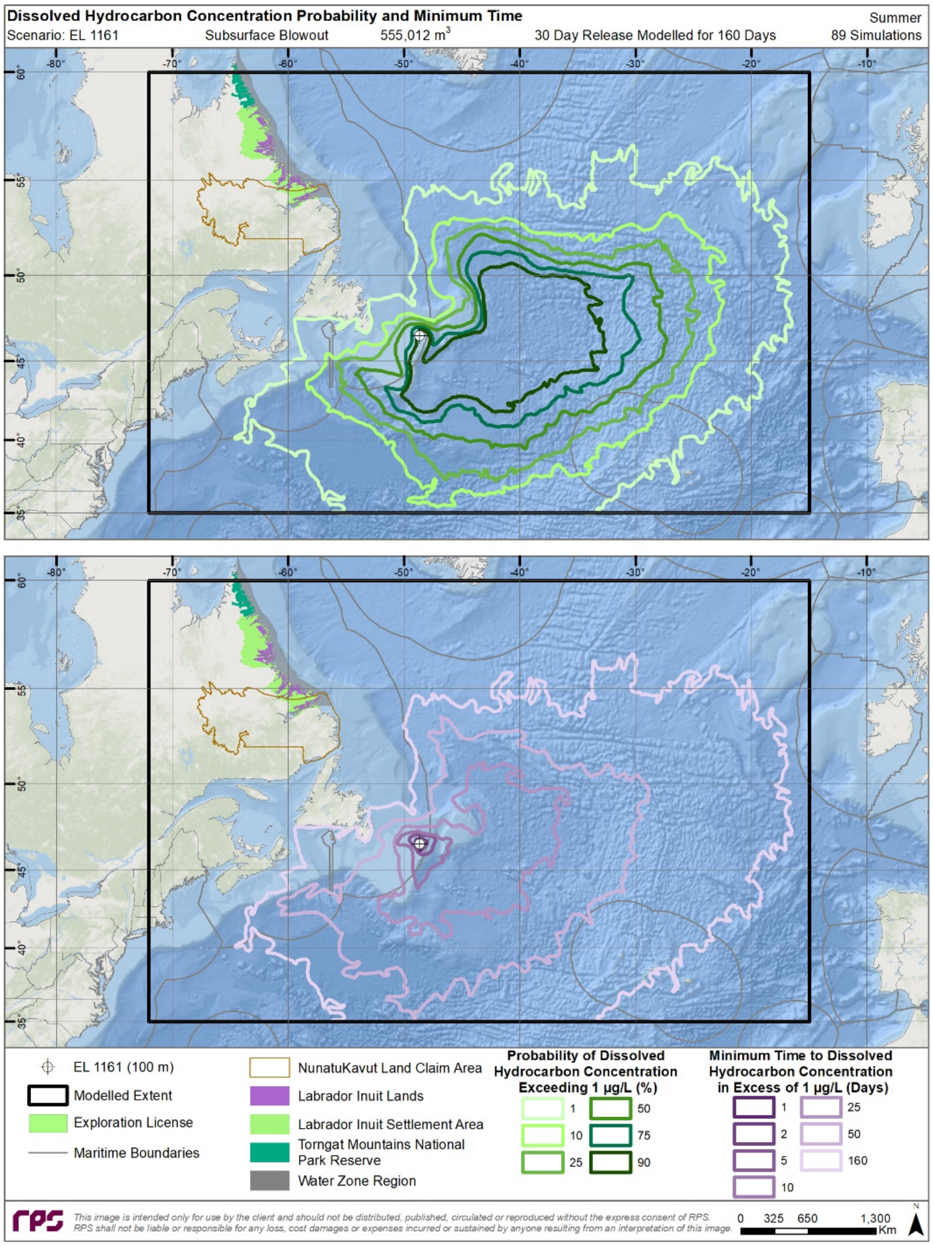


Figure 4-5. Summer probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 30-day subsurface blowout at EL 1161.

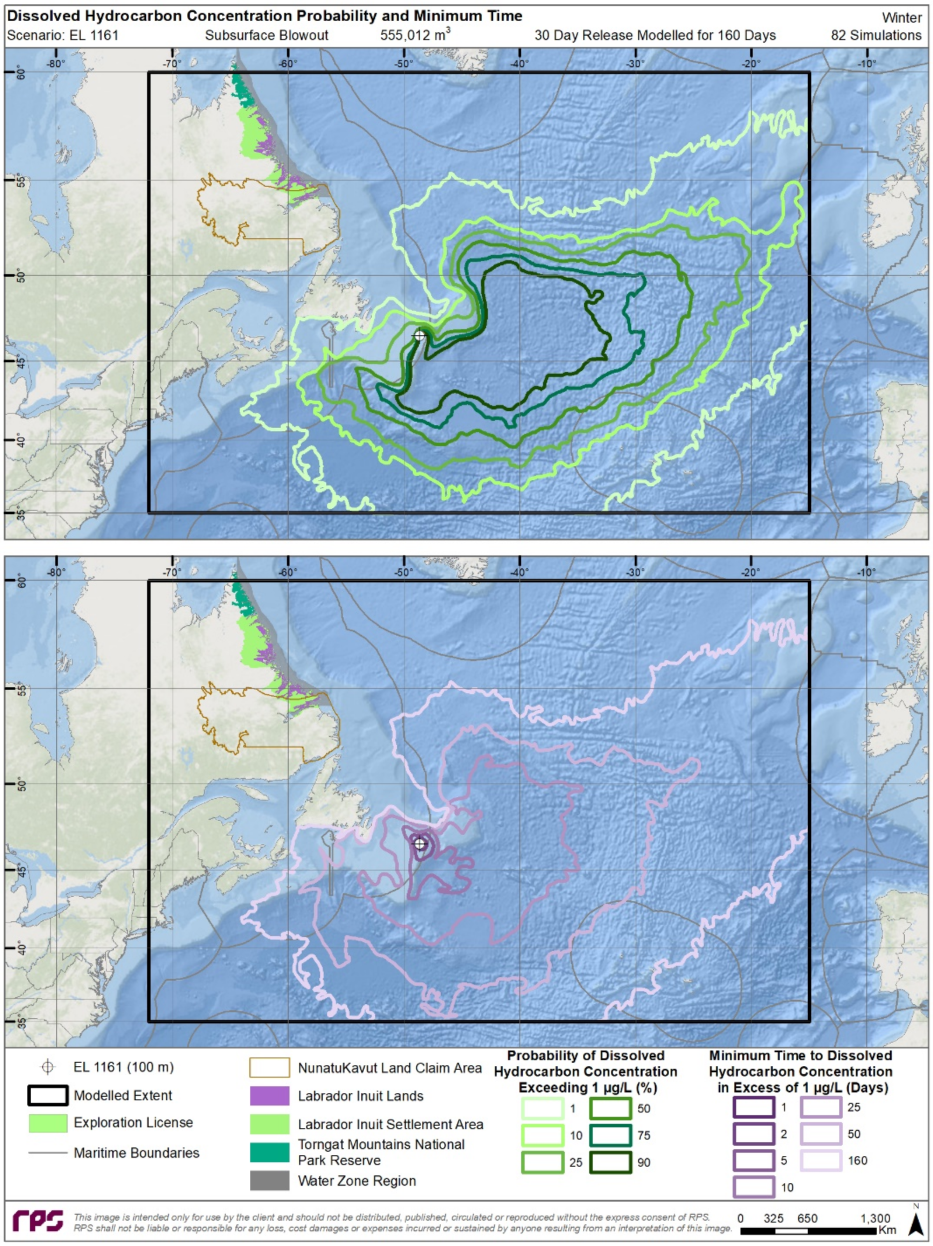


Figure 4-6. Winter probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 30-day subsurface blowout at EL 1161.

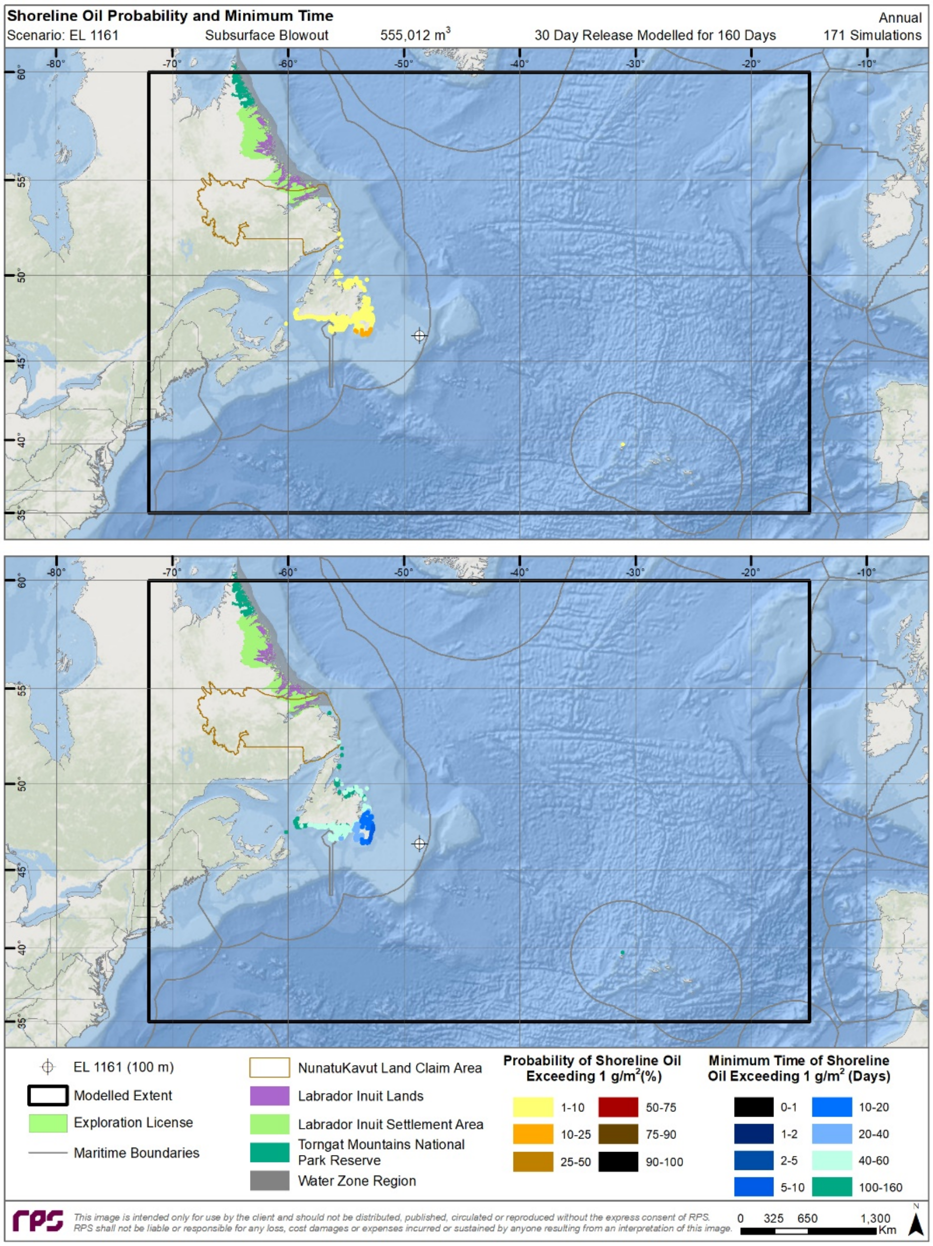


Figure 4-7. Annual probability of shoreline contact >1 g/m² (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 30-day subsurface blowout at EL 1161.

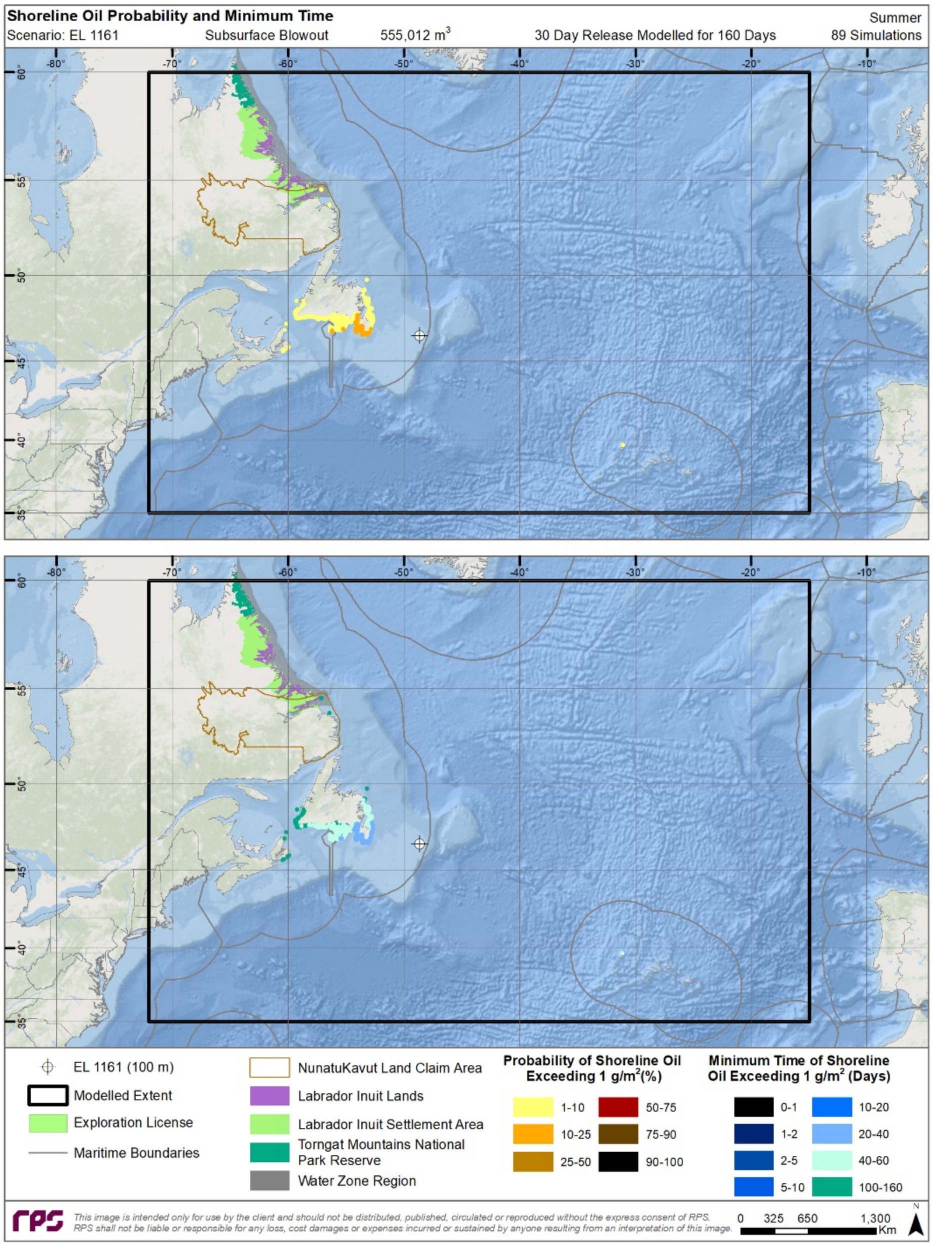


Figure 4-8. Summer probability of shoreline contact >1 g/m² (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 30-day subsurface blowout at EL 1161.

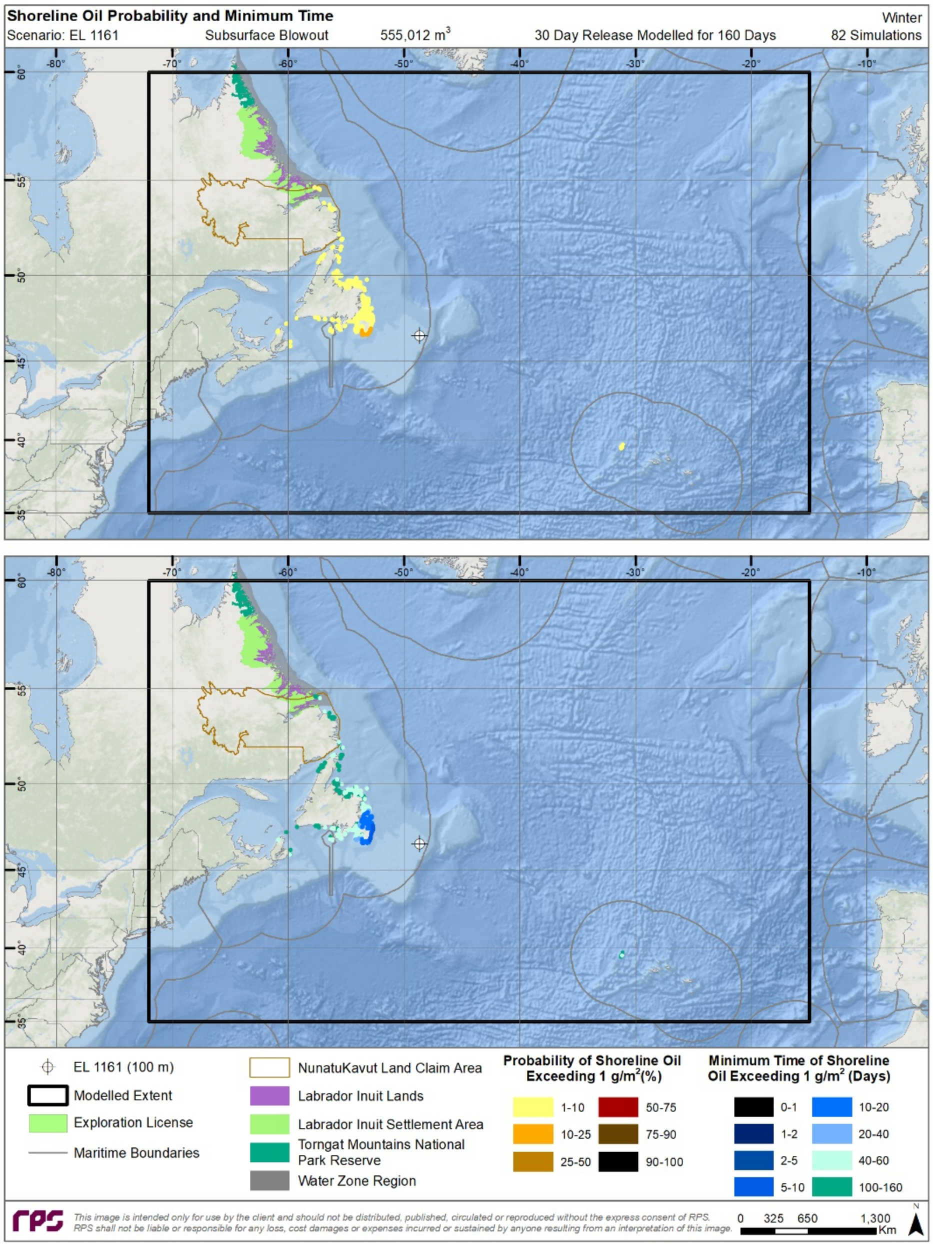


Figure 4-9. Winter probability of shoreline contact >1 g/m² (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 30-day subsurface blowout at EL 1161.

4.1.2 EL 1161 120-day Subsurface Release

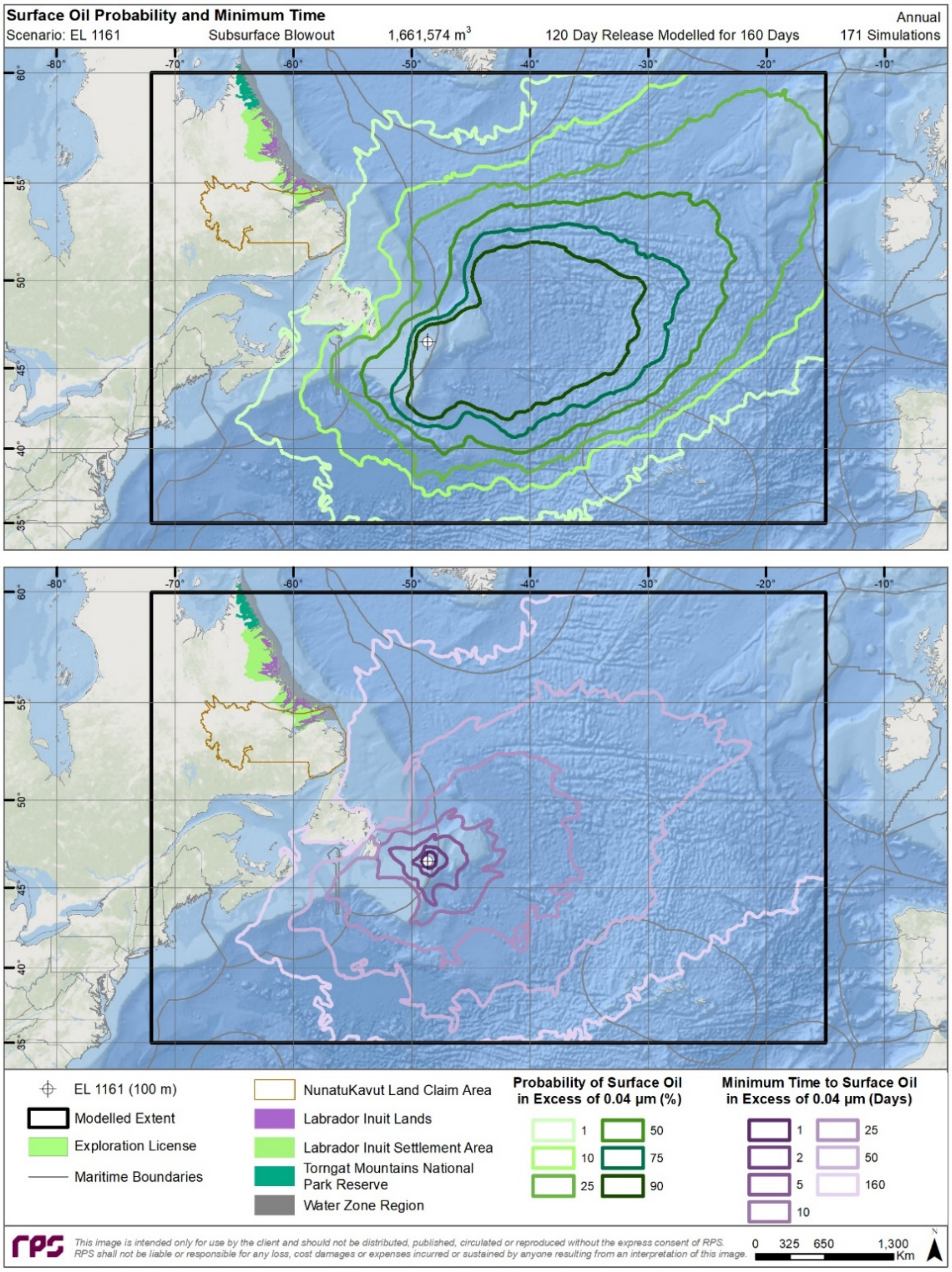


Figure 4-10. Annual probability of surface oil thickness >0.04 µm (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 120-day subsurface blowout at EL 1161.

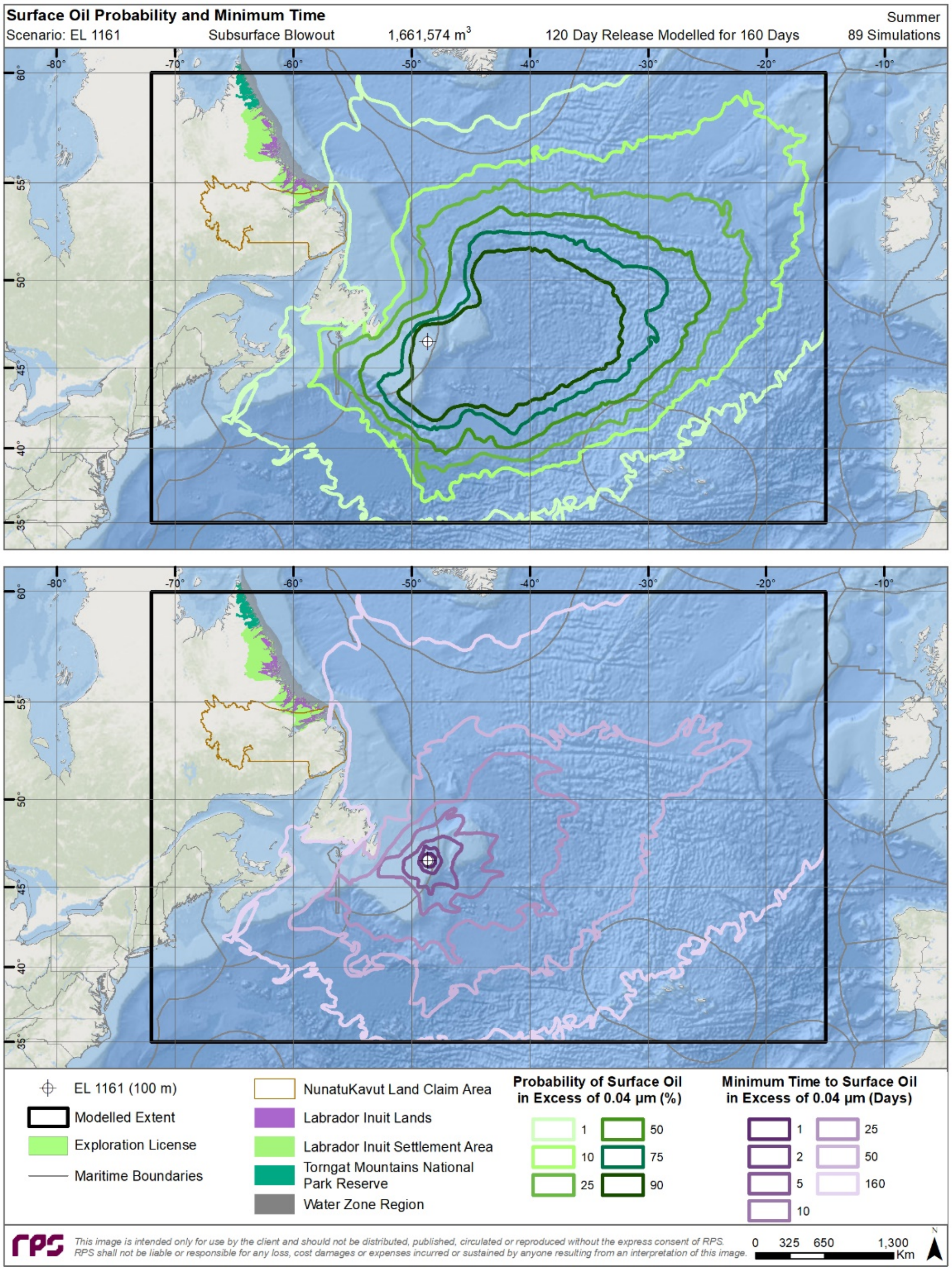


Figure 4-11. Summer probability of surface oil thickness >0.04 µm (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 120-day subsurface blowout at EL 1161.

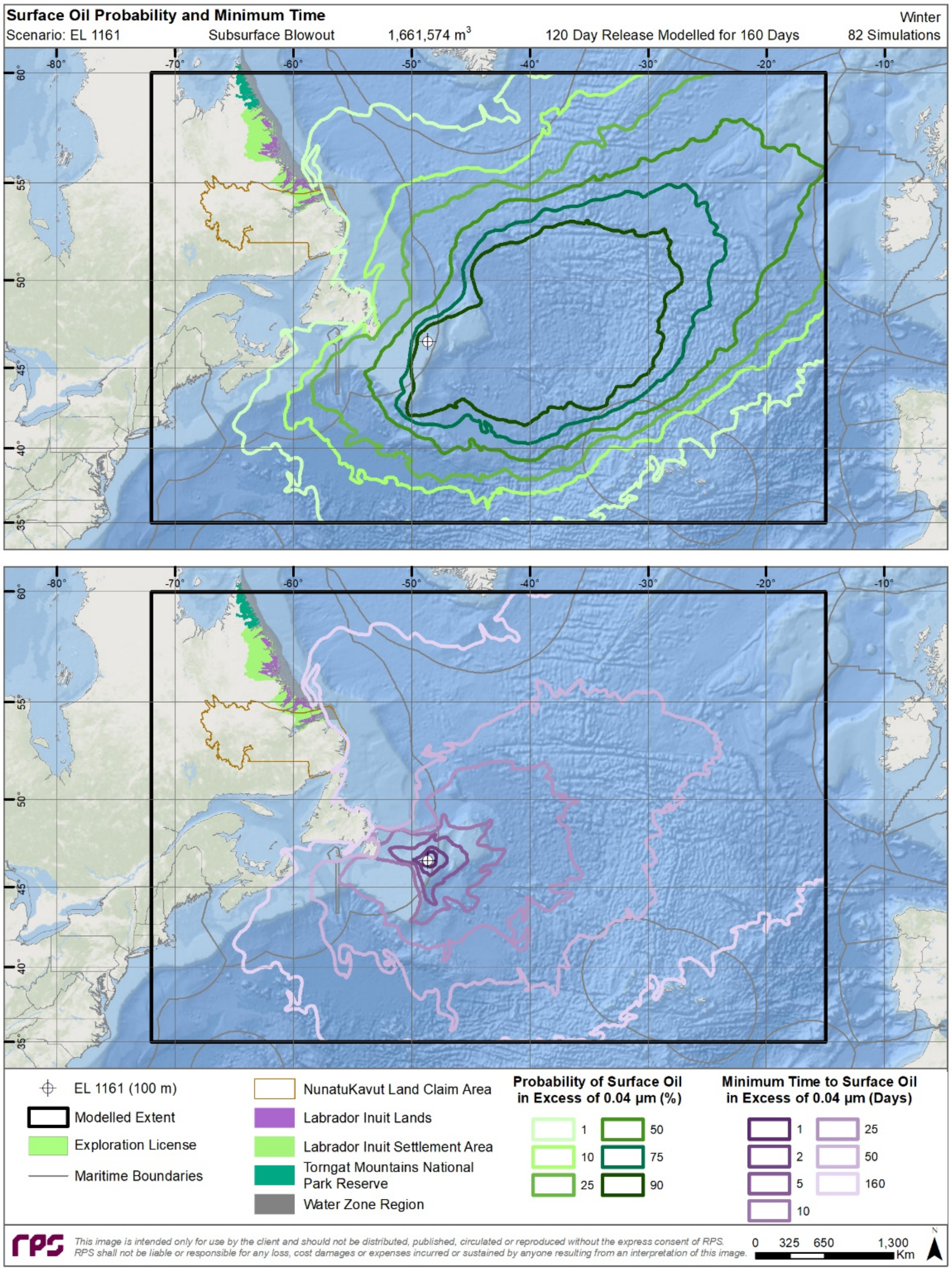


Figure 4-12. **Winter probability of surface oil thickness >0.04 µm (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 120-day subsurface blowout at EL 1161.**

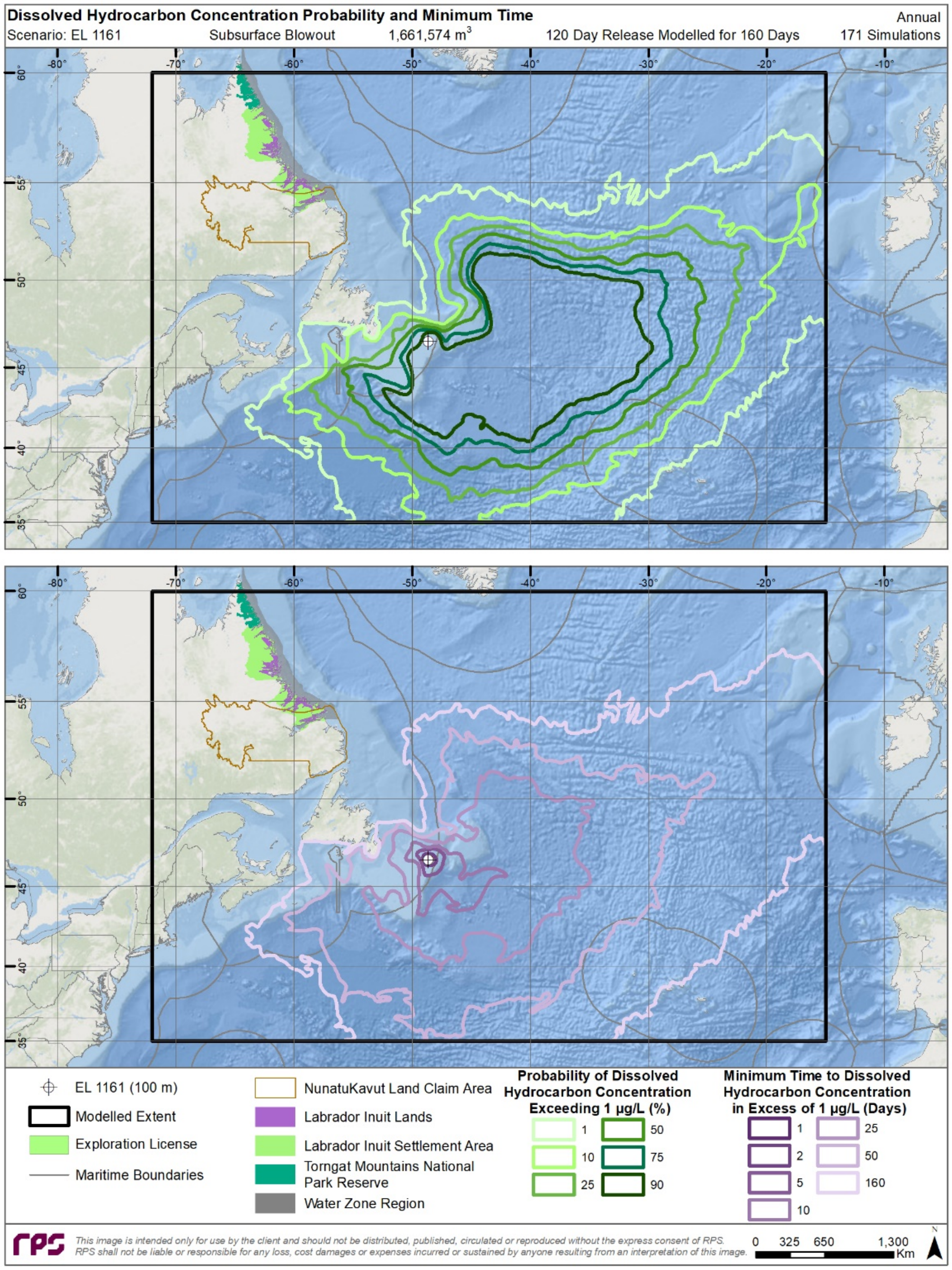


Figure 4-13. Annual probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 120-day subsurface blowout at EL 1161.

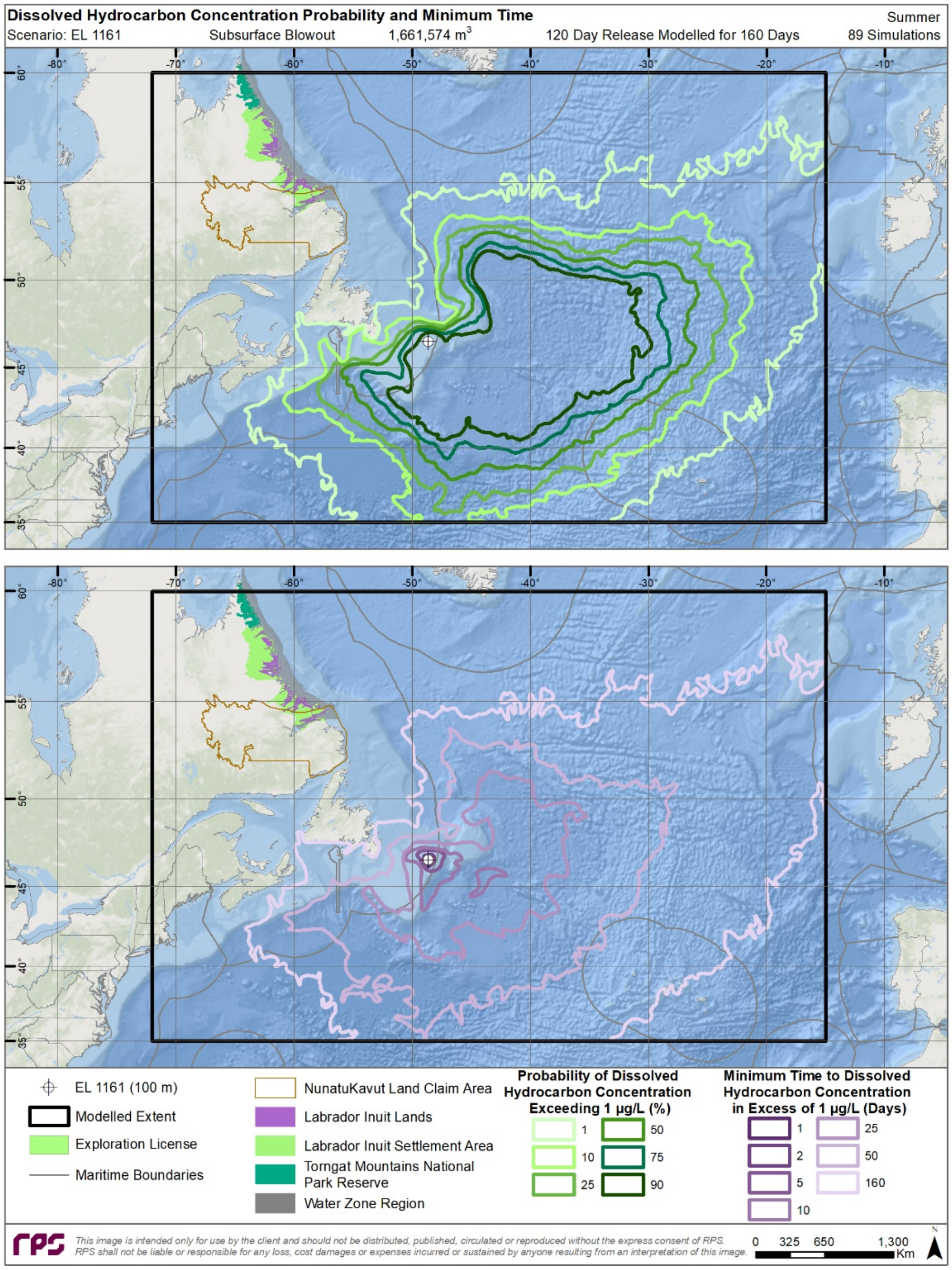


Figure 4-14. Summer probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 120-day subsurface blowout at EL 1161.

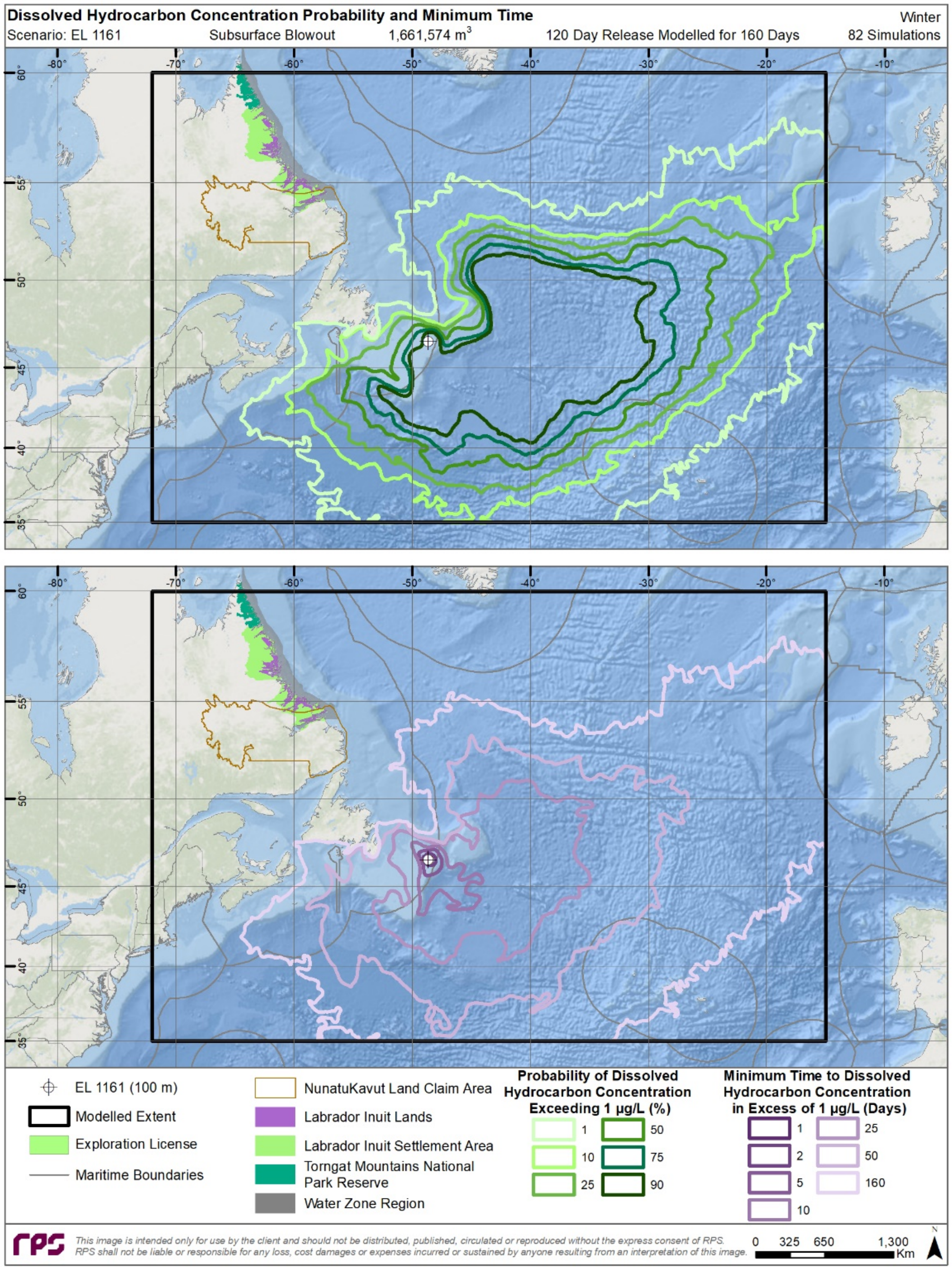


Figure 4-15. Winter probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 120-day subsurface blowout at EL 1161.

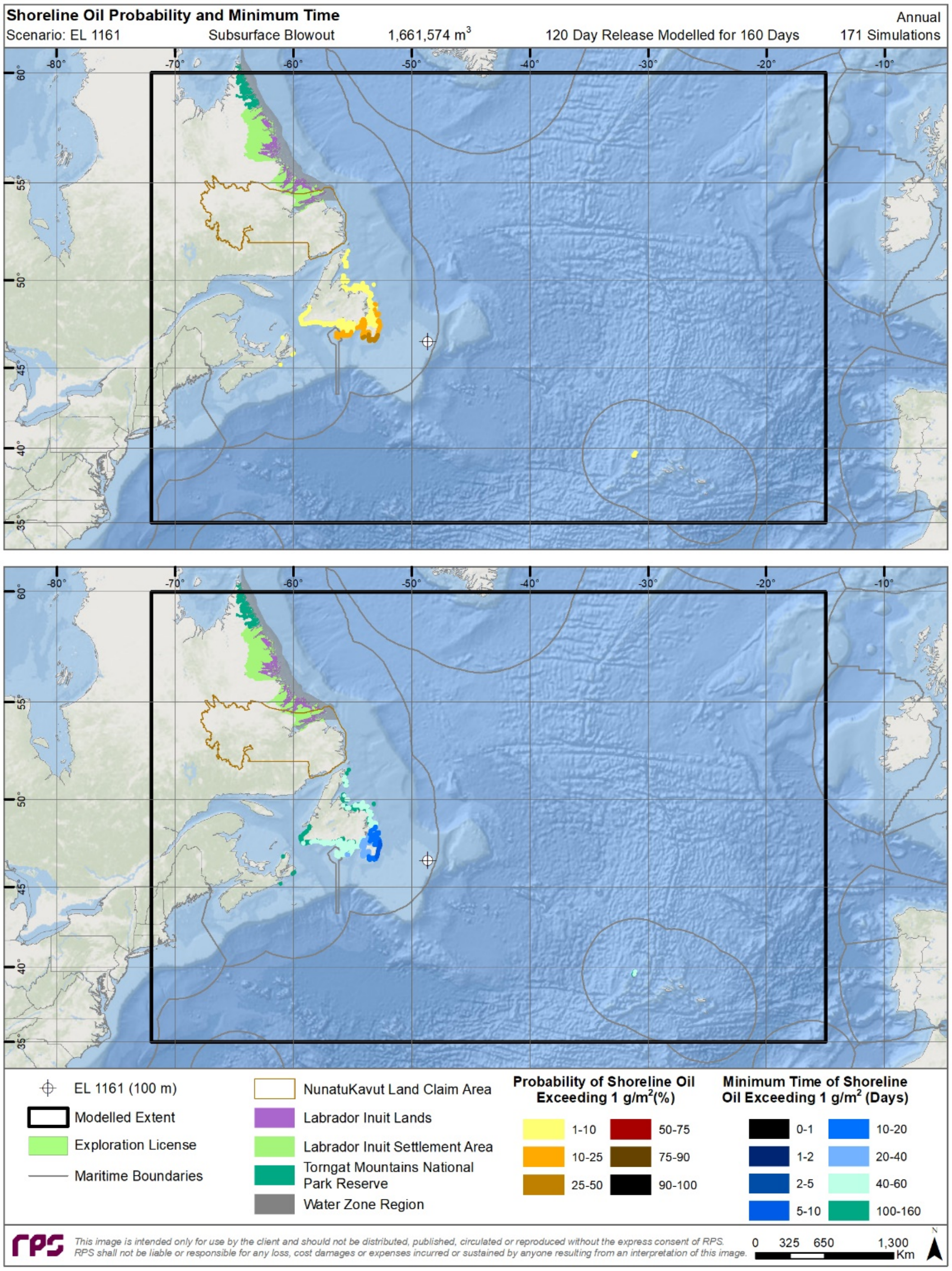


Figure 4-16. Annual probability of shoreline contact >1 g/m^2 (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 120-day subsurface blowout at EL 1161.

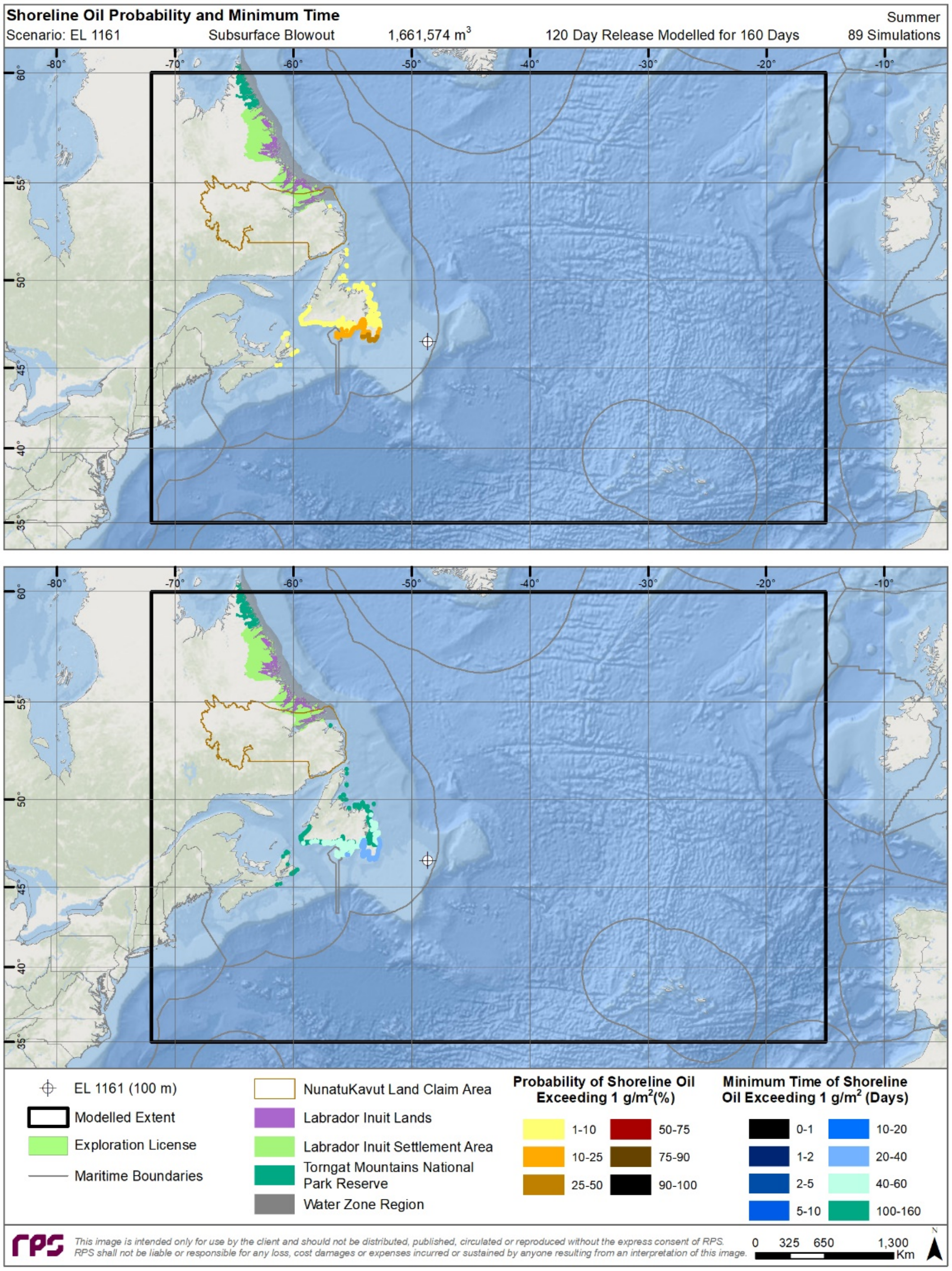


Figure 4-17. Summer probability of shoreline contact >1 g/m^2 (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 120-day subsurface blowout at EL 1161.

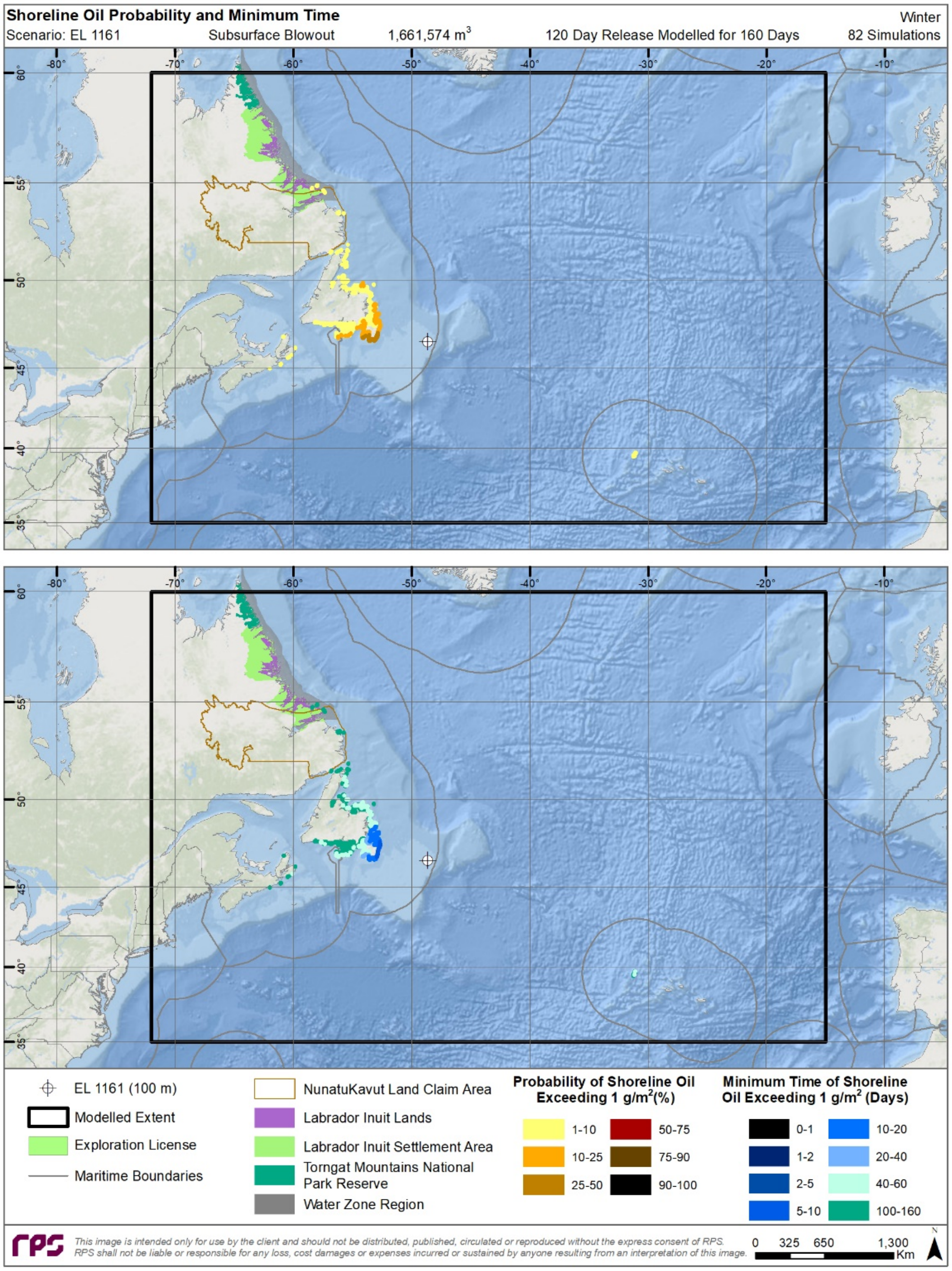


Figure 4-18. Winter probability of shoreline contact >1 g/m^2 (top) and minimum time (bottom) to socio-economic threshold exceedance predictions resulting from a 120-day subsurface blowout at EL 1161.

4.1.3 Summary of Stochastic Results

A total of 171 unique model simulations were conducted for each stochastic analysis at the EL 1161 hypothetical release site, representing subsurface blowouts in waters offshore of Newfoundland. Two blowout release scenarios were modelled for 160-day periods to simulate short (30-day) and long (120-day) duration blowouts. The 120-day release represent the conservative anticipated time to kill the well (effectively stopping the subsurface release) by mobilizing a drilling platform and drilling a relief well, while the 30-day release represents the successful mobilization and implementation of a capping stack to contain the release. The total model duration of 160 days was used to track the trajectory and fate of spilled product as it continued to weather after the release had stopped.

Summaries of the stochastic analyses of potential surface oil and water column exposure by dissolved hydrocarbons depict areas to the east of the release site as having the highest potential likelihood (>90%) to exceed socio-economic thresholds (Figure 4-1 through Figure 4-6 and Figure 4-10 through Figure 4-15). The >90% likelihood area typically extended up to 1,500 km to the east to the edge of the model domain for the surface and water column oil. This is the result of persistent fractions of the Terra Nova being on the surface (emulsified, tarballs, and when environmental conditions are below the pour point). Notably, the high probability contours for surface oil thickness were much greater during winter months, when the temperature was lower than the pour point and surface oil remained thick, as it did not spread (Figure 4-2 and Figure 4-3 for the 30-day release and Figure 4-11 and Figure 4-12 for the 120-day release). As a result of this “freezing” behavior, also note that the water column exceedance footprints for winter were typically slightly smaller than that of summer, the result of the less entrainment and dissolution from surface oil because the oil was below the pour point during winter months. Predicted water column probability footprints were typically smaller than surface oil footprints, with the probability of threshold exceedance predicted to decrease more rapidly for water column results as distance from the release site increased (Table 4-1; Figure 4-4 through Figure 4-6; Figure 4-13 through Figure 4-15). In nearly all stochastic scenarios, lower probabilities of threshold exceedance are generally predicted for surface and/or water column oil contamination north of 60 degrees N. However, higher probabilities of threshold exceedance (90% or above) are predicted for surface and/or water column oil contamination primarily to the east and in many cases to the south (Figure 4-1 through Figure 4-6; Figure 4-10 through Figure 4-15). In addition, <50% of the simulated 30-day releases were predicted to result in surface threshold exceedance >200 km to the west of the release location, while <50% of the 120-day releases were predicted to result in surface threshold exceedance >500 km west of the release location (Figure 4-1 through Figure 4-3, Figure 4-10 through Figure 4-12). Due to the weathering of the oil (i.e., evaporation, dissolution, degradation, emulsification, and formation of tarballs) that took place over the week or more required for oil to reach shorelines, the viscosity of the oil increased, resulting in greater predicted thicknesses of surface oil, and typically resulted in stranding oil on shorelines greater than the threshold of 1 g/m^2 (Figure 4-7 through Figure 4-9, Figure 4-16 through Figure 4-18).

Due to the primarily eastward transport of oil from wind and currents, and the distance of the release location to the shoreline of Newfoundland, the maximum average annual probability of Canadian shoreline exposure above the 1 g/m^2 threshold was approximately 4% and 8% for the two subsurface blowouts, when one considers probabilities of all shorelines susceptible of oiling (Table 4-2). However, maximum probabilities of shoreline oil contamination at specific points ranged from 18-45% depending on the release scenario and season, focused on the Avalon Peninsula (Figure 4-7 through Figure 4-9; Figure 4-16 through Figure 4-18).

As the Labrador current flowed southward along the continental shelf, it was predicted to transport subsurface oil to the south, parallel to the coast (Figure 4-4 through Figure 4-6, Figure 4-13 through Figure 4-15). This oil was predominantly the small droplet sizes that remained underwater for long periods of time (Table 3-5). However, this trend is generally absent in the surface oil projections, as wind forcing was more likely to transport oil to the east (Figure 4-1 through Figure 4-3, Figure 4-10 through Figure 4-12). Oil that was predicted to make its way to the shorelines of Canada would be patchy and discontinuous due to the considerable amount of weathering and natural dispersion that would take place over the weeks or months that were required for oil to reach shore. The minimum time to shorelines for threshold exceedance was 3.7 days in one winter scenario (but typically greater than a week for other scenarios), along the Avalon peninsula and southeastern Newfoundland, >40 days along the northern shores of Newfoundland, southeastern Labrador, and the Azores (Table 4-2; Figure 4-7 through Figure 4-9; Figure 4-16 through Figure 4-18).

Seasonal variability in predicted spill behavior was present in the stochastic results. Regardless of the release duration, the average stochastic probability of shoreline oiling was consistently higher for summer releases than for winter releases (Table 4-2). Similarly, the minimum time to socio-economic shoreline threshold exceedance was approximately three to four times longer in the summer (28 days) than the winter (4-9 days) (Table 4-2). The probability footprints exceeding the threshold for surface oil contamination were larger in the summer compared to winter footprints (Table 4-1). This is due to the potential for greater westward transport of surface oil during the winter, associated with dynamic transitional periods, low pressure systems, and tropical and extra-tropical storms, when compared to the summer. As mentioned previously, as surface oil was transported to the east, it was predicted to reach the model domain boundaries in each modelled scenario due to the prevailing westerly winds and Gulf Stream current (Sections 3.4 and 3.5). However, the minimum time for oil to leave the boundary was nearly always >50 days and in many cases well in excess of 100 days for oil exceeding the highly conservative socio-economic threshold, implying that the oil that left the domain was highly weathered, patchy, and discontinuous.

Intuitively, the longer release durations led to larger spill volumes. The 30-day spill simulations released 555,012 m^3, while 120-day simulations released 1,661,574 m^3, respectively (Table 2-1). Despite the larger spill volume for the 120-day releases (almost three times more), the size of the predicted stochastic footprints did not increase proportionally. This is due to the same underlying forcing (i.e., winds and currents) transporting different volumes of oil with the same speed and direction. While the overall footprint (down to the 1% contour) did not change markedly, the higher probability contours (e.g., 90%) extended much further for the 120-day releases (Table 4-1). The annual stochastic 90% probability footprints of threshold exceedance for surface and water column oil increased by 156% and 62%, respectively, from the 30-day to the 120-day release. Nearly all expansion of footprints for long releases occurred to the east, northeast, and southeast of the release locations with very little expansion of lower probability footprints to the west. In other words, the longer spill duration mainly expanded probability footprints meridionally within the high probability areas east of the release site. Increased release duration also resulted in more predicted potential for shoreline oiling above the 1% probability of threshold exceedance (1,911 km 30-day vs 2,564 km 120-day) (Table 4-1). In addition, there were predicted increases (near doubling) in the overall probability of shoreline oiling for the 120-day releases (Table 4-2).

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. Furthermore, the largest-area threshold exceedance footprints from the 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 171 (annual), 89 (summer), or 82 (winter) individual releases analyzed together.

Table 4-1. Summary of socio-economic threshold exceedances predicted for surface, water column, and shoreline exposure within the modelled domain are provided by season. Predicted areas (km^2) are provided for the >1%, 10%, or 90% likelihood of exposure to oil contours. Predicted shoreline lengths (km) are provided for probability bins of 1-5%, 5-15%, and 15-45%.

Stochastic Scenario Parameters			Areas Exceeding Threshold (km^2)		
Component	Release Scenario	Probability Contour or Bin*	Annual	Winter (ice cover)	Summer (ice-free)
Surface Oil	30-day release	1%	7,167,000	7,601,000	7,037,000
		10%	4,797,000	5,295,000	3,370,000
		90%	450,400	816,600	421,700
	120-day release	1%	7,443,000	7,895,000	7,369,000
		10%	5,438,000	5,840,000	4,516,000
		90%	1,155,000	1,537,000	1,031,000
Water Column Dissolved Hydrocarbons	30-day release	1%	5,992,000	6,146,000	5,930,000
		10%	3,512,000	3,630,000	3,423,000
		90%	775,400	770,400	786,000
	120-day release	1%	6,058,000	6,246,000	6,192,000
		10%	4,064,000	4,143,000	3,894,000
		90%	1,258,000	1,279,000	1,272,000
Shoreline Oil	**Lengths Exceeding Threshold (km)**				
	30-day release	1 – 5%	1,241	864	754
		5 – 15%	648	432	721
		15 – 45%	23	23	32
		All Probabilities	1,911	1,319	1,507
	120-day release	1 – 5%	1,052	809	754
		5 – 15%	1,144	937	804
		15 – 45%	368	423	496
		All Probabilities	2,564	2,169	2,054

*Bins are based on stochastic probabilities; for example, 450,400 km^2 of the ocean surface is predicted to exceed the 0.04 µm surface oil threshold in 90% of the 171 modelled simulations from the 30-day release at EL 1161 over the entire 160-day modelled duration.

Table 4-2. Shoreline contamination probabilities and minimum time predicted for oil exposure for all shorelines.

All Shorelines						
Threshold	**Scenario**	**Scenario Timeframe**	**Probability of Shoreline Oil Contamination (%)**		**Time to Shore (days)**	
			Average	**Maximum**	**Minimum**	**Maximum**
Oil exposure exceeding 1 g/m^2 for all shorelines	30-day release	Annual	4.2	19.0	9.2	142.0
		Winter	3.7	21.0	3.7	158.3
		Summer	5.9	18.0	28.0	159.8
	120-day release	Annual	8.3	43.0	9.2	156.1
		Winter	9.0	45.0	9.2	159.9
		Summer	9.4	40.0	28.0	159.6

4.2 Deterministic Analysis Results

Individual trajectories of interest were selected from the stochastic ensemble of results for the deterministic analysis. The deterministic trajectory and fate simulations provided an estimate of the transport of oil through the environment as well as its physical and chemical behavior for the specific set of modelled environmental conditions. Representative 95th percentile credible “worst-case” trajectories for surface oil exposure, water column contamination, and contact with shoreline were identified from the stochastic subsurface scenarios and release duration (i.e., 30 vs. 120 days). These highly conservative individual cases were selected based upon the size of the surface oil footprint, volume of oil in the water column, and the length of shoreline contacted with oil. Three individual trajectories representative of the 95th percentile for surface, water column, and shoreline exposure for each release, as well as the 1,000 L marine diesel batch spill are presented below. This resulted in a total of seven individual trajectories (six associated with subsurface blowouts and one associated with the marine diesel batch spill) (Table 2-6).

The following sections (Sections 4.2.1 through 4.2.4) contain figures corresponding to each identified representative case and tables summarizing the areas exceeding specified thresholds. During modelling, components of oil were tracked as floating surface oil, entrained droplets of whole oil, dissolved hydrocarbon constituents, stranded oil on shorelines and sediments, evaporated, degraded, and left the model domain. The figures provided depict the cumulative footprint of all oil predicted to be within a region over the entire modelled duration. Therefore, the depicted footprints are much larger than the amount of oil that would be present in a region at any given time following the release of oil. This concept is illustrated in Figure 4-19 which portrays predicted surface oil thickness at five specific time steps or “snapshots” in time (days 2, 10, 50, 100, and 160) for the 95th percentile surface oil thickness case for the 30-day release at EL 1161. Note the patchy and discontinuous nature of the predicted footprint as the released oil dispersed and thinned over time. Figure 4-20 portrays the cumulative footprint for the exact same simulation. The area covered is much larger, depicting the maximum surface oil thickness that was predicted to occur at each location over the entire modelled time period. The remaining figures in this report will depict cumulative footprints as opposed to “snapshots” at given time steps to provide conservative estimates of potentially affected areas.

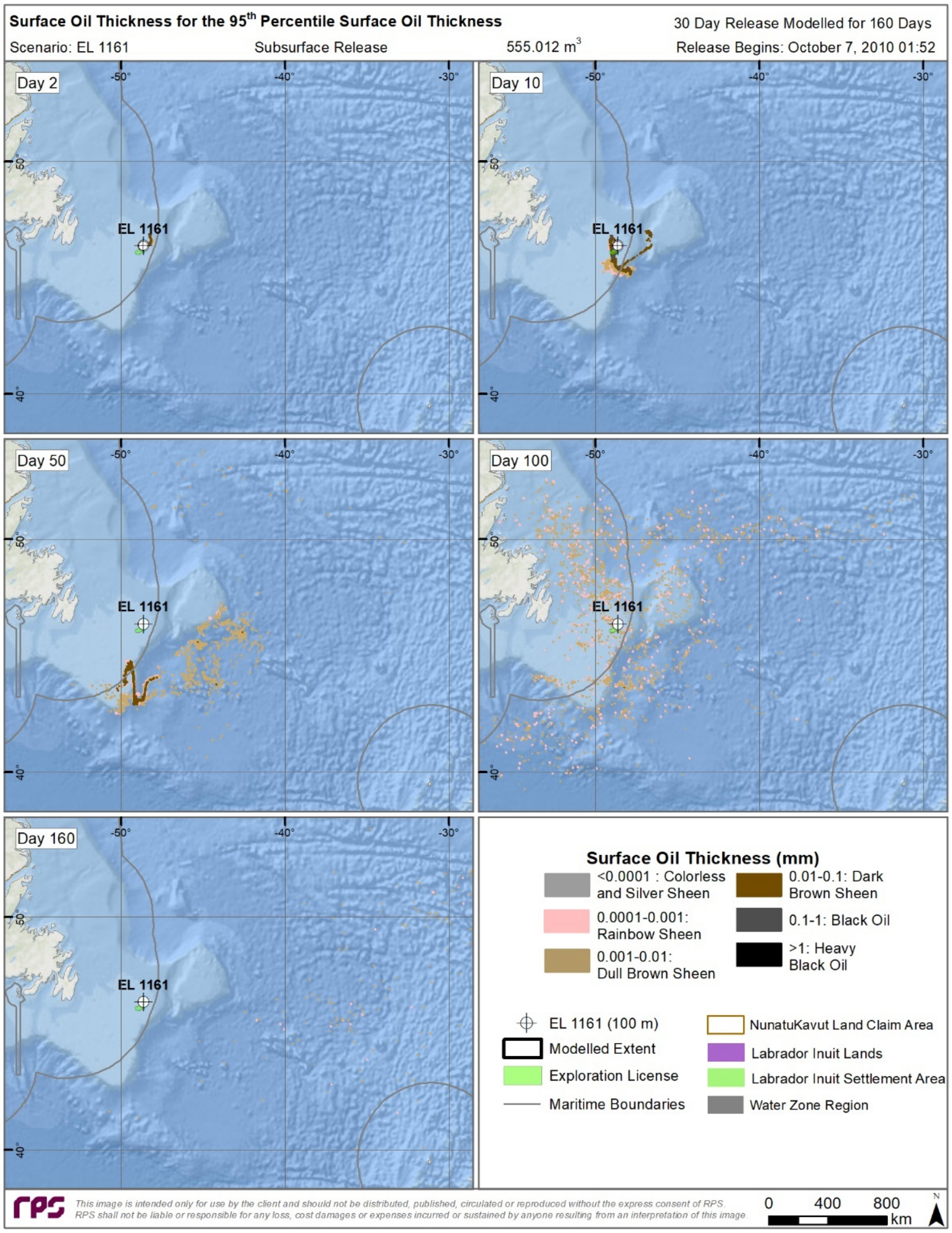


Figure 4-19. Predicted surface oil thickness for the 95th percentile surface oil exposure case for the 30-day release at EL 1161 at days 2, 10, 50, 100, and 160 to illustrate the variation in size of the surface oil footprint over the course of the model duration.

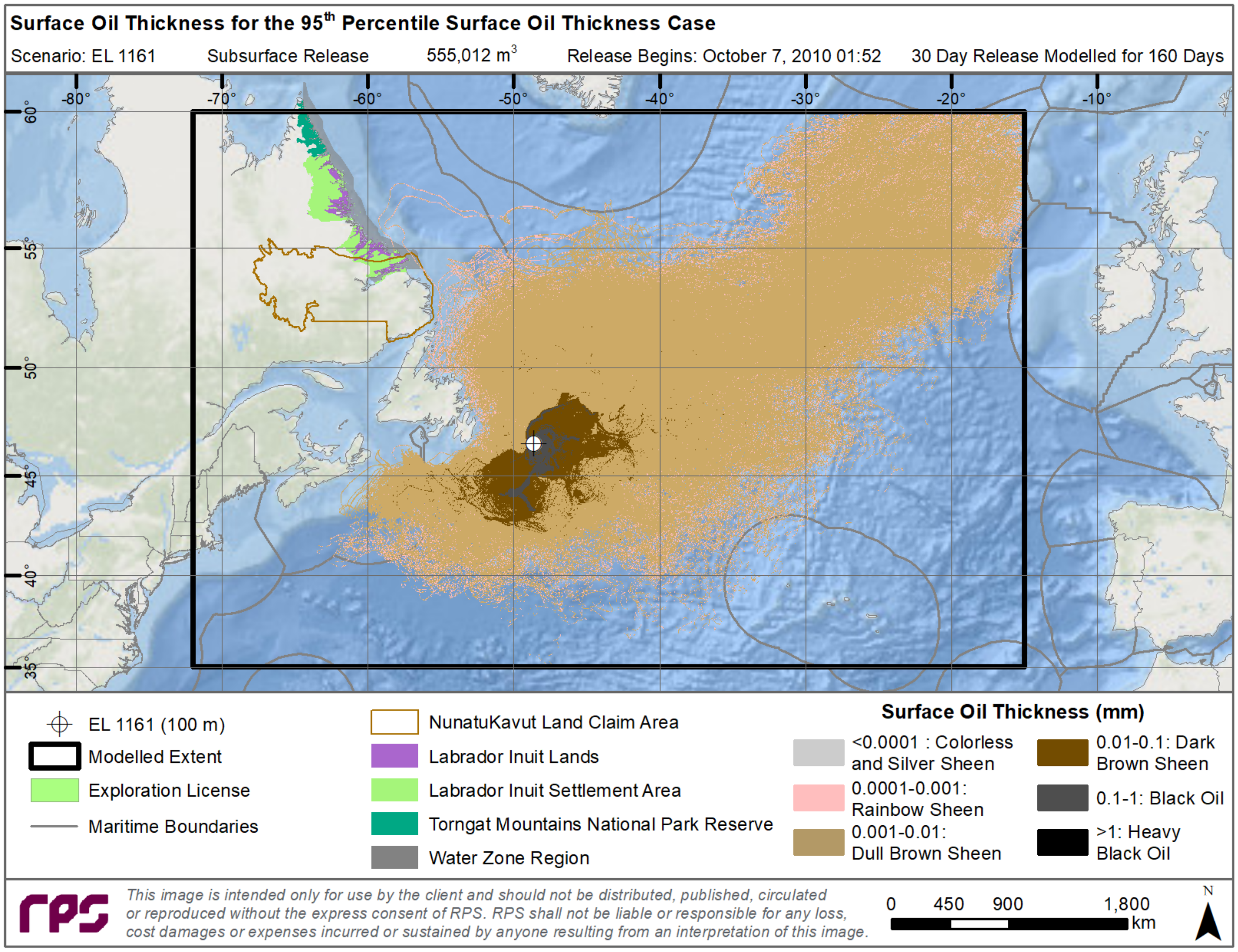


Figure 4-20. Maximum cumulative surface oil thickness for the 95th percentile surface oil exposure case for the 30-day release at EL 1161 to illustrate the much larger size of the cumulative surface oil footprint over the entire model duration, compared to the size of the surface oil footprint on any one day or time step. Note that the information contained in this figure is from the same scenario that was presented in (Figure 4-19).

The types of figures that were used to summarize modelling results are provided, along with brief descriptions of the information that they portray. Note that the thicknesses and concentrations for the modelled blowouts were calculated on a grid with a resolution (i.e., grid cell size) of 4 km by 5 km, which is equivalent to 0.045 degrees by 0.045 degrees. For concentration grids, vertical binning included 50 m increments over the entire water column.

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, the amount of oil in contact with the shore or sediments, the amount of oil evaporated into the atmosphere, and the amount of oil 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. The minimum thickness of surface oil >0.04 µm is displayed (cumulative over all modelled time steps). Note that floating oil mass is calculated as an average over grid cells, thus in reality, the oil would be patchy and discontinuous and could be thinner or thicker within particular areas of a single grid cell.
3. **Water Column Dissolved Hydrocarbon Concentration (DHC) 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 (Table 2-3).
4. **Water Column Total Hydrocarbon Concentration (THC) 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 2-3).
5. **Shoreline and Sediment Total Hydrocarbon Concentration (THC) Maps:** Depict the predicted total mass of oil (per unit area as g/m^2) deposited onto the shoreline and on sediments.

Note that for the diesel batch spill scenario, only a mass balance graph and surface oil thickness map are provided.

4.2.1 Surface Oil Exposure Cases

Results for the identified 95th percentile (i.e., credible "worst-case") surface oil exposure cases for the 30- and 120-day releases at EL 1161 are provided. Note that the modelled release dates for each of the representative scenarios differed from one another (Table 2-6). Each of the trajectories in the stochastic analysis represented a different start date and associated environmental conditions (e.g., wind and current speed/direction), which resulted in different predicted outcomes. For example, the 30-day release is representative of a winter case (i.e., start date in October) and the 120-day case was representative of a summer case (i.e., start date in July).

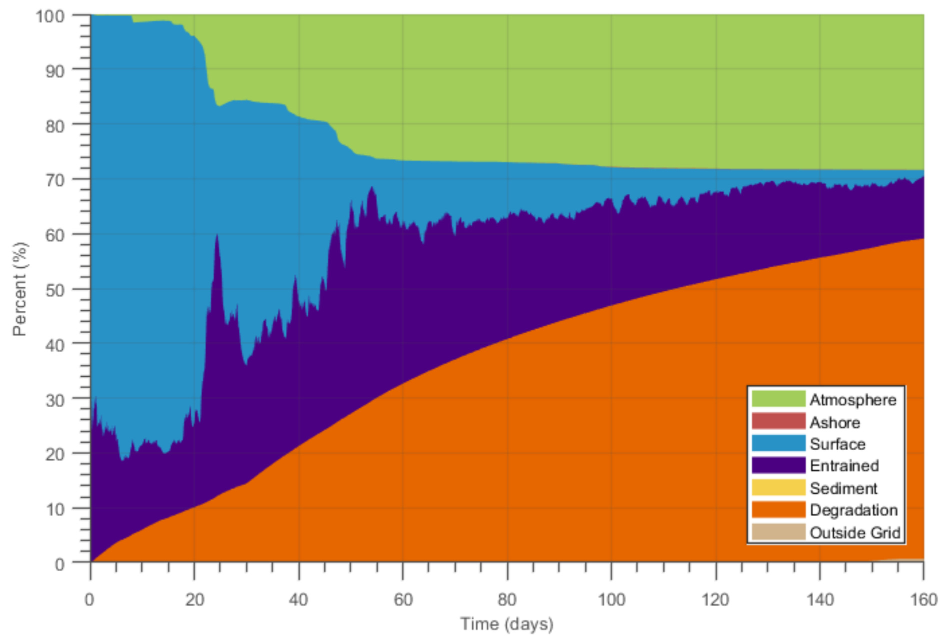
Overall predicted surface area exposed to oil >0.001 mm (dull brown sheens to heavy black oil) was similar (same order of magnitude) between release durations for the selected deterministic cases, although slightly larger surface areas were predicted for the 120-day releases compared to the 30-day releases (Figure 4-22; Table 4-3). Smaller regions within 100 km of the release location were predicted to have heavy black oil (>1 mm), while black oil extended out to nearly 300 km within the two representative 95th percentile "worst cases" for surface oil. It is important to note that these scenarios were identified as some of the largest predicted cumulative surface oil footprints (95th percentile) out of all (171) of the 160-day simulations.

Water column concentrations (THC and DHC) were predicted to be of a similar magnitude between releases. Most of the waters with potential elevation in dissolved hydrocarbon concentrations (>500 µg/L) were within 200 km of the release site. This was due to the soluble hydrocarbons entering the water column during the initial ascent of the oil to the surface, the rapid dispersion and degradation within the water column, and the rapid rate of evaporation of the soluble fraction (which is also volatile) at the surface, when compared to the slower rate of dissolution. Elevated concentrations of dissolved hydrocarbon contamination at depth were not predicted to cross into shallower waters over the shelf, as subsurface currents follow pressure surfaces (isopycnals), which circulated around the Flemish Cap and southwest along the shelf break (Figure 4-23). The highest concentrations of total hydrocarbons (>15,000 µg/L) were predicted to occur at the release location, with the highest levels of contamination to the south and southeast, depending on the wind and currents at the time of release (Figure 4-24). The much larger extent of THC, when compared to the DHC, is the result of the entrainment of surface oil into the upper wave mixed layer. While this THC footprint is quite large, compared to the DHC, it is low concentration and transient.

The 95th percentile 30-day surface oil exposure case was predicted to result in shoreline oiling of generally 100 to >500 g/m^2 (exceeding the socio-economic threshold) along approximately 358 km of north eastern Newfoundland, the northern Avalon peninsula, and southeastern Labrador coastlines (Table 4-3 and Figure 4-25). The 95th percentile 120-day surface oil exposure case was not predicted to contact any shorelines. Sediment oil contamination was predicted to the south of the release location on the Grand Banks for each representative scenario at concentrations generally <0.1 g/m^2 (Figure 4-25).

At the end of the 160-day simulations for the 95th percentile surface oil exposure for 30- and 120-day releases, large percentages of the oil were predicted to degrade (~52-58%) and evaporate (~25-28%), accounting for >77% of each modelled release. The amount of oil predicted to remain on the water surface was <3%, while <17% was predicted to remain entrained in the water column (Table 4-4). Less than 4% of the released oil (predominantly persistent surface oil) was predicted to be transported outside of the modelled domain. Shoreline contact made up a very small proportion of releases (<1%) and oil transported to the sediment was not a major fate pathway, with <0.1% predicted to settle on sediments (Table 4-4).

Frequent cycling of wind and calm events were evident in all surface oil exposure cases, as indicated by "see-sawing" between oil on the surface and entrained oil in the water column (Figure 4-21). During calmer more quiescent periods, oil was predicted to rise to the surface forming slicks, while during periods with wind, surface breaking waves were formed, which resulted in surface oil becoming entrained into the water column.



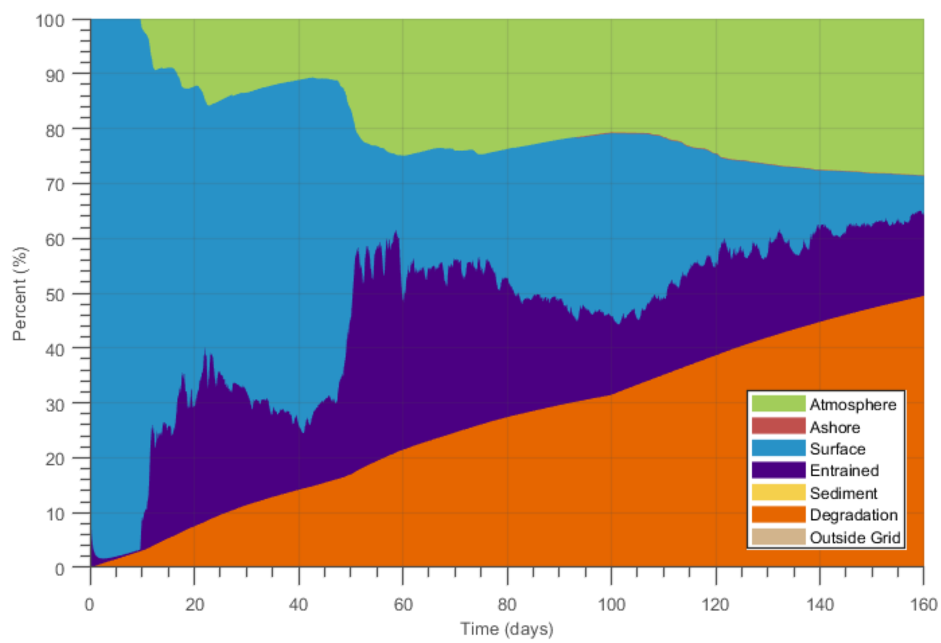


Figure 4-21. Mass balance plots of the 95th percentile surface oil thickness cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.

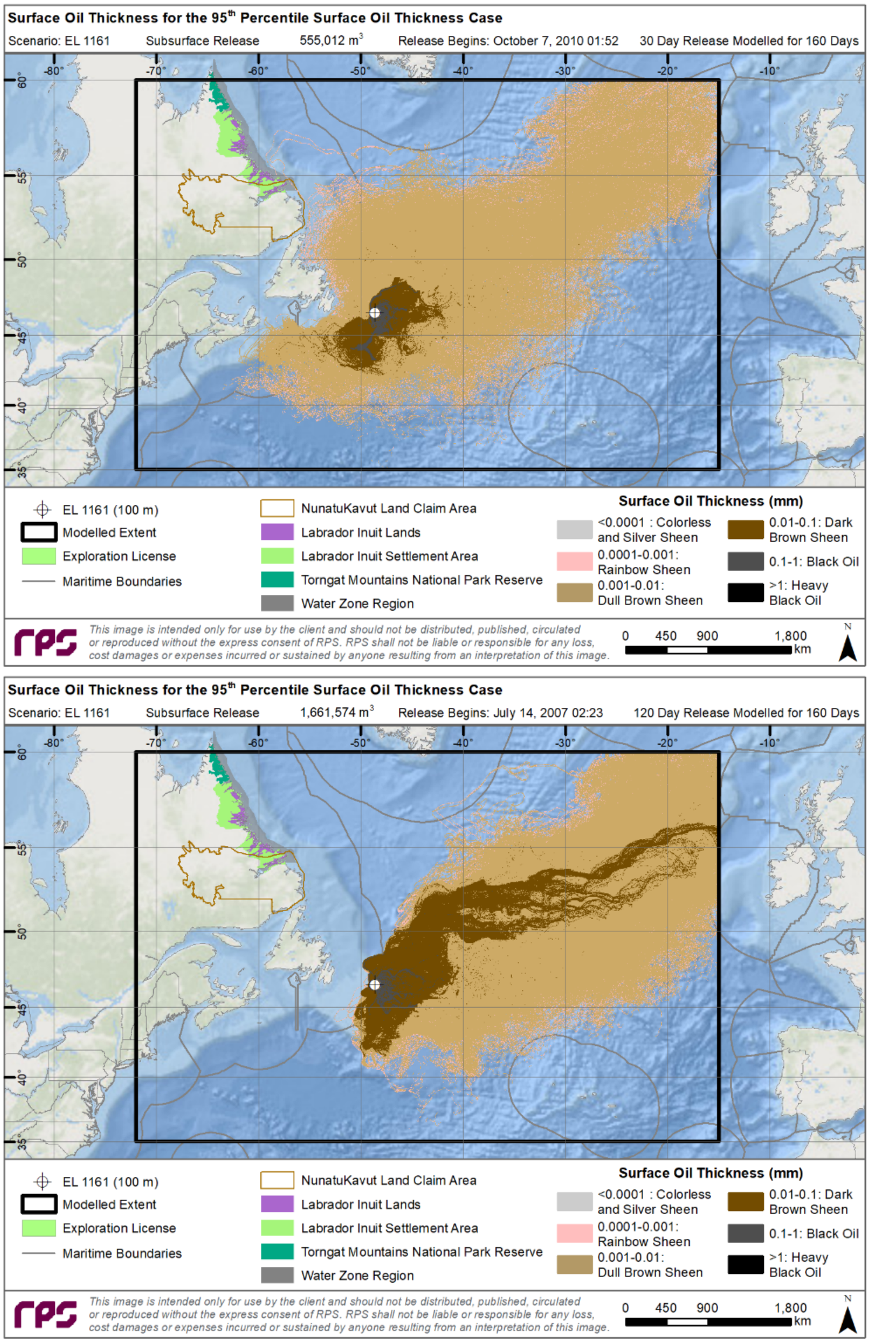


Figure 4-22. Surface oil thickness for the 95th percentile average surface oil thickness cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.

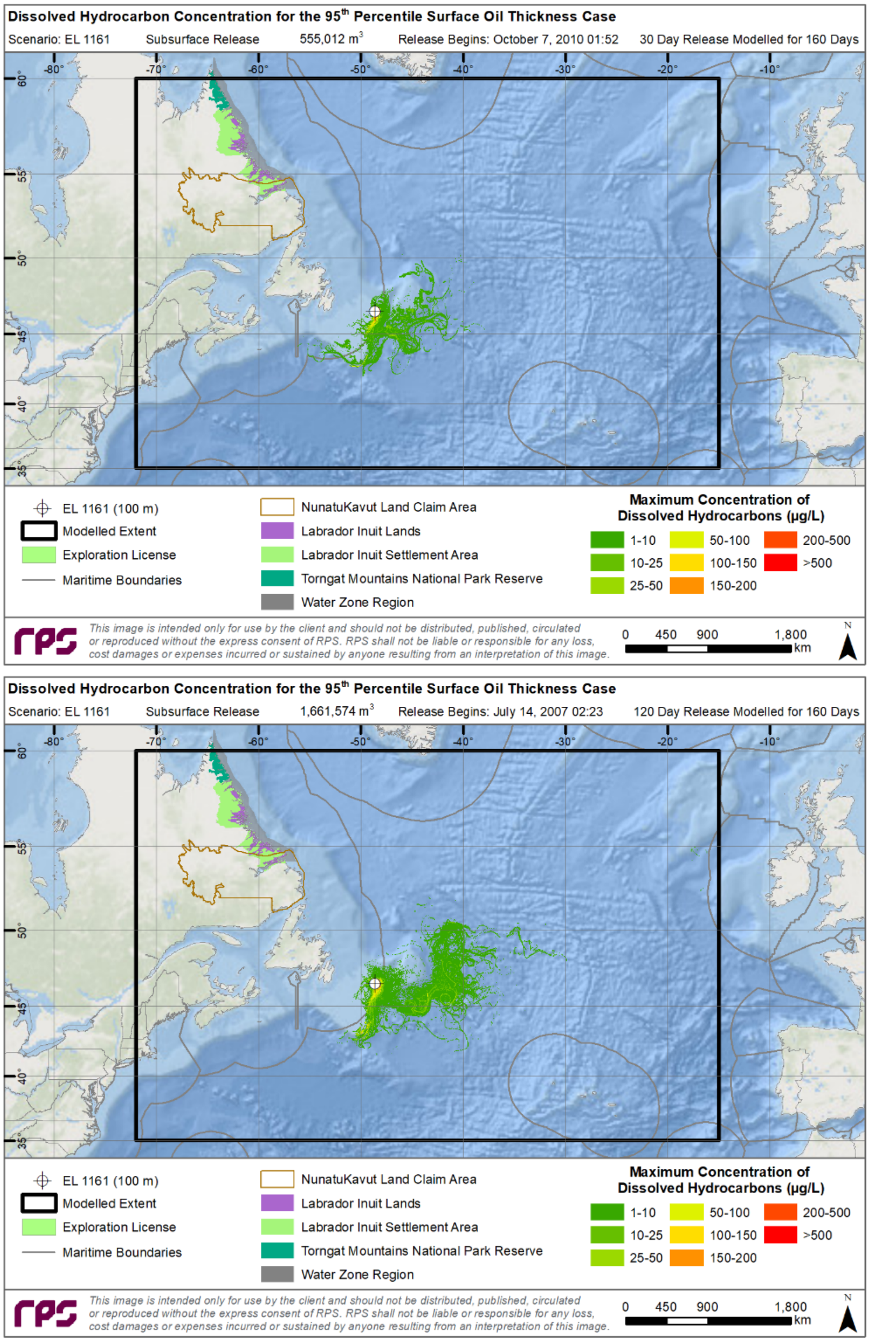
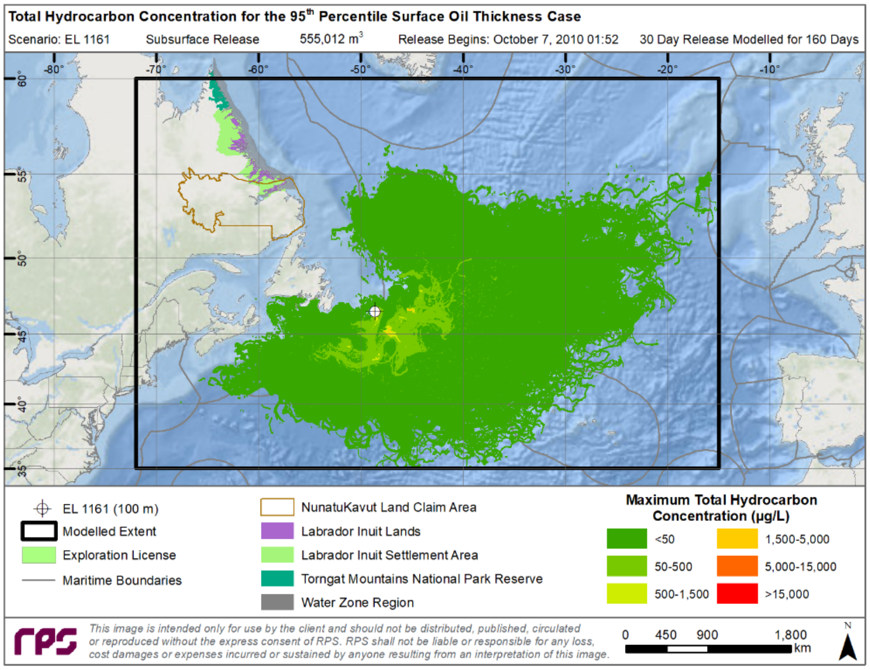


Figure 4-23. Maximum DHC at any depth in the water column for the 95th percentile average surface oil thickness cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.



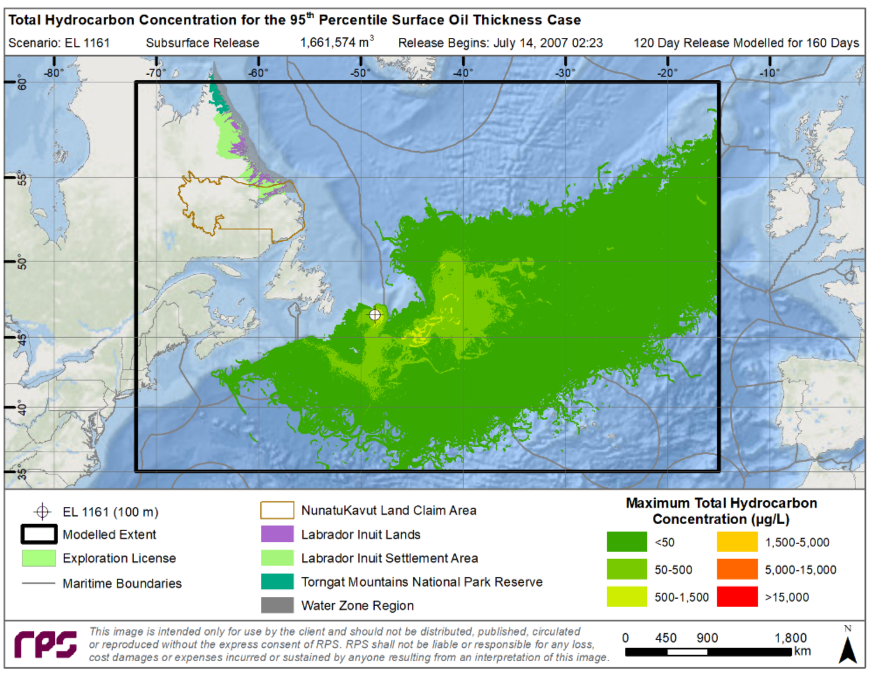


Figure 4-24. Maximum THC at any depth in the water column for the 95th percentile average surface oil thickness cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.

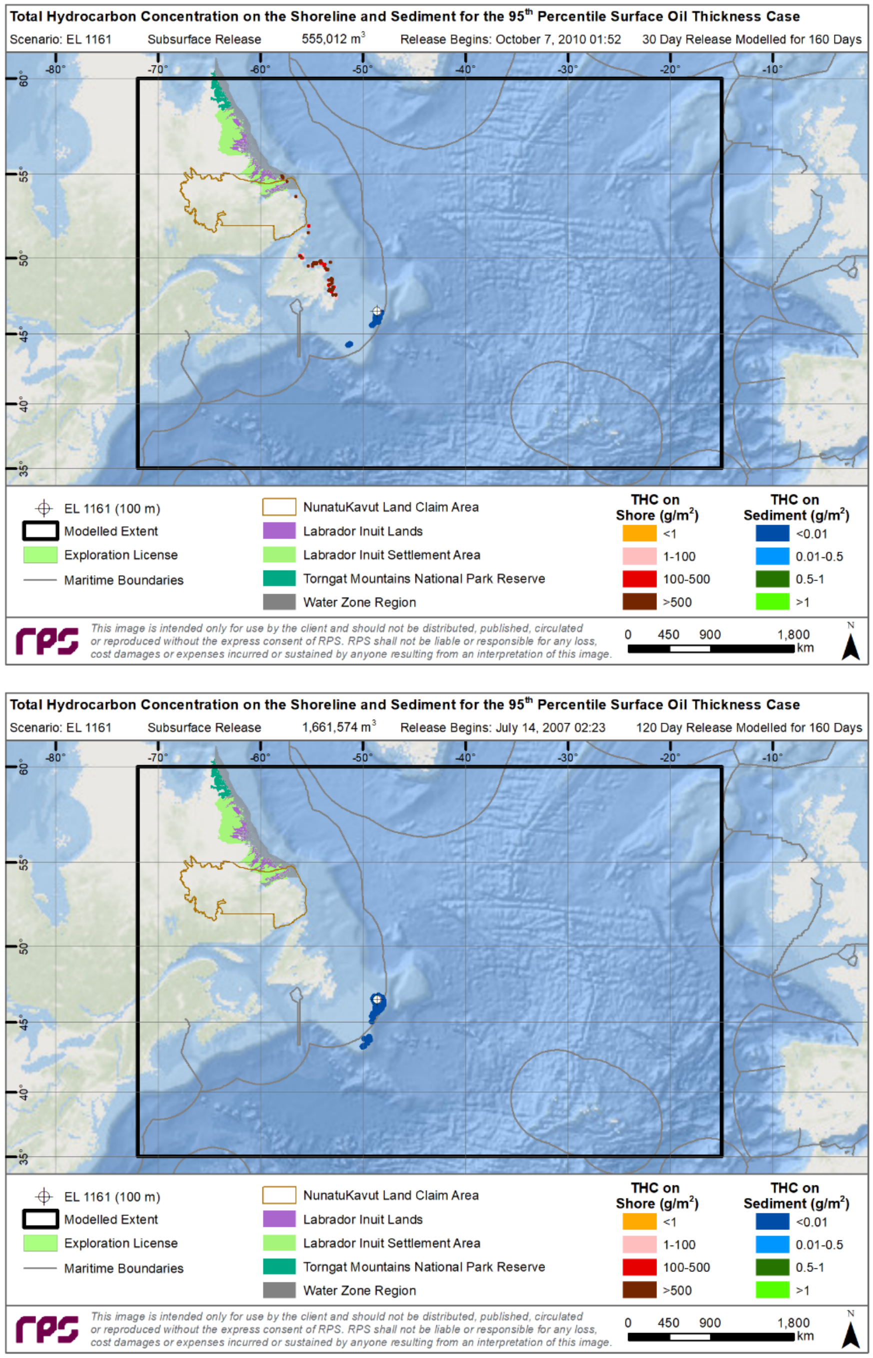


Figure 4-25. THC on the shore and sediment for the 95th percentile average surface oil thickness cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.

4.2.2 Water Column Exposure Cases

The results for the identified 95th percentile (i.e., credible “worst-case”) water column exposure cases for the 30- and 120- day duration releases are provided. Note that the modelled release dates for the representative scenarios at each site differed (Table 2-6). Both the 30- and 120-day cases were representative of summer, with corresponding start dates in April 2011 and April 2007.

The predicted total surface area and the cumulative footprints of surface area exposed to oil >0.001 mm (dull brown sheens) were generally comparable (i.e., order of magnitude) between release durations for the selected deterministic cases (Table 4-3; Figure 4-27). Both releases were predicted to result in similar areas affected by dark brown sheens (0.01-0.1 mm), when compared to the 30-day releases (Table 4-3; Figure 4-27). Small patchy regions of black oil (0.1 - 1 mm) were predicted each of the selected deterministic scenarios (Table 4-3).

The high potential for surface oil entering into the water column in these two representative scenarios is the result of high wind speeds in the region, which resulted in surface breaking winds that entrained surface oil into the water column. Because these two scenarios occurred during summertime conditions, the water temperature exceeded the pour point of the oil, and the product remained “entrain-able.” Additionally, there was a small fraction of oil that did not surface from the release and was permanently entrained in the water column (due to small droplet sizes). The formation of persistent emulsions increased the likelihood that oil would be see-sawing between the surface mixed layer and the surface of the water. Total hydrocarbon concentrations were predicted to be more uniform (low level contamination) than dissolved concentrations. This was due to the rapid dispersion, degradation, and volatilization of soluble constituents, and the rapid transport of surface oil by winds and persistence of the whole oil after it formed emulsions and tarballs. The highest predicted concentrations of total hydrocarbons (up to 5,000 µg/L for the 120-day release) extended primarily to the east and southeast (Figure 4-29). Note that high concentrations (>1,500 µg/mL) were also predicted to be present in discontinuous regions beyond the continental shelf. This was due to the high pour point of the oil which was predicted to cause surface oil to “freeze” when the ambient water temperature dropped below pour point of the oil. Therefore, once surface oil was predicted to move off the continental shelf, where water temperatures tended to be warmer (i.e. above the pour point), the oil was predicted to entrain.

The 30-day representative case was predicted to contact shorelines, while the 120-day representative case was not predicted to reach the shore (Figure 4-30 and Table 4-3). The representative 30-day release was predicted to result in 87 km of Newfoundland shorelines, predominantly along the southern Avalon peninsula, to be contaminated above the socio-economic threshold (Table 4-3 and Figure 4-30).

At the end of the 160-day simulations for the representative 30- and 120-day releases, large percentages of the oil were predicted to evaporate (28-29%) and degrade (51-52%), accounting for ~80% of each modelled release. The amount of oil predicted to remain on the water surface was <1%, with up to 19-20% within the water column. Oil transported to the sediment was not a major fate pathway with <0.1% predicted to settle on sediments. Shoreline oil contamination of <0.4% of the released oil was predicted (Table 4-4). Frequent cycling of wind and calm events were evident in all water column oil exposure cases, as indicated by “see-sawing” between oil on the surface and entrained oil in the water column (Figure 4-26).

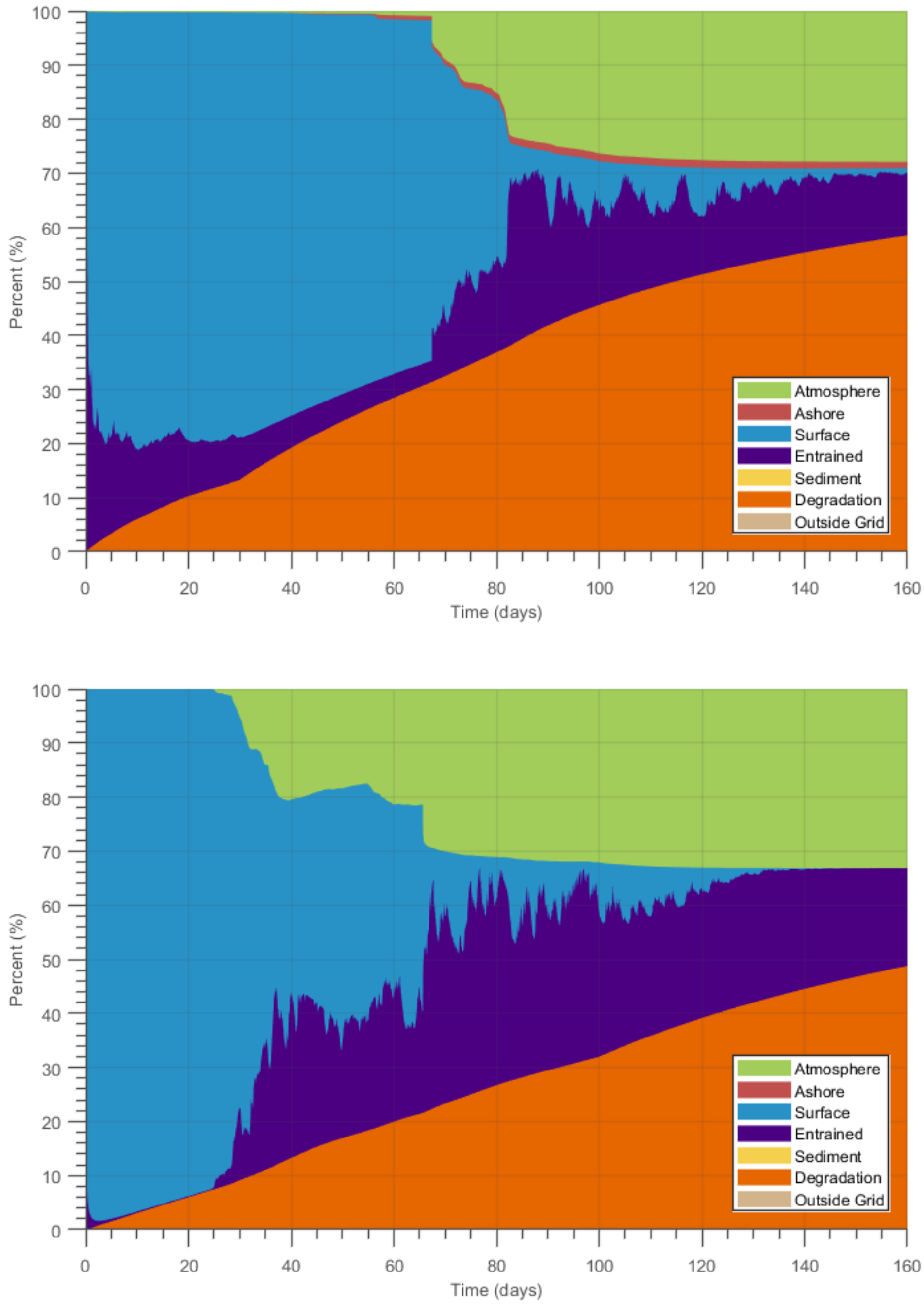


Figure 4-26. Mass balance plots of the 95th percentile water column cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.

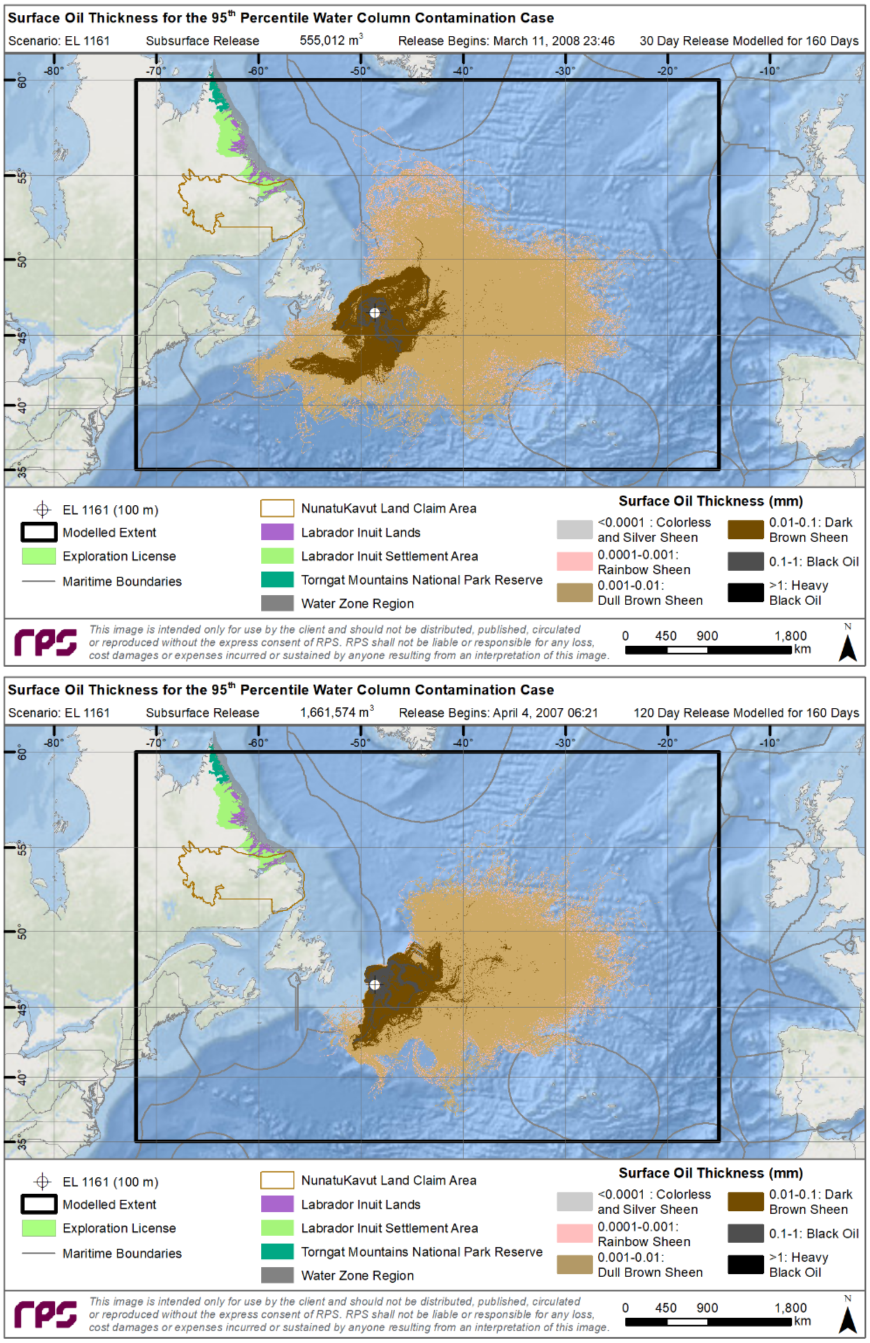


Figure 4-27. Surface oil thickness for the 95th percentile water column cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.

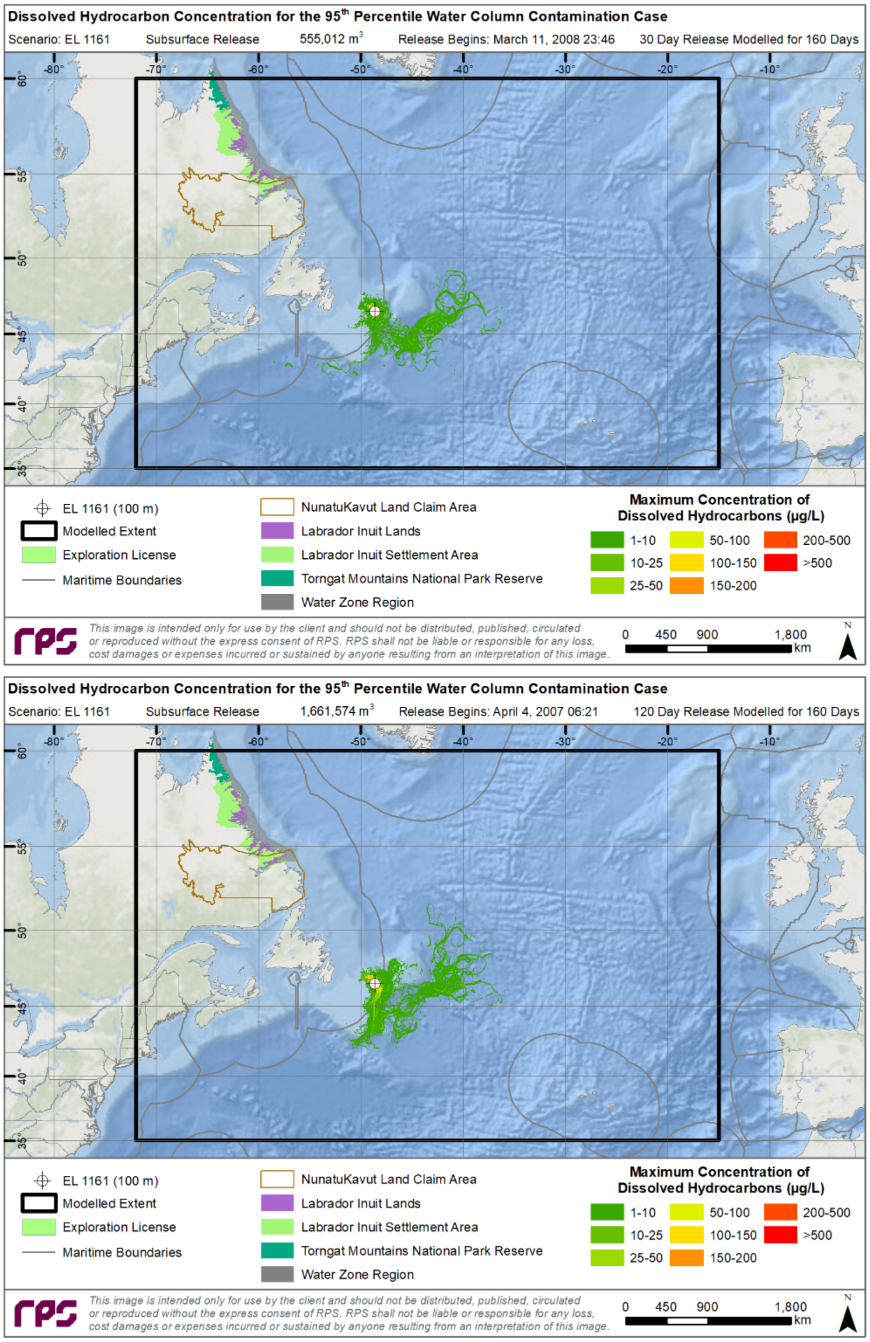


Figure 4-28. Maximum DHC at any depth in the water column for the 95th percentile water column cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.

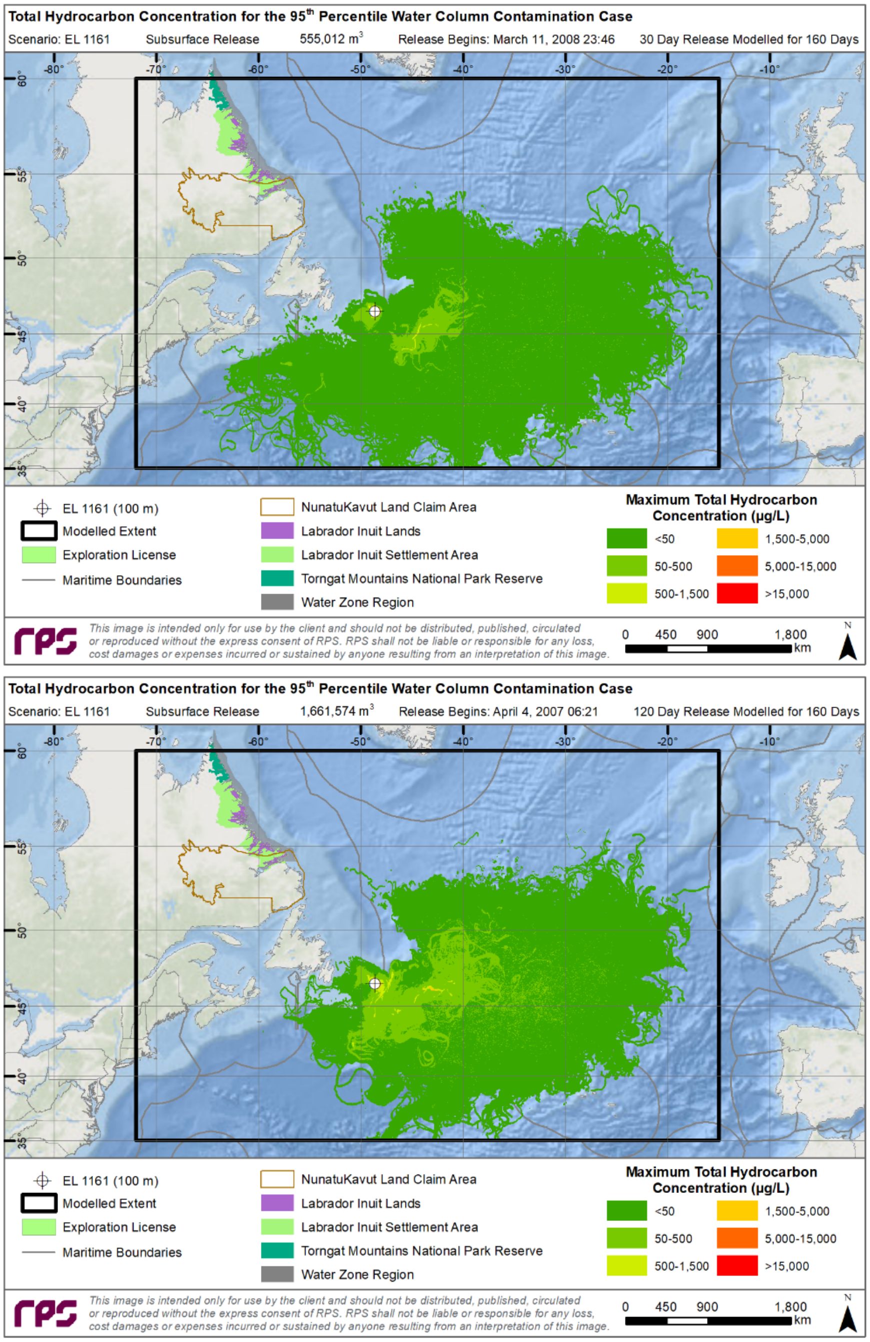
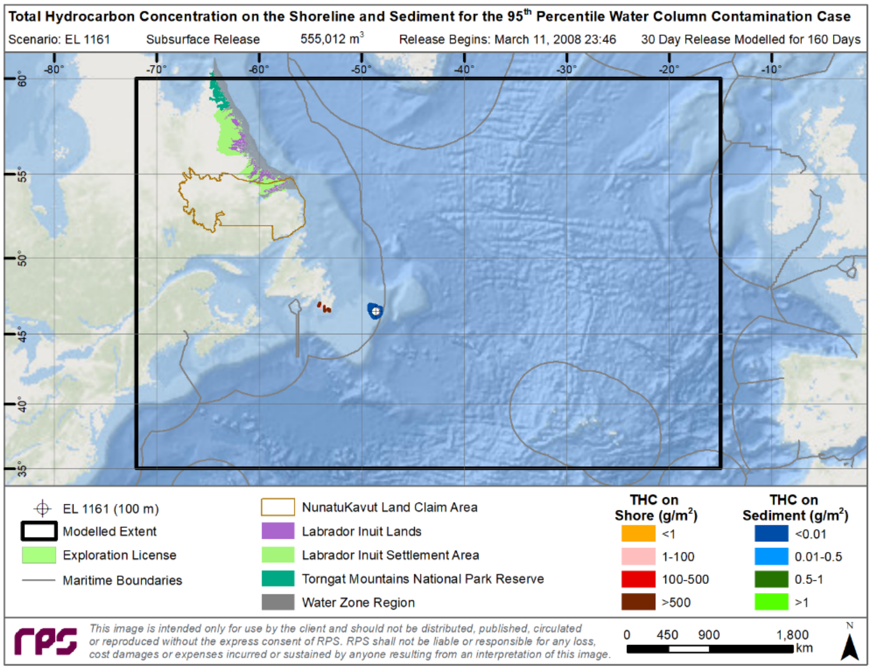


Figure 4-29. Maximum THC at any depth in the water column for the 95th percentile water column cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.



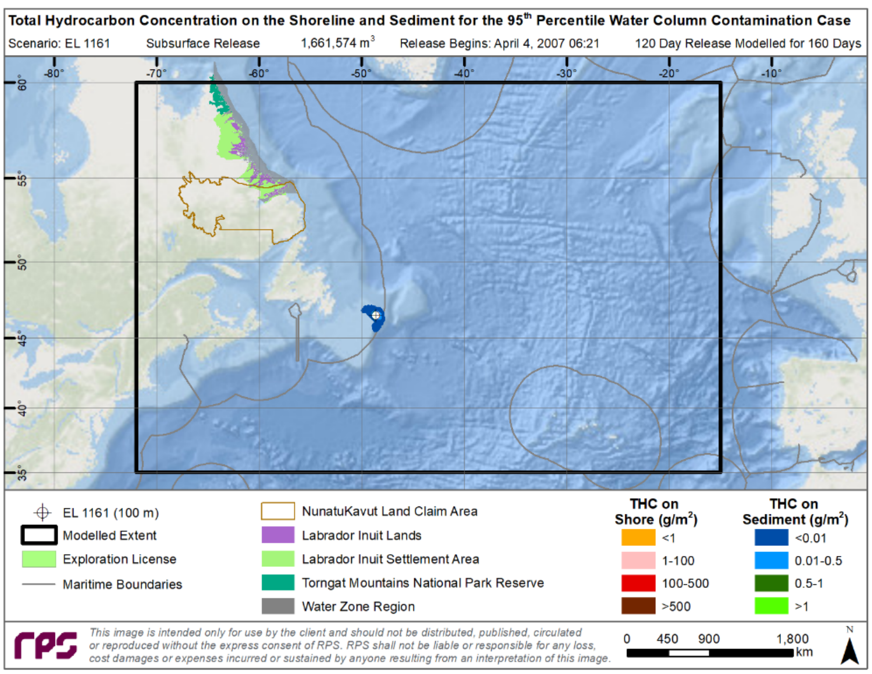


Figure 4-30. THC on the shore and sediment for the 95th percentile water column cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.

4.2.3 Shoreline Exposure Cases

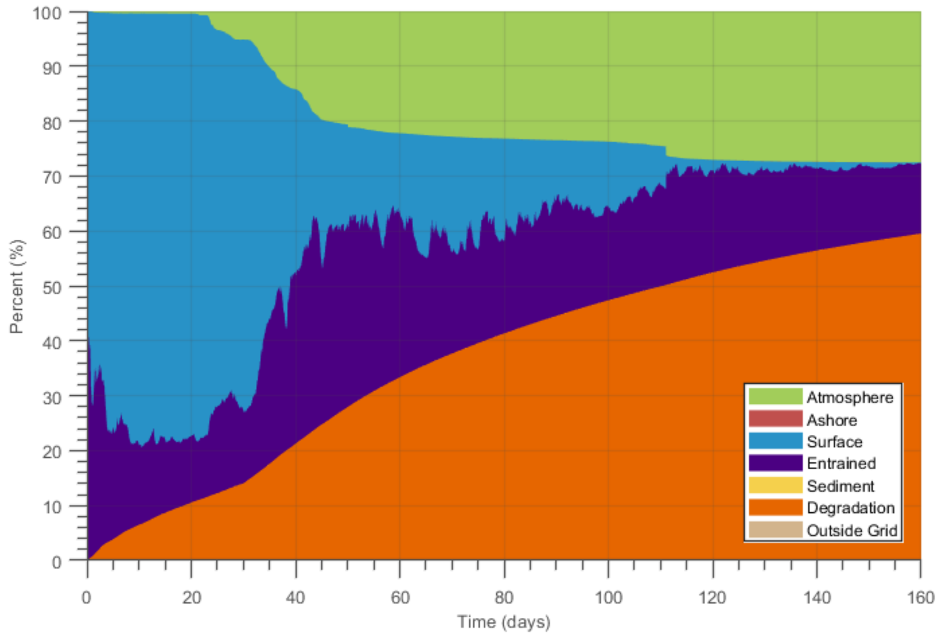
The results of the identified 95^{th} percentile (i.e., credible worst-case) cases for shoreline exposure for the 30- and 120-day releases are provided. Note that the modelled release dates for the representative scenarios were the same for the 30- and 120-day releases (with a start date in March) (Table 2-6).

The predicted total surface area and the cumulative footprints of surface area exposed to oil >0.001 mm (dull brown sheens) were generally similar between release durations for the selected deterministic cases (Table 4-3; Figure 4-32). However, note the difference in predicted thickness and trajectory, when compared to the 95^{th} percentile surface oil exposure case (Figure 4-22 versus Figure 4-32). Each of the shoreline exposure cases were predicted to result in cumulative surface oil footprints of the same magnitude. The 120-day release was predicted to result in much larger areas affected by dark brown sheens (0.01-0.1 mm) and black oil (0.1-1 mm) than the 30-day release. Although, heavy black oil (>1 mm) was not noticeably present in any of the selected deterministic scenarios, the potential for socio-economic impacts would be expected within the cumulative oiled region based on surface oil thickness (Table 4-3; Figure 4-32).

Generally, the representative cases were comparable with similar volumes of water exposed to DHC (Table 4-3; Figure 4-33). Predicted cumulative THC footprints were larger than DHC, particularly for the 120-day release as the dissolved portion was predicted to disperse, degrade, and volatilize/evaporate. The highest concentrations of total hydrocarbons (>500 µg/mL) were predicted to occur generally within 1,000 km of the release location (Figure 4-34). Note that high concentrations (>1,500 µg/mL) were also predicted to be present in discontinuous regions beyond the continental shelf. This was due to the high pour point of the oil which was predicted to cause surface oil to “freeze” when the ambient water temperature dropped below pour point of the oil. Therefore, once surface oil was predicted to move off the continental shelf, where water temperatures tended to be warmer (i.e. above the pour point), the oil was predicted to entrain.

The identified representative shoreline exposure cases were predicted to result in 1,461-1,452 km of contaminated shorelines. The releases resulted in similar lengths of shoreline oiling with the potential for contamination along the southern and southeastern coasts of Newfoundland (including the Avalon Peninsula), mostly in excess of 500 g/m^2 (Figure 4-35). In general, the oil that was predicted to reach shorelines was expected to be relatively weathered, patchy, and discontinuous, as it would have degraded for well over a week (or more) before contacting shore. Limited sediment contamination of generally <0.01 g/m^2 was predicted in the immediate vicinity (within ~100 km) of the release location (Figure 4-35).

At the end of the 160-day simulations of the 95^{th} percentile shoreline exposure for 30- and 120-day releases, large percentages of the oil degraded (52-59%) and evaporated (28%), accounting for >80% of each modelled release. The amount of oil predicted to remain on the water surface was <1%, with 13-19% within the water column. Less than 1% of the released oil (predominantly persistent surface oil) was predicted to be transported outside of the modelled domain. Oil transported to the sediment was not a major fate pathways with <0.1% predicted to settle on sediments, however up to 0.4% was predicted to remain on the shoreline (Table 4-4).



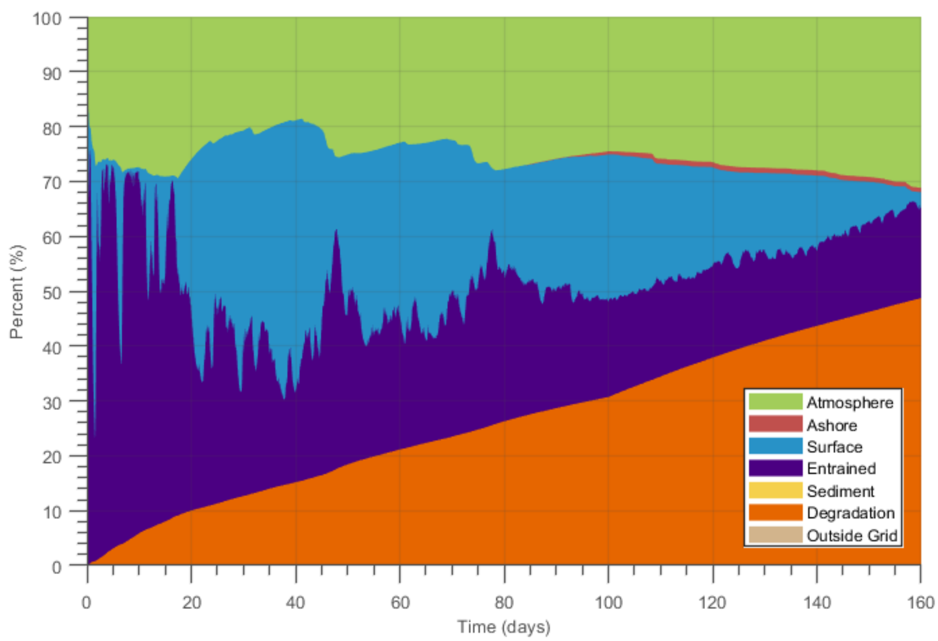


Figure 4-31. Mass balance plots of the 95th percentile shoreline cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.

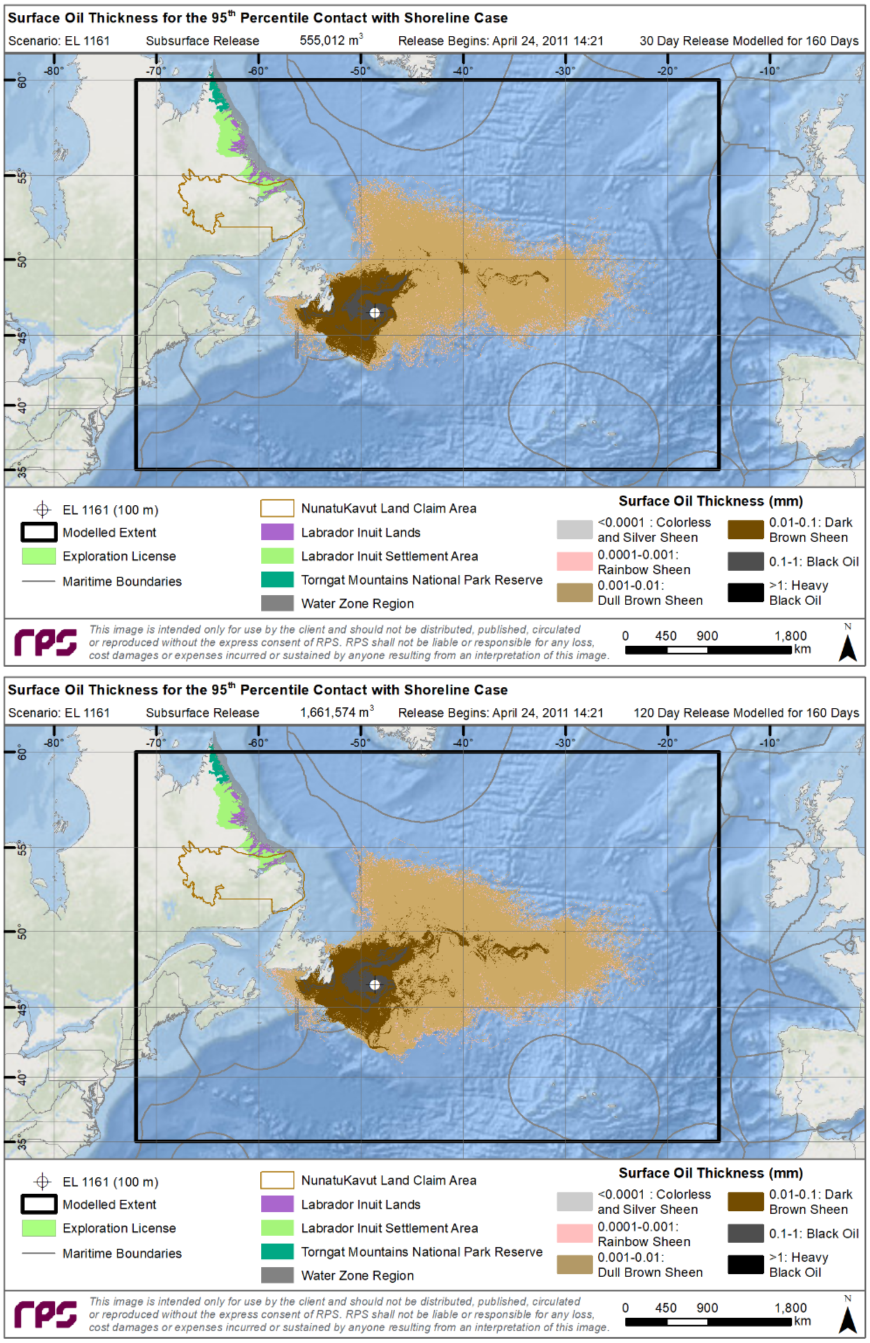
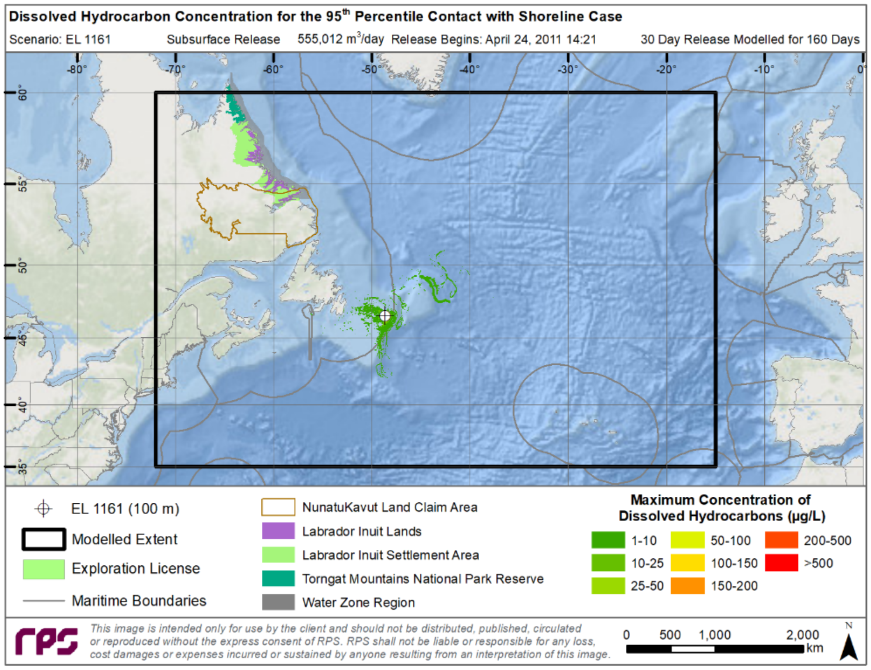


Figure 4-32. Surface oil thickness for the 95th percentile shoreline cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.



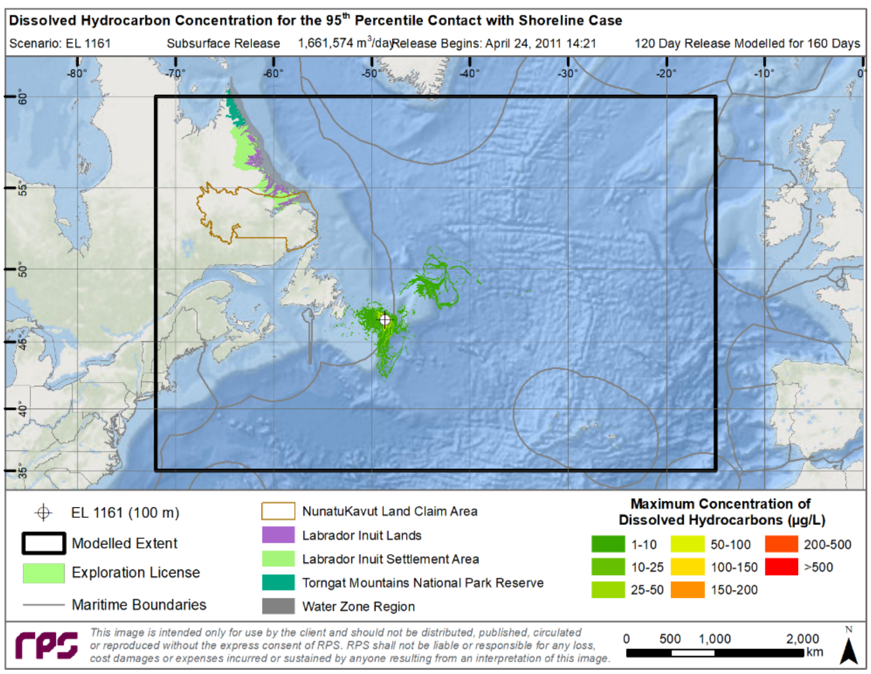
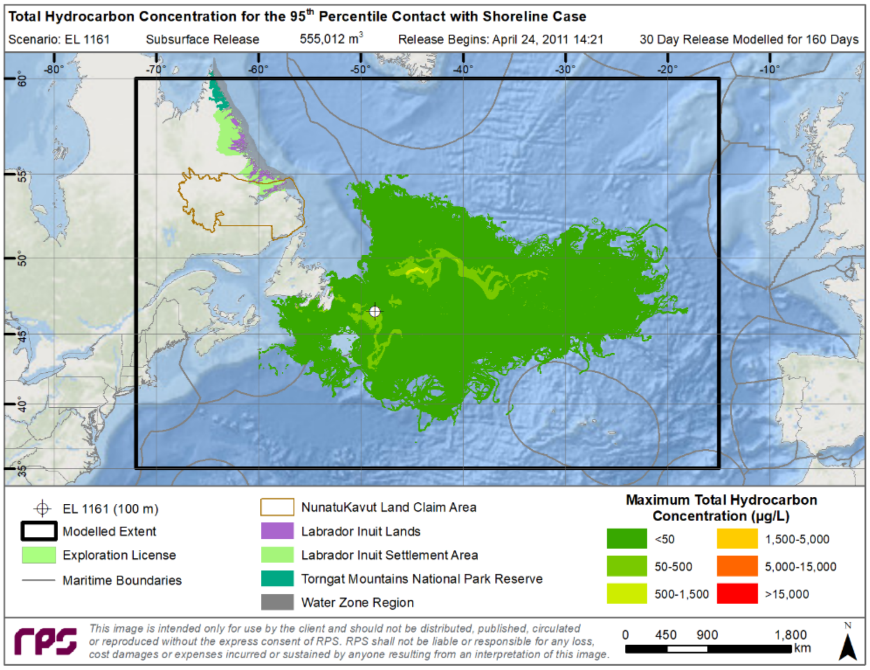


Figure 4-33. Maximum DHC at any depth in the water column for the 95th percentile shoreline cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.



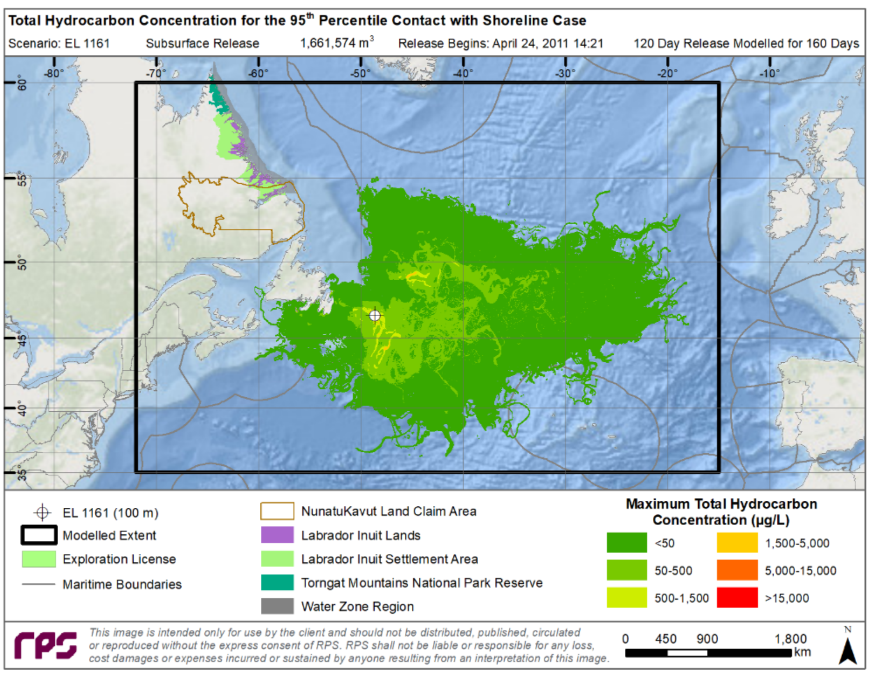
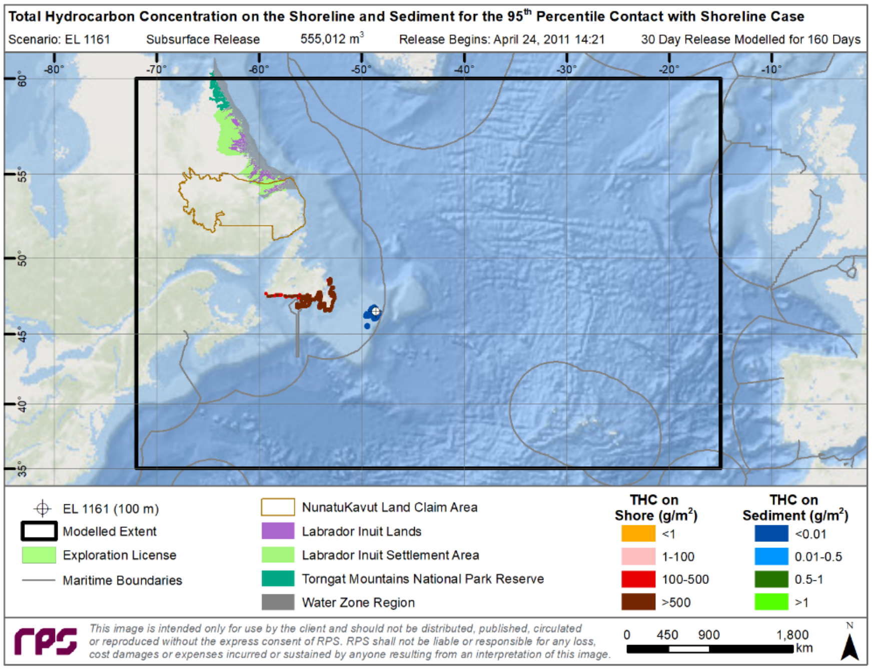


Figure 4-34. Maximum THC at any depth in the water column for the 95th percentile shoreline cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.



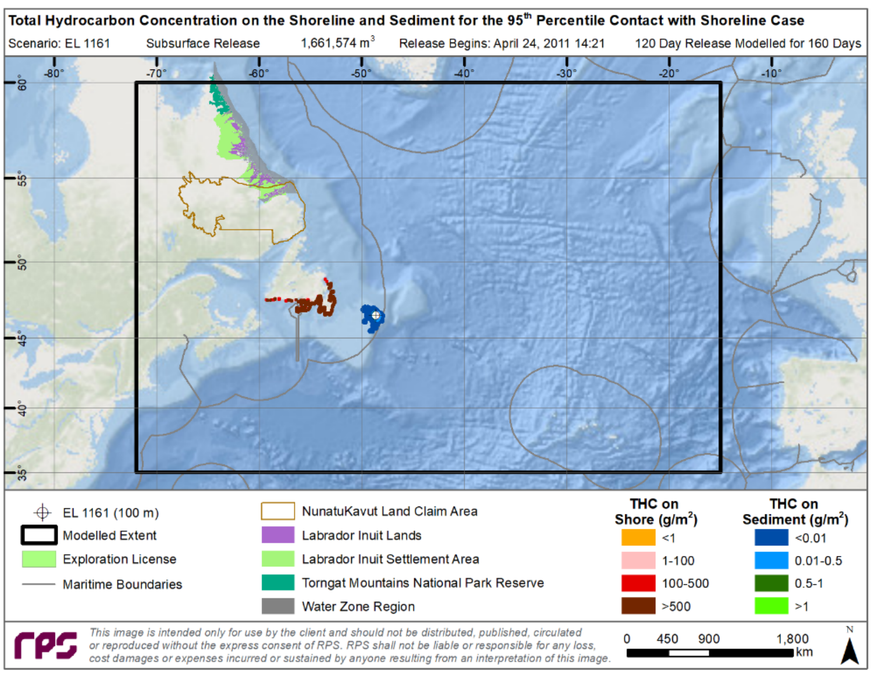


Figure 4-35. THC on the shore and sediment for the 95th percentile shoreline cases resulting from 30- (top) and 120-day (bottom) blowouts at EL 1161.

4.2.4 Surface Diesel Batch Spill

Results for the hypothetical batch spill release of marine diesel from EL 1161 are provided. The simulation was comprised of a nearly instantaneous release of 1,000 L of marine diesel at the surface, which was then modelled for 30 days.

The batch spill release of 1,000 L marine diesel was predicted to result in silver or colorless sheens (<0.0001 mm) of oil floating on the water surface (Figure 4-37). Generally, oil within this representative scenario was predicted to be transported to the west and south, within 175 km of the release location (Figure 4-37). Note that THC and DHC concentrations in the water column were not predicted for the marine diesel batch spills modelled due to the relatively small volume of diesel oil released on the water surface and the large amount of natural dispersion from wind and waves that dispersed and diluted the marine diesel. Thus, figures of THC and DHC are not presented below.

At the end of the 30-day marine diesel batch spill simulation, 44% was predicted to evaporated into the atmosphere, 42% degraded, 15% remained entrained in the water column, while 0.1% of the released volume was predicted to remain floating on the water surface. No marine diesel was predicted to strand on shorelines or settle on sediments in this representative scenario (Figure 4-36 and Table 4-4).

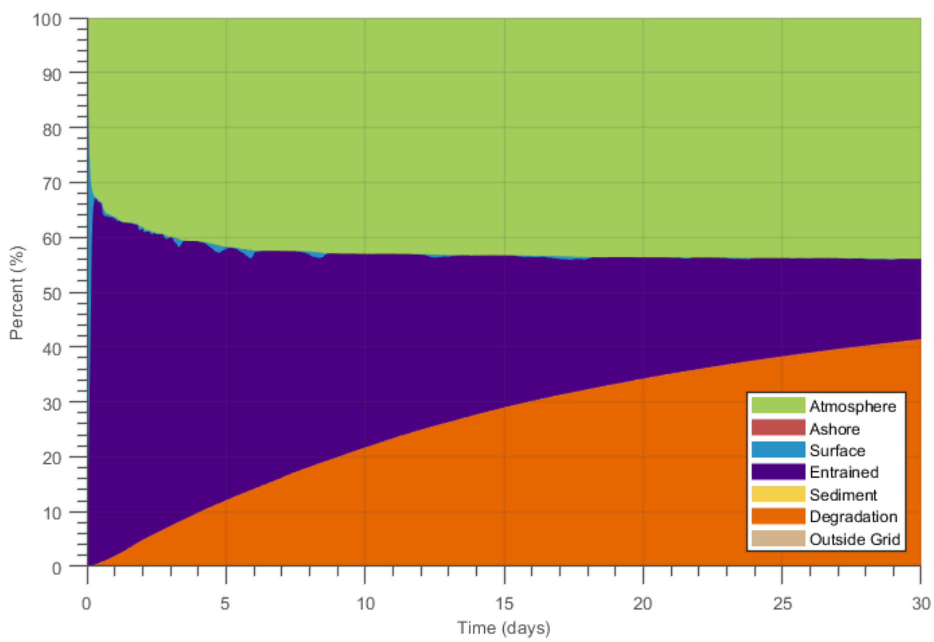


Figure 4-36. Mass balance plot of the Marine Diesel batch spill of 1,000 L at EL 1161.

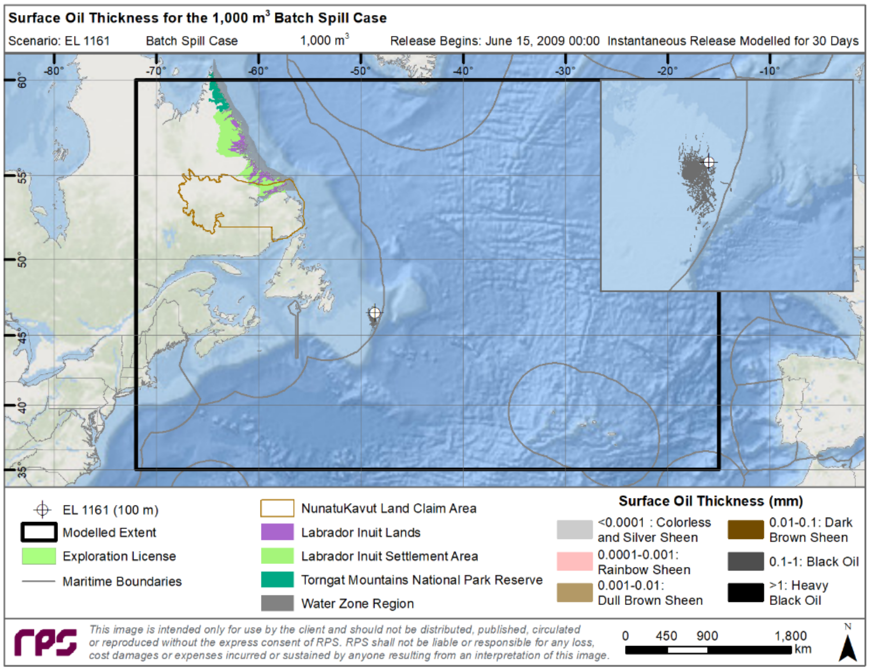


Figure 4-37. Surface oil thickness for the Marine Diesel spills of 1,000 L at EL 1161.

4.2.5 Summary of Deterministic Results

4.2.5.1 Representative Cases: Surface, Water Column, and Shoreline Oil

For the six representative credible “worst-case” deterministic scenarios, subsurface oil was predicted to rise through the water column, where it surfaced and was predominantly transported to the east and south. In several simulations, oil was predicted to strand on the Avalon peninsula and the southern and eastern shores of Newfoundland, as well as to a lesser extent the southeastern shores of Labrador. In each scenario, nearly a third of the oil was predicted to evaporate, while over half was predicted to degrade by natural processes over the simulated 160 days (Table 4-4). Of the remaining volume of released oil, <3% was predicted to remain on the surface, ≤20% remain in the water column, <1% stranded on shorelines, and <0.1% settled onto sediments over the course of the 160-day simulations. Because the simulations were so long, a small amount (<4%) of the oil was predicted to leave the model domain to the east, predominantly in the form of highly weathered emulsifications and tarballs at the surface. Note that all scenarios assumed a completely unmitigated release, which is an unlikely situation, because various emergency response tactics would typically be employed immediately in the event of a spill.

The predicted cumulative surface oil footprints of most of the identified representative cases were centered to the east of the release site, due to surface oil transport by winds mainly towards the east, with natural dispersion to the north and south. Cumulative maximum surface oil in all cases was predicted to have an average thickness within the range of 0.001 – 0.1 mm (1 –100 µm), which would appear as discontinuous and patchy brown sheens to dark brown sheens, with thinner features predicted further from the release site (Figure 4-22; Figure 4-27; Figure 4-32). In some cases, patchy black oil (0.1-1 mm) was predicted to occur near the release site as it was transported, primarily to the east, hundreds of kilometers away. The 30-day release was predicted to have the potential to affect a total of 1,728,000 - 2,816,000 km^2 above the socio-economic threshold over 160 days and 120-day releases having the potential to affect a total of 2,012,000 - 3,604,000 km^2 over 160 days (Table 4-3).

The maximum subsurface water volumes exposed to THC concentrations for the 95th percentile water column cases were predicted to range between 162,150 km^3 and 228,550 km^3 (Table 4-3). Areas of relatively high THC concentration (500-5,000 µg/L) occurred in the vicinity of the release location and in the waters beyond the continental shelf (Figure 4-29). Regions of >500 µg/L dissolved hydrocarbons were predicted to be transported primarily east and southeast of the release site in the 95th percentile cases, and the result of dissolution from the small oil droplets released from the blowout and from fresh entrained surface oil. Entrained oil concentrations in surface waters were predicted to vary considerably from day to day as expected from variable wind and wave conditions that control entrainment, mixing, and resurfacing rates. High concentrations (>1,500 µg/mL) were also predicted to be present in discontinuous regions beyond the continental shelf. This was due to the high pour point of the oil which was predicted to cause surface oil to “freeze” when the ambient water temperature dropped below pour point of the oil. Therefore, once surface oil was predicted to move off the continental shelf, where water temperatures tended to be warmer (i.e. above the pour point), the oil was predicted to entrain

For the 30- and 120-day representative shoreline oil exposure cases, shoreline oil contamination was predicted to range from approximately 1,461 to 1,493 km, respectively (Table 4-3). In general, most oiling was predicted along the Avalon Peninsula and the southern and eastern shores Newfoundland for these representative deterministic simulations. For the stochastic simulations, predicted results did include the potential for shoreline oiling from southern Newfoundland up to southeastern Labrador and the western edge of the Azores. The oil that was predicted to strand along shorelines was generally in the 100 to >500 g/m^2 range (exceeding the socio-economic threshold), but would be patchy, discontinuous, and generally highly weathered by the time it reached shore. Offshore sediment contamination was much less prevalent and generally occurred at low levels (<0.01 g/m^2) at locations near and to the south of the release site (Table 4-3; Figure 4-35).

The contrasting results (e.g., areas predicted to be affected and resulting levels of contamination) within the representative deterministic simulations demonstrate the importance of stochastic probability footprints outlining the range of spill outcomes that may result from environmental variability rather than differences in the specific release and site characteristics. In general, stochastic results provided an understanding of the locations that were susceptible to potential effects, while representative deterministic results provided more context with regard to the anticipated magnitude of effects for 95th percentile “worst-case” scenarios.

4.2.5.2 Batch Spill

A smaller scale near-instantaneous batch spill of marine diesel was modelled as an accidental release. A 1,000 L release was modelled at EL 1161 and was simulated for thirty days (Table 2-6). The marine diesel used in this scenario was a standard diesel that had a low viscosity and a high aromatic content, which resulted in rapid predicted evaporation during the summertime release. The marine diesel release was also predicted to result in a patchy distribution of colorless or silver sheen of oil <0.0001 mm (0.1 µm) which was rapidly dispersed in this turbulent environment (Figure 4-37). The marine diesel batch spill scenario was not predicted to contaminate shorelines.

Table 4-3. Representative deterministic cases and associated areas, lengths, and volumes predicted to exceed specified thresholds for representative trajectories at EL 1161.

95th Percentile Scenario	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)
			Socio-economic (0.04 µm)	Ecologic (10 µm)	Socio-economic (1 g/m^2)	Ecologic (100 g/m^2)	Socio-economic* (1 µg/L)
Subsurface Blowout Releases							
Surface oil exposure case - 30 d	EL 1161	555,012 m^3	2,817,000	286,800	358	340	224,050
Water column case - 30 d			2,236,000	438,100	87	83	228,550
Shoreline contact case - 30 d			1,728,000	334,700	1,461	1,452	138,800
Surface oil exposure case - 120 d		1,661,574 m^3	3,604,000	833,500	-	-	227,300
Water column case - 120 d			2,070,000	317,600	-	-	196,950
Shoreline contact case - 120 d			2,012,000	445,000	1,493	1,479	162,150
Batch Spill							
Surface Batch Spill	EL 1161	1,000 L	-	-	-	-	-

*There is only 1 category threshold (socio-economic) for THC –calculated by multiplying the area times the depth of the grid cell.

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 at the end of the representative deterministic scenarios.

95th Percentile Scenario	Site	Percent of Total Released Oil (%)						
		Surface	Evaporated	Water Column	Sediment	Ashore	Degraded	Outside Grid
Subsurface Blowout Releases								
Surface oil exposure case- 30 d	EL 1161	1.2	28.4	11.3	<0.1	<0.1	58.4	0.7
Water column case- 30 d		0.5	28.3	19.2	<0.1	0.4	51.7	0.0
Shoreline contact case- 30 d		0.2	27.5	12.7	<0.1	<0.1	59.4	0.1
Surface oil exposure case- 120 d		2.4	25.3	16.7	<0.1	0.0	52.2	3.4
Water column case- 120 d		0.2	29.2	19.6	<0.1	0.0	51.0	0.0
Shoreline contact case- 120 d		0.5	28.3	19.2	<0.1	0.4	51.7	0.0
Batch Spill								
Surface Batch Spill	EL 1161	0.0	43.9	14.6	0.0	0.0	41.4	0.0

5 DISCUSSION AND CONCLUSIONS

Most surface oil from both release locations was predicted to move eastward because of prevailing westerly winds and the North Atlantic current. The Labrador and North Atlantic currents have relatively steady velocities in the region throughout the year, resulting in similar subsurface oil exposure patterns between scenarios. However, wind speeds increase during the winter months, leading to an increase in the probability of shoreline oiling. Because the pour point of the Terra Nova crude oil was +10ºC, slightly enhanced persistence of surface floating oil was predicted during colder periods. Based on the results of the stochastic analysis of hundreds of modelled scenarios, the average probability of shoreline oiling ranged from 6-9% in the summer and 4-9% in the winter. Individual points along shore did have maximum probability of shoreline oil contamination ranging from 18-45%, depending on the scenario. The locations that had the highest potential for shoreline oiling were centered around the Avalon Peninsula. Depending on the time of year and environmental conditions associated with the time of release, areas susceptible to shoreline oiling included most of the Newfoundland shorelines (exception on the west coast), the Avalon peninsula, and the southern and eastern shores of Labrador. The Azores had a <10% chance of shoreline oiling predicted. Oil that reached Newfoundland shorelines was expected to be patchy, discontinuous, and weathered, as it would have taken a minimum of nearly 4 days from the 30-day releases and 9 days from the 120-day releases, but usually much longer (i.e. weeks) to reach shore.

Surface exposures above the socio-economic impact threshold were predicted to be between 1,728,000 and 3,604,000 km^2 for selected deterministic simulations. Subsurface volumes predicted to exceed the THC socio-economic threshold ranged from 138,800 to 228,550 km^3. Shoreline lengths predicted to exceed the socio-economic mass per unit area thresholds for scenarios that resulted in shoreline contact ranged from a mode of 87 up to 1,493 km. In general, most simulated subsurface blowout cases led to predicted surface oil thickness and water column concentrations at or above the socio-economic threshold for potential impacts in the immediate vicinity and to the east of the release site. In all representative deterministic cases <1% of the total volume of released oil was predicted to strand on shorelines after 160 days.

The hypothetical releases modelled in this study are not intended to predict a specific future event, but rather are intended to be used as a tool in environmental assessments and spill 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 at any point throughout the year. The specific trajectories and fates vary greatly for each release based upon the environmental conditions occurring at the time of the release. While each oil release is unique, and uncertainties exist, the results of this modelling study suggest that, if oil were to be released in the Project Area, it has a high likelihood of moving away from shore to the east with less likelihood of shoreline oil exposure. Furthermore, this modelling assumes completely unmitigated releases, which is an unlikely situation because emergency response measures would typically be employed in the event of a spill.

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