Trajectory Modelling in Support of the Nexen Energy ULC Flemish Pass Exploration Drilling Project (2018-2028) Relief Well Modelling

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Executive Summary

Study Summary

Oil spill trajectory and fate modelling were performed to support an Environmental Impact Statement for the Nexen Energy ULC's Flemish Pass Exploration Drilling Project (2018-2028). The Project Area includes the Exploration Licenses EL 1144 and EL 1150, with the western edge approximately 400 km offshore, buffered by 20 km on all sides to accommodate the location and extent of ancillary activities that may be carried out in support of such drilling activities. The Project Area includes portions of the Flemish Cap and Flemish Pass. Stochastic modelling was performed at representative sites that were located approximately 420-460 km east of the Newfoundland Coast, where exploratory drilling is anticipated in waters that range in depth from 330 m to 1,200 m.

Hypothetical releases were modelled as continuous unmitigated subsurface blowouts with scenarios of Bay du Nord crude oil (BdN) at two representative example well site locations within the Exploration Licenses: EL 1144 and EL 1150. The water depths for the two example well sites are approximately 1,137 m for EL 1144 and 378 m for EL 1150, which are representative examples of the range of expected water depths where exploration may take place. In addition, the EL 1144 release location was an example of a deeper Jurassic well, while EL 1150 was an example of a shallower Cretaceous well. Using an example of each was important, as Jurassic and Cretaceous reservoirs have different properties. Release rates modelled and associated total volumes discharged varied by location. Unmitigated 120-day subsurface blowouts of BdN were simulated for 160 days at EL 1144 and EL 1150 example wells. The larger release was modelled at the EL 1144 example well site with a blowout rate of 184,000 barrels per day (bpd), totaling 22,080,000 bbl. A smaller release was modelled at the EL 1150 example well site with a blowout rate of 44,291 bpd, totaling 5,314,920 bbl. These scenarios represent the range of water depths, release rates, and a conservatively long spill duration that is representative of the time that is expected to be required to mobilize a MODU (Mobile Offshore Drilling Unit) and install a relief well to stop a subsurface release. This study is a follow on to the original modelling report "Trajectory Modelling in Support of the Nexen Energy ULC Flemish Pass Exploration Drilling Project (2018-2028)" authored on January 26, 2018, which investigated shorter release durations (30-day subsurface blowouts) contained through the use of a "Capping Stack" technology. In addition, this modelling study included a larger model domain than the previous assessment.

Study Goals

There were several goals of the modelling study. A stochastic assessment was used to provide an understanding of the probability of minimum time to exposure from unmitigated releases of oil, based upon highly conservative thresholds for shoreline oiling, concentrations of hydrocarbons in the water column, and oil on the water surface. The goal was to identify the areas where contamination has the potential to occur and the minimum time to exposure based upon variable environmental conditions. To determine the level of potential contamination (i.e. actual time-varying concentrations rather than simply the knowledge of a threshold exceedance), individual deterministic scenarios were selected to represent 95th percentile maximum potential effects. These highly conservative 95th percentile scenarios were identified from the area of surface oil, the length of shoreline oiled, and the mass of oil in the water column.

Study Use

It is understood that the hypothetical releases modelled in spill trajectory studies are in no way intended to predict a specific future event. Rather, they are used as a planning tool for application 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 may result following a release of crude oil, based upon the environmental variability that may occur over the course of a year or many years. If an event such as a subsurface blowout or topside release were to occur, it is likely that a different volume and different type of oil would be released from a different location and under different environmental conditions than modelled here. While it is impossible to know the exact trajectory and fate of an oil release in the future, inferences may be made from this study.

Models

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

Geographic Data

Geographic data including habitat mapping and shoreline identification and classification were obtained from multiple data sources. For Canadian areas, data were used from the New Brunswick, Nova Scotia, and Newfoundland Departments of Natural Resources and from Environment and Climate Change Canada. For the U.S. shoreline, the U.S. National Oceanic and Atmospheric Administration (NOAA)

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 the General Bathymetric Chart of the Oceans (GEBCO).

Winds and Currents

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. 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. 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, processed, and used for the period between 2006 and 2012.

Stochastic Analysis

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

It is important to note that, although large footprints of oil contamination are depicted for stochastic analyses, they are not the expected distribution of oil from any single release. These maps do not provide any information on the quantity of oil in a given area. They simply denote the probability of oil exceeding the specific threshold passing through each grid cell location in the model domain over the entire model duration (160 days), based on the entire ensemble of runs (171 individual releases for both locations). Only probabilities of 1% or greater were included in the map output, as lesser probabilities represent random noise in each set of 171 trajectories. Stochastic maps of water column contamination depict the likelihood that dissolved and total hydrocarbon concentrations will exceed the identified threshold at any depth within the water column. 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 trajectories) were identified from each set of stochastic subsurface blowout results. Individual scenarios were selected based upon the size of the surface oil footprint, the mass of oil on shorelines, and the concentration of dissolved hydrocarbons in the water column, based upon a set of highly conservative socio-economic thresholds:

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

The selected scenarios included the 95th percentile runs for surface oil footprint, shoreline oil length, and water column contamination and were identified for both release locations when appropriate. These representative deterministic simulations tend to maximize the predicted effects from the suite of stochastic simulations in an effort to bound the upper range of predicted effects in a “credible worst case” scenario.

Results

Stochastic results are useful in planning for oil spill response, as they characterize the probability that regions may experience contamination above specified thresholds over 160 day unmitigated releases, taking into account the environmental variability that is expected from many, potentially-different release scenarios over time. Stochastic footprints for potential surface oil exceeding a thickness of 0.04 µm were between 8,152,000-8,211,000 km^2 for the annual results at EL 1144 and EL 1150. These footprints depict areas with the highest predicted likelihood of potential oil contamination to the east of the release sites, with a much lower probability (1-10% and 10-25%) for oil to be transported to the west towards Canadian waters. While these areas are quite large, most of this footprint represents a relatively low probability (<10%) of surface oil thickness >0.04 µm. Footprints depicting higher probability contours (90%) yield only a fraction of the total footprint, ranging from 2,069,000 – 2,236,000 km^2 for the annual results, depending on the scenario.

Seasonal variations were evaluated yielding different predicted surface oil results for summer versus winter scenarios. For the releases at the EL 1144 and EL 1150 example well sites, larger surface oil footprints associated with >90% probability contours were predicted for summer scenarios at both sites indicating more coherency in the release.

The highest predicted potential (77% and 70%) for oil to make contact with any shoreline exceeding 1 g/m^2 occurred only in the summer scenarios from the EL 1144 and EL 1150 example well releases, associated predominantly with oil reaching the islands of the Azores. The maximum probability of oil reaching the shores of Newfoundland is less than 25% (and typically less than 10%) and for Labrador was always less than 10%. The minimum time estimates for first shoreline oil exposure for Newfoundland was 15 days, the Azores was 45 days and for Labrador was 68 days for releases from EL 1144 and EL 1150 example well sites. The minimum predicted time for oil to contact shorelines for the modelled 95th percentile representative deterministic shoreline scenario at EL 1144 was 81 days into the release for the shores of Newfoundland, 111 days for the Azores, and no oil was predicted to reach the shores of Labrador following the modelled 120-day releases. For EL 1150, oil was only predicted to contact the shores of the Azores, 80 days into the release for the modelled 95th percentile shoreline scenario. In all cases, based upon the minimum time to shore, oil was predicted to be extremely weathered by the time it reached shorelines.

Individual trajectories of interest were identified and selected from the stochastic ensemble of results for deterministic analysis. The identified simulations represented the 95th percentile for exposure area to surface oil, mass of oil in the water column, and shoreline length. For most representative deterministic scenarios, the amount of evaporation and degradation was relatively consistent between model runs. Approximately 43-51% of the releases were predicted to evaporate and another 34-40% to degrade by the end of the 160-day simulation. Most of the remaining variability in the mass balances was associated with the amount of oil found either on the surface or entrained within the water column. Predicted surface oil was <12%, while entrained oil in the water column ranged between 3% and 7%. The mass of oil contacting shorelines was minimal (<0.09%) with respect to the total release volume for these modelled simulations, where even the 95th percentile shoreline contact case was predicted to have 0.03% and 0.09% of the total volume of released oil reaching shore. Oil on sediments was typically 0.01%, making up the smallest portion of the predicted mass balance.

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 were to occur, and those trajectories and fates vary based upon the environmental conditions occurring at the time. While each oil release is unique and therefore uncertainties exist, the results of this modelling study suggest that, if oil were to be released in the Project Area, the highest likelihood would be for the oil to move away from shore to the east.

Comparison with Previous Modelling Study

The larger potential for oil making contact with shorelines (70-77% in this modelling study versus 3% in the previous study) is based upon the much longer release duration (120 day release modelled for 160 days used in this modelling study vs. the previous study, which investigated 30 day releases for 60 days) and the much larger model domain used in this study, which included the Azores to the east (which accounted for as much as 44% of the increase in potential shoreline oiling). However, this larger domain was predicted to result in only a slight decrease in the maximum total mass of oil leaving the model domain (<1.75% in this study vs. <1.82% previously). While the larger model domain suitably captured the larger area over which oil would be expected to be transported, the simulation duration was nearly three times longer and the release duration (and resulting release volume) was four times larger than was used in the previous modeling. Therefore, the longer (and subsequently larger) simulated release and longer simulation duration (60 vs. 160 days) negated a portion of the benefits of this spatially and temporally broader analysis.

Document Summary

This report includes an introduction describing the region, the modelling approach, the methodology, and finally the 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 within the water column, on the water surface, and along shorelines. This document is broken down into several sections.

- Section 1 – Introduction
- Section 2 – Background and Scenarios, including description of 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 model runs
- 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.

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List of Acronyms and Abbreviations

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

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

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

BAOAC: Bonn Agreement Oil Appearance Code

BdN: Bay du Nord crude oil

BPD : Barrels per day

BTEX: Benzene, toluene, ethylbenzene, and xylene

CFS: Climate Forecast System

CFSR: Climate Forecast System Reanalysis

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

CIS: Canadian Ice Service

EEZ: Exclusive Economic Zone

EIS: Environmental Impact Statements

EL 1144/EL 1150: Exploration License 1144 and 1150 hypothetical release locations

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

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

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

MICOM: Miami Isopycnic-Coordinate Ocean Model

MODU: Mobile Offshore Drilling Unit

NCEP: National Centers for Environmental Prediction

NCODA: U.S. Navy Coupled Ocean Data Assimilation

NOAA: U.S. National Oceanic and Atmospheric Administration

NRC: U.S. National Research Council

NRDA: The U.S. Natural Resource Damage Assessment

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

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

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

PPM: Part per million, as referring to concentration

SCF/BBL: Standard cubic feet per barrel

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

THC: Total hydrocarbon concentrations

UNESCO: United Nations Educational, Scientific, and Cultural Organization

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

1 Introduction

RPS (previously Applied Science Associates, Inc.) conducted trajectory and fate modelling in support of an Environmental Impact Statement (EIS) for the Nexen Energy ULC Flemish Pass Exploration Drilling Project (2018-2028) proposed in the region of the Flemish Pass offshore Newfoundland.

This modelling was conducted to evaluate hypothetical unmitigated release events associated with exploration drilling, including large-scale, long-duration, deep-water blowouts of Bay du Nord (BdN) crude oil from the wellhead at the seafloor. Modelled scenarios represent the range of water depths, release rates, and a conservatively long spill duration that is representative of the time that is expected to be required to mobilize a MODU (Mobile Offshore Drilling Unit) and install a relief well to stop a subsurface release. This study is a follow on to the original modelling report "Trajectory Modelling in Support of the Nexen Energy ULC Flemish Pass Exploration Drilling Project (2018-2028)" authored on January 26, 2018 which investigated shorter release durations (30-day subsurface blowouts) contained through the use of a "Capping Stack" technology. In addition, this modelling study included a larger model domain than the previous assessment.

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 within the Project Area and their potential to affect regions of the Northwest Atlantic Ocean offshore Newfoundland. RPS's nearfield OILMAPDeep blowout model and the far-field Spill Impact Model Application Package (SIMAP) oil trajectory and fate models were used. This report provides a description of the Project Area and modelled scenarios, an overview of the modelling approach, details about the model input data used, and a presentation and discussion of the modelled results.

2 Background and Scenarios

2.1 Project Area

Newfoundland is comprised of a series of islands off the east coast of Canada, and along with Labrador forms the easternmost Canadian province. The relatively shallow waters of the continental shelf extend eastward into the northwest Atlantic Ocean up to 500 km off the Newfoundland coast. This area is known to contain substantial petroleum resources. The Hebron, Hibernia, White Rose, and Terra Nova oil fields sit atop this biologically productive region. Bathymetry in the area ranges from less than 100 m over the Grand Bank to greater than 4,000 m deep in the Labrador Basin.

The Nexen Energy ULC Project Area (approximately 47° 2’ 40.6” – 47° 58’ 8.5” N, 45° 46’ 27.9” – 47° 16’ 11.5” W) is located on the Flemish Cap and Flemish Pass (Figure 2-1). The Project Area includes the Exploration Licenses EL 1144 and EL 1150, with the western edge approximately 400 km offshore, buffered by 20 km on all sides to accommodate the location and extent of ancillary activities that may be carried out in support of such drilling activities. The Project Area includes portions of the Flemish Cap and Flemish Pass. Stochastic modelling was performed at representative sites that were located approximately 420-460 km east of the Newfoundland Coast, where exploratory drilling is anticipated in waters that range in depth from 330 m to 1,200 m. Major currents, including the Labrador Current and the Gulf Stream, influence the circulation and biological productivity in this region.

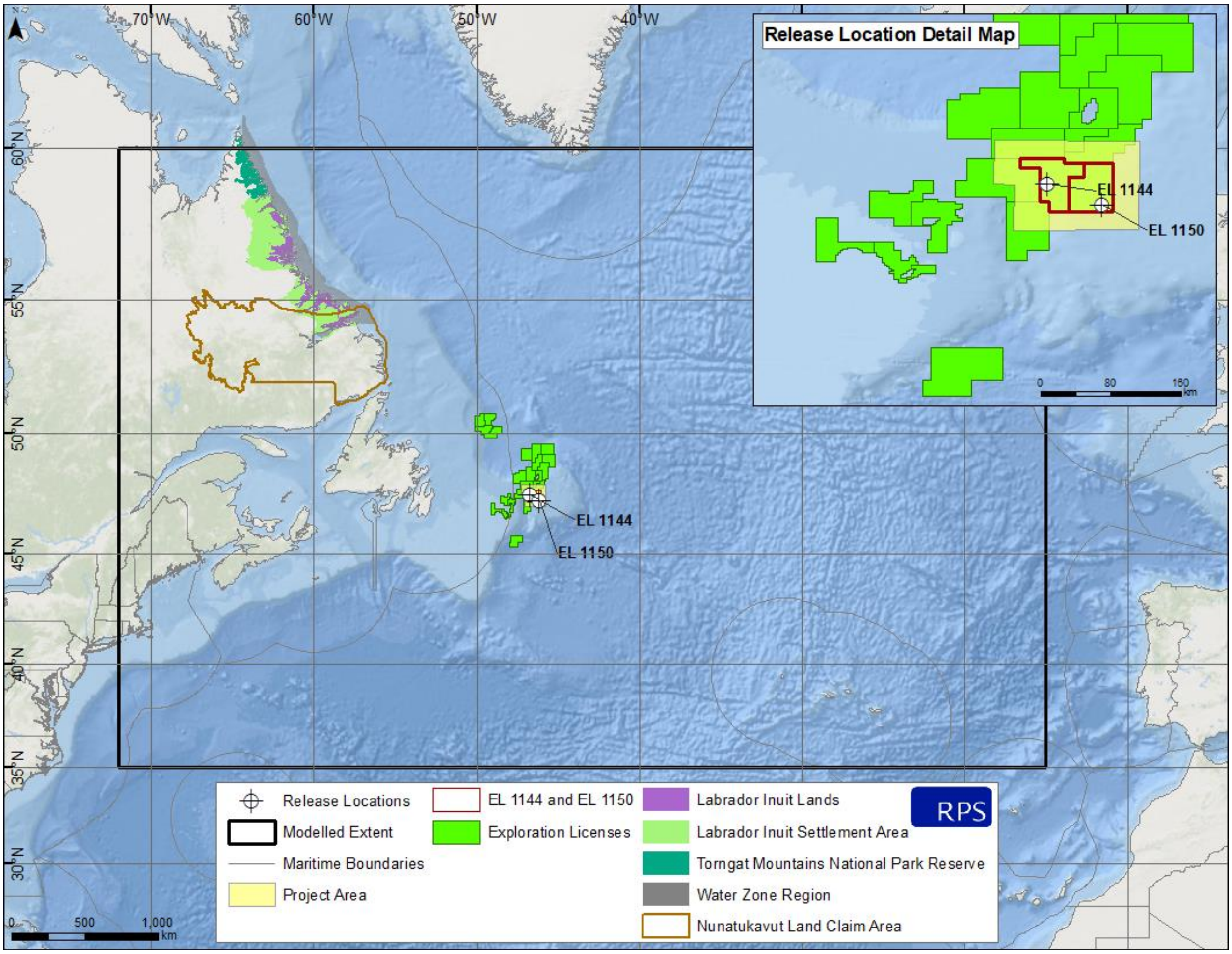


Figure 2-1. Project Area, including the two hypothetical release locations for the subsurface blowouts (EL 1144 and EL 1150 example well sites). The black bounding box represents the modelling extent, while the smaller shaded boxes represent the Project Areas. The corresponding water depths (bathymetry) are depicted in shades of blue, whereby lighter shades represent shallow waters and darker shades represent deeper waters.

The model domain extends from 35°N north to 60°N and as far west as 72°W and east to 15°W, encompassing Canadian, U.S., other national territorial seas, and International Waters. This modelled extent is much larger than the Project Area and the model extent used previously, as hypothetical releases of oil will be tracked for extended periods of time (160 days).

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 two sites east of Newfoundland including example well sites for the two Exploration Licenses (EL 1144 and EL 1150) (Table 2-1). Stochastic modelling provides a probabilistic view of the likelihood that a given region might be exposed to released hydrocarbons over specified thresholds given the range of possible environmental conditions that may occur within and across multiple years. A deterministic analysis provides a view of the time history of the specific movement and behavior of released product from a given (e.g., representative) individual release. Together, these methods provide a more complete view of both the likelihood and degree of potential exposure.

For this report, stochastic information is presented for predicted surface oil thickness, shoreline oil mass, and dispersed oil in the water column exceeding the threshold concentration for the full year (i.e., annual), and for different seasons with variable ice-cover conditions (i.e., summer/ice-free and winter/ice-covered). Individual representative deterministic trajectories that characterize single release scenarios are also presented. Stochastic analyses of hypothetical blowouts were modelled at two sites using the physical-chemical properties of the specific oil type that may be released over seven years of variable environmental data, which are discussed in Section 3. At each location, a total of 171 individual oil spill trajectories were modelled throughout the year (81 winter and 90 summer) Modelled scenarios represent the range of water depths, release rates, and a conservatively long spill duration that is representative of the time that is expected to be required to mobilize a MODU and drill a relief well to stop a subsurface release. This study is a follow on to the original modelling report “Trajectory Modelling in Support of the Nexen Energy ULC Flemish Pass Exploration Drilling Project (2018-2028)” authored on January 26, 2018 which investigated shorter release durations (30-day subsurface blowouts) contained through the use of a “Capping Stack” technology. In addition, this modelling study included a larger model domain than the previous assessment.

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

Spill Location	Depth of Release	Release Duration	Model Duration	Number of Model Runs	Released Product	Release Type	Release Volume
EL 1144 Example Well	1,137 m	120 days	160 days	171	BdN	Subsurface Blowout	3,510,440 m^3 (22,080,000 bbl)
EL 1150 Example Well	378 m						845,005 m^3 (5,314,920 bbl)

2.2.1 Modelling Tools

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

OILMAPDeep Model

The OILMAPDeep model incorporates the basic dynamics of a subsurface oil and gas plume and the associated complexities of increased hydrostatic pressure at depths deeper than 200 m. It contains two sub-models, i.e., a plume model and a droplet size model. The plume model predicts the evolution of plume position, geometry, centerline velocity, and oil and gas concentrations until the plume either surfaces or reaches a terminal height (i.e., trap height). At this height, the plume no longer rises by buoyant forces, and the oil contained within the plume escapes to the surrounding water and rises based on the individual buoyancies of the droplets. The jet created by the blowout is modelled by considering the momentum of the oil discharge, the density difference between the expanding gas bubbles in the plume and the receiving water, the entrainment of water into the plume, the mixing by turbulence within the plume, hydrate formation, and 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 the length of time that oil will remain within the water column before surfacing. Large oil droplets surface faster than small ones, thus large droplets more quickly generate a floating oil slick, which may be transported by winds and surface currents. Small droplets remain in the water column longer than large droplets and are subjected to subsurface advection-diffusion processes. The small droplets are therefore transported for a longer period. As oil is transported by subsurface currents away from the release location, natural dispersion of the oil droplets quickly reduces concentrations within the water column. However, the lower rise velocities associated with smaller oil droplets correspond to longer residence times of oil suspended in the water column, which can increase the dissolution of soluble components and potentially result in larger volumes of water being affected. Details of the OILMAPDeep model background, theory, inputs, algorithms, and outputs can be found in Appendix A.

SIMAP Model

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

The 3D physical fates model estimates the distribution of whole oil and oil components on the water surface, on shorelines, in the water column, and in sediments as both mass and concentration. Because oil contains many chemicals with varying physical and chemical properties, and the environment is spatially and temporally variable, the oil rapidly separates into different environmental compartments through multiple fate processes. Oil fate processes included in SIMAP are oil spreading (gravitational and by shearing), evaporation, transport, randomized dispersion, emulsification, entrainment (natural and facilitated by dispersant), dissolution of the soluble fraction of oil into the water column, volatilization of dissolved hydrocarbons from the surface water, adherence of oil droplets to suspended sediments, adsorption of soluble and sparingly-soluble aromatics to suspended sediments, sedimentation, and degradation. Oil trajectory and weathering endpoints include surface oil, emulsified oil (mousse), tar balls, suspended oil droplets, oil adhered to particulate matter, dissolved hydrocarbon compounds in the water column and pore water, and oil on and in bottom sediments and shoreline surfaces. Additional details of the SIMAP model background, theory, inputs, algorithms, and outputs may 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 approach is a statistical analysis of results generated from many different individual trajectories of the same release scenario with each trajectory starting at a randomized time from a relatively long-term window. For this project, individual trajectory start dates were selected randomly every 14 days throughout the window of environmental data coverage to ensure that the data were 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.

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

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

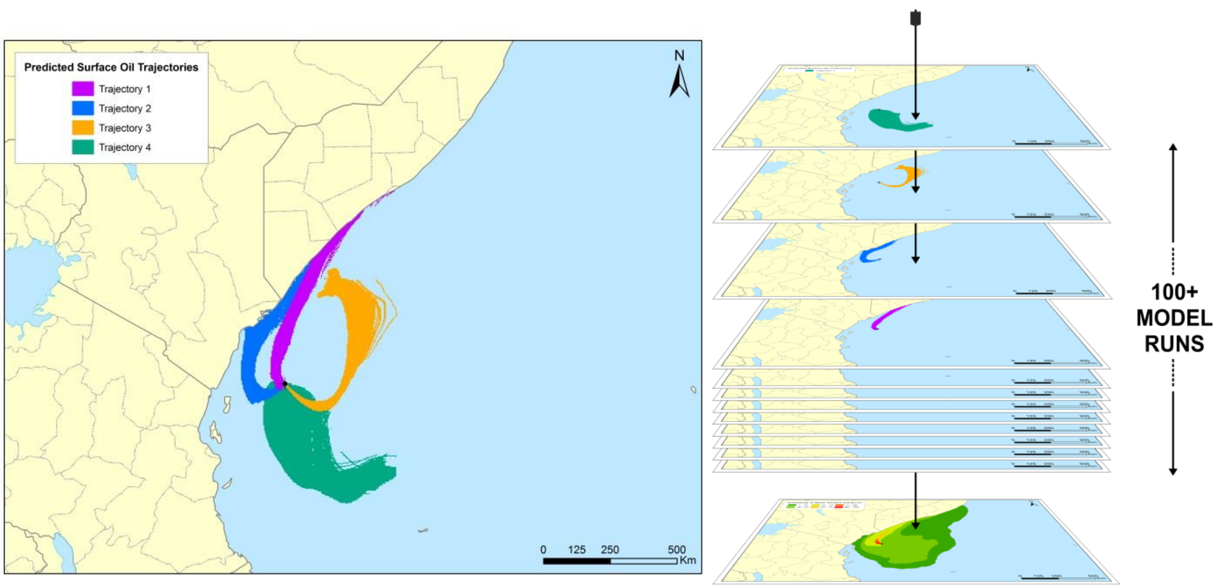


Figure 2-2. Example of four individual release trajectories predicted by SIMAP for a generic release scenario at a generic location simulated with different start dates and therefore environmental conditions. Tens to hundreds of individual trajectories are overlain (shown as the stacked runs on the right)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

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

2.2.3 Thresholds of Interest

In a stochastic analysis, multiple model runs (tens to hundreds of releases) are overlaid upon one another to create a cumulative footprint of the potential trajectories. When combined with one another, the many individual deterministic footprints can be used to generate an area of probability that describes the potential areas that may be exposed to oil contamination from the entire suite of modelled conditions. To determine the probability or likelihood of potential exposure, specific thresholds for surface oil thickness, oil on shorelines and sediments, and in-water contamination were required (Table 2-2). Above these conservative, socio-economic thresholds, previous studies identified there is the potential for negative effects to occur. Figures and further analyses 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. Should a higher, less conservative stochastic threshold be used (e.g., ecological threshold), the predicted probability footprint would be much smaller.

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

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

Threshold Type	Cutoff Threshold*	Rationale/Comments (Socio-economic, Response, Ecological)	Visual Appearance	References
Oil Floating on Water Surface	0.04 µm (equivalent to 0.04 g/m²)	**Socio-economic:** A conservative threshold used in several risk assessments to determine effects on socioeconomic resources (e.g., fishing may be prohibited when sheens are visible on the sea surface). Socio-economic resources and uses that could be affected by floating oil include commercial, recreational and subsistence fishing; aquaculture; recreational boating, port concerns such as shipping, recreation, transportation, and military uses; energy production (e.g., power plant intakes, wind farms, offshore oil and gas); water supply intakes; and aesthetics.	Fresh oil at this minimum thickness corresponds to a slick being barely visible or scattered sheen (colorless or silvery/grey), scattered tarballs, or widely scattered patches of thicker oil.	French McCay et al., 2011; French McCay et al., 2012; French McCay, 2016; Lewis, 2007, Bonn Agreement
	10 g/m² (equivalent to 10 g/m²)	**Ecological:** Mortality of birds on water has been observed at and above this threshold. Sublethal effects on marine mammals, sea turtles, and floating Sargassum communities are of concern.	Fresh oil at this thickness corresponds to a slick being a dark brown or metallic sheen.	French et al., 1996; French McCay, 2009 (based on review of Engelhardt, 1983, Clark, 1984, Geraci and St. Aubin 1988, and Jenssen 1994 on oil effects on aquatic birds and marine mammals); French McCay et al., 2011; French McCay et al., 2012; French McCay, 2016
Shoreline Oil	1.0 g/m²	**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 could 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/m²	**Ecological:** This is a screening threshold for potential ecological effects on shoreline flora and fauna, based upon a synthesis of the literature showing that shoreline life has been affected by this degree of oiling. Sublethal effects on epifaunal intertidal invertebrates on hard substrates and on sediments have been observed where oiling exceeds this threshold. Assumed lethal effects threshold for birds on the shoreline.	May appear as black opaque oil.	French et al., 1996; French McCay, 2009; French McCay et al., 2011; French McCay et al., 2012**;** French McCay, 2016
In Water Concentration	1.0 ppb (µg/L) of dissolved PAHs; corresponds to ~100 ppb (µg/L) of whole oil (THC) in the water column (soluble PAHs are approximately 1% of the total mass of fresh oil)	Water column effects for both **ecological** and **socioeconomic** (e.g., seafood) resources may occur at concentrations exceeding 1 ppb dissolved PAH or 100 ppb whole oil; this threshold is typically used as a screening threshold for potential effects on sensitive organisms.	N/A	Trudel et al., 1989; French-McCay 2004; French McCay 2002; French McCay et al., 2012

*Thresholds used in supporting stochastic results figures. For comparison, a bacterium is 1-10 µm in size, a strand of spider web silk is 3-8 µm, and paper is 70-80 µm thick. Oil averaging 1 g/m² is roughly equivalent to 1 µm.

Table 2-3. Oil appearances based on NOAA (2016), Bonn (2009, 2011), and Lewis (2007).

Code	Description	Layer-Thickness		Concentration		Generalized Thickness Used in Modelling Results*
		microns (µm)	Inches (in.)	m^3 per km^2	bbl/acre	microns (µm)
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}	0.01
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}	0.1
M	Metallic Sheen	5.0 - 50	2.0×10^{-4} - 2.0×10^{-3}	5.0 - 50	1.28×10^{-1} - 1.28	1-10
T	Transitional Dark (or true) Color	50 - 200	2.0×10^{-3} - 8×10^{-3}	50 - 200	1.28 - 5.1	100
D	Dark (or true) Color	>200	$>8 \times 10^{-3}$	>200	>5.1	>100
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

*Visual appearances and corresponding thicknesses of surface oil vary by oil type and environmental condition. Therefore, generalized thicknesses are used the portrayal of modelling results

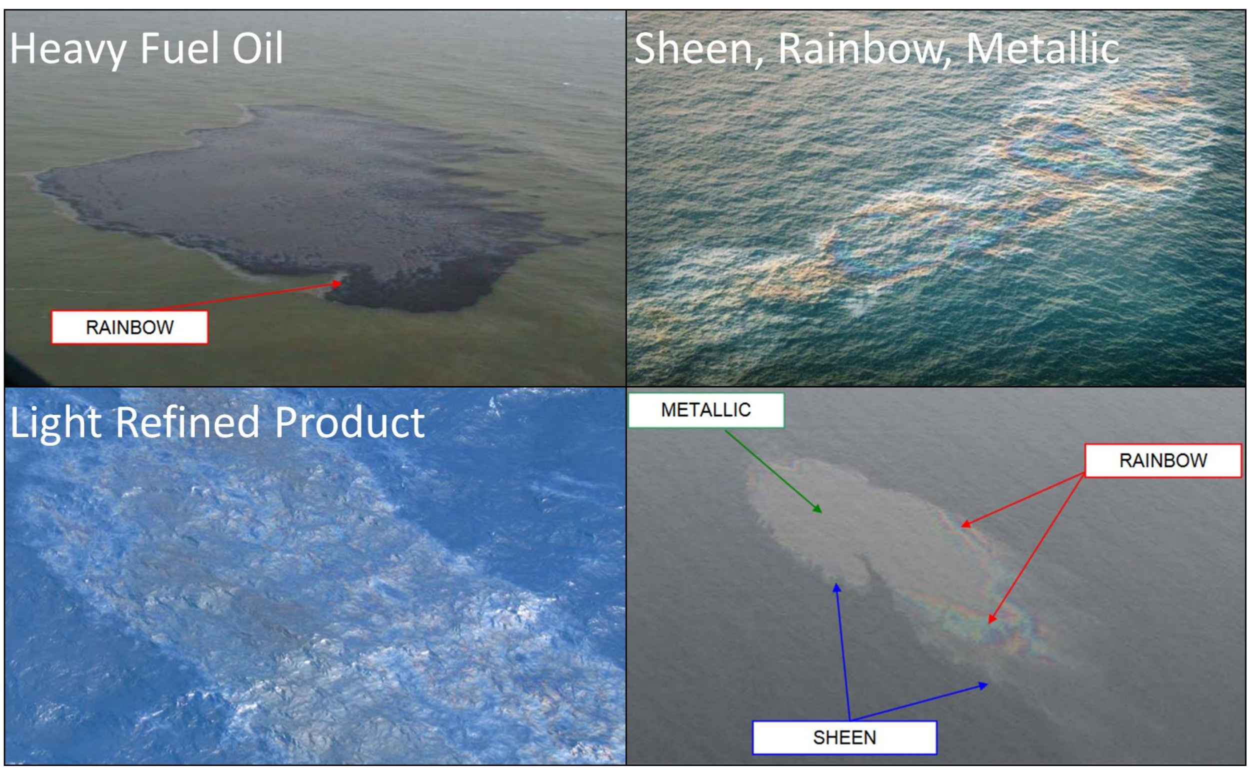


Figure 2-3. Aerial surveillance images of released oil in the environment as examples of different visual appearances based on surface oil thickness and product type (Bonn Agreement, 2011).

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 run within a stochastic analysis represents a specific set of wind and current conditions for the modelled time period. When analyzed together, tens to hundreds of stochastic model runs provide a range of expected exposures. The exposures between cases may differ as the trajectory of each individual modelled release is unique. Therefore, the movement and behavior, as well as the resulting area of surface oil, mass of oil along the shoreline, and mass of oil within the water column, will be different for each modelled simulation. The 95th percentile "worst case" exposures for surface, shoreline, and in-water contamination were identified for each release location based upon the area, mass, and length of oil that was predicted in each environmental compartment of interest (i.e., water surface area, shoreline length, or mass in the water column). Each simulation includes its own trajectory, mass balance, surface oil thickness, in-water concentration of dissolved hydrocarbons, etc. reported individually.

In addition, deterministic analyses of "batch spills" were modelled in the original modelling report "Trajectory Modelling in Support of the Nexen Energy ULC Flemish Pass Exploration Drilling Project (2018-2028)" authored on January 26, 2018. In that body of work, surface releases at one site (the EL 1144 example well site) for small (100 L) and large (1,000 L) release volumes were used to evaluate any potential discharges during bunkering operations (i.e., transfer from a vessel) between surface vessels and MODU. A 750,000 L release was also modelled at the VCL to represent a vessel collision and complete loss of cargo and fuel from a supply vessel. Each "batch spill" scenario was conservatively chosen to occur during the calmest wind-speed period during the summer/ice-free conditions, as they would result in the largest amount of oil on the surface.

The results of the deterministic simulations provide a time history of the fate and weathering of oil over the duration of the release (mass balance), expressed as the percentage of released oil on the water surface, on the shoreline, evaporated, entrained in the water column, and degraded. In addition, cumulative footprints of the individual trajectories over the course of the entire modelled duration will depict the cumulative path of floating surface oil, the mass of shoreline oil, and the maximum concentration of dissolved hydrocarbons in the water column at any instant in time. The results are shown in figures presented in Section 4.2.

2.3 Model Scenarios

Two release locations were identified within the Project Area for modelling subsurface blowouts (Figure 2-1). One example well site was selected in each license, reflecting the range of potential wells that are planned to be drilled (water depth, total depth, reservoir properties, etc.). One hypothetical location represents a deeper Jurassic well in a deeper water depth in EL 1144 while the other represents a shallower Cretaceous well in a shallower water depth in EL 1150. Subsurface blowouts near the seafloor were modelled separately with OILMAPDeep and SIMAP at each location in a stochastic analysis that included 171 individual model runs per location. This analysis investigated the influence of environmental variability, throughout the year over multiple years, on trajectory and fate (Table 2-4). The estimated volumes of hydrocarbons released in the subsurface blowout scenarios represent the best technical estimate of potential wells that may be drilled during the license period. In essence, these blowout rates represent a credible "worst case" release volume given realistic inputs and drilling scenarios.

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

Scenario Parameter	Release Locations of Unmitigated Subsurface Blowout Scenarios	
	EL 1144 Example Well	EL 1150 Example Well
Latitude	47°31'1.2194" N	47° 18' 54.757" N
Longitude	46°43'9.1987" W	46° 9' 40.394" W
Water Depth of Release	1,137 m	378 m
Product	Bay du Nord	
Release Duration	120 d	120 d
Gas to Oil Ratio	500 scf/bbl	
Pipe Diameter	12.35"	12.35"
Oil Discharge Temperature	96.3 °C	63.6 °C
Release Rate	184,000 bpd	44,291 bpd
Total Released Volume	22,080,000 bbl	5,314,920 bbl
Model Duration	160 d	160 d
Number of Stochastic Runs	171 annual (81 winter & 90 summer) for each site	

Results from the stochastic analyses were then used to inform an analysis of seasonal affects (i.e. wind and current speed and direction and ice cover) and deterministic analyses (i.e. representative individual trajectories), which identify credible "worst case" periods of time that result in the potential for larger predicted effects to the water surface, water column, and shorelines, separately. Results from the stochastic analyses were broken into two seasons depending on the majority of modelled days falling in ice free conditions (summer) from May – October or periods with ice-cover (winter) from November – April. This procedure allowed for comparisons between probability and minimum time footprints based upon seasonal factors. In addition, analysis of representative deterministic scenarios were conducted for individual trajectories identified as the 95th percentile for surface oil exposure, contact with shoreline, and water column contamination from blowouts near the seafloor modelled in the stochastic analysis (Table 2-5). These representative deterministic simulations tend to maximize the predicted effects from the suite of stochastic simulations in an effort to bound the upper range of predicted effects in a "credible worst case" scenario.

Table 2-5. Selected representative deterministic scenarios.

Scenario Parameter	Release Parameters for Representative Deterministic Scenarios					
	95th Percentile – EL 1144 Example Well			95th percentile – EL 1150 Example Well		
Representative Scenario	Surface Oil Exposure Area	Water Column Oil Mass	Shoreline Contact Length	Surface Oil Exposure Area	Water Column Oil Mass	Shoreline Contact Length
Release Site	EL 1144 Example Well			EL 1150 Example Well		
Release Type	Subsurface Blowout					
Depth of Release	1,137 m			378 m		
Released Product	BdN			BdN		
Release Rate	184,000 bpd			44,291 bpd		
Release Duration / Model Duration	120 d / 160 d			120 d / 120 d		
Total Release Volume	22,080,000 bbl			5,314,920 bbl		
Modelled Start Date and Season	10/22/2009 Winter	06/19/2012 Summer	03/7/2006 Summer	02/5/2008 Winter	05/28/2009 Summer	07/22/2006 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 is:

- Oil contains thousands of chemicals with differing physical and chemical properties that determine their fate in the environment. The model must, out of necessity, treat the oil as a mixture of a limited number of components, grouping chemicals by physical and chemical properties.
- The 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 of contamination.
- Several physical parameters, including but not limited to, hydrodynamics, water depth, total suspended solids concentration, and wind speed were not sampled extensively throughout the entire modelled domain. However, the data that did exist was sufficient for this type of modelling. When data were lacking, professional judgment and previous experience was used to refine the model inputs.

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

3 Model Input Data

3.1 Oil Characterization

Bay du Nord (BdN) crude oil was modelled at two release sites for this study. The physical and chemical data used to characterize these oils was provided by Nexen Energy ULC (BdN oil), with additional assays and measurements by S.L. Ross Environmental Research Ltd. (2016) and Petroforma (2013).

BdN is a light crude oil with low viscosity and a high aromatic content (Table 3-1 &

Table 3-2). The low viscosity and high soluble content of this oil product provide conservative approximations of anticipated concentrations in the water following a release, as a relatively large proportion of constituents have the potential to dissolve into the water column, when compared to oils with lower soluble content.

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 were grouped by physical-chemical properties, and the resulting component category behaved as if it were a single chemical with characteristics typical of the chemical group. In this component breakdown, aromatic (AR) groups were treated as both soluble (i.e., dissolve into the water column) and volatile (i.e., evaporate to the atmosphere), while the aliphatic (AL) groups were only volatile. The total hydrocarbon concentration (THC) within the boiling range of volatile components was the sum of all AR and AL components. The remainder of the oil was considered to be residual oil, which did not dissolve or volatilize but will degrade over time.

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

Physical Property	BdN Crude Oil
Density (g/cm^3)	0.853441 @16°C 0.863 @0°C
Viscosity (cP)	5.48 @20°C 9.45 @0°C
API Gravity	34.07
Pour Point (°C)	-9
Interface Tension (dyne/cm)	15.5
Emulsion Maximum Water Content (%)	72

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

Distillation Cut[1]	Boiling Point (°C)	Description	BdN Crude Oil
AR1	<180	highly volatile and soluble monoaromatic hydrocarbons (BTEX[2] and MAHs C6-C9)	0.023739
AR2	180 – 264	semi-volatile and soluble 2-ring aromatics (MAHs and PAHs C10-C12)	0.004166
AR3	265 – 380	low volatility and solubility 3-ring aromatics (PAHs C13-C18)	0.066998
AL1	<180	highly volatile aliphatics (C4-C8)	0.206261
AL2	180 – 280	semi-volatile aliphatics (C9-C16)	0.160834
AL3	280 – 380	low volatility aliphatics (C17-C23)	0.168002
THC1	<180	total hydrocarbon fraction 1 (sum of AR1 and AL1)	0.230000
THC2	180 – 280	total hydrocarbon fraction 2 (sum of AR2 and AL2)	0.165000
THC3	280 – 380	total hydrocarbon fraction 3 (sum of AR3 and AL3)	0.235000
Residuals	>380	aromatics ≥4 rings and aliphatics >C20 that are neither volatile nor soluble	0.37000

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

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 data required for modelling (Table 3-3). Habitat data were used to define the bottom type and vegetation found in subtidal areas, areas of extensive mud flats and wetlands, and the shoreline type (e.g., sandy beach, rocky shoreline, etc.).

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, 2017
	National Oceanic and Atmospheric Administration Environmental Sensitivity Index	United States (except Maine)	NOAA, 2016
	Maine Environmental Vulnerability Index	United States - Maine	MDEP, 2016
Bathymetry	General Bathymetric Chart of the Oceans Digital Atlas	Global	GEBCO, 2003

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

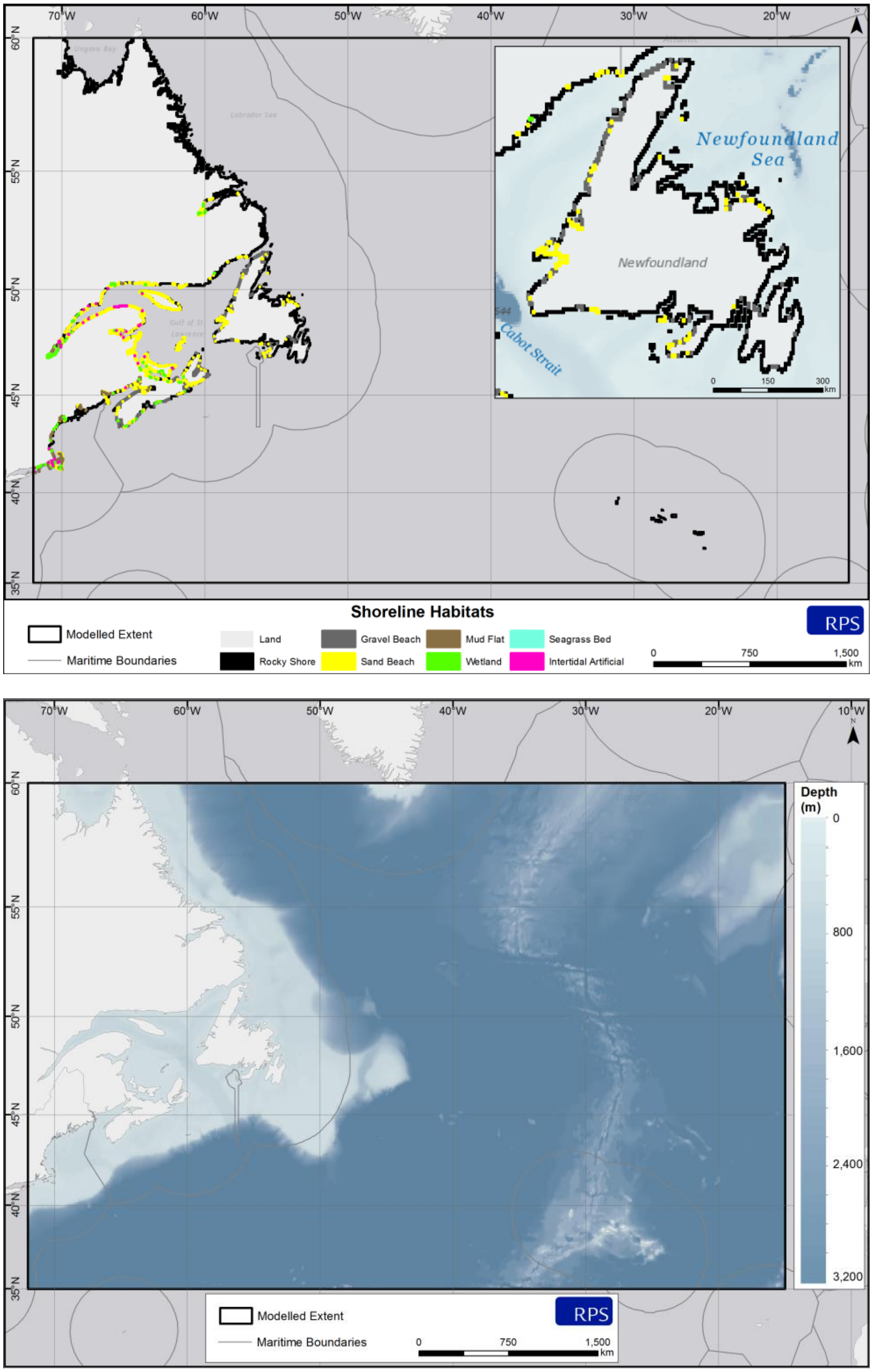


Figure 3-1. Shoreline habitat data (top) and bathymetry (bottom) throughout the modelled domain. The black box represents the modelled extent.

3.3 Ice Cover

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

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

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

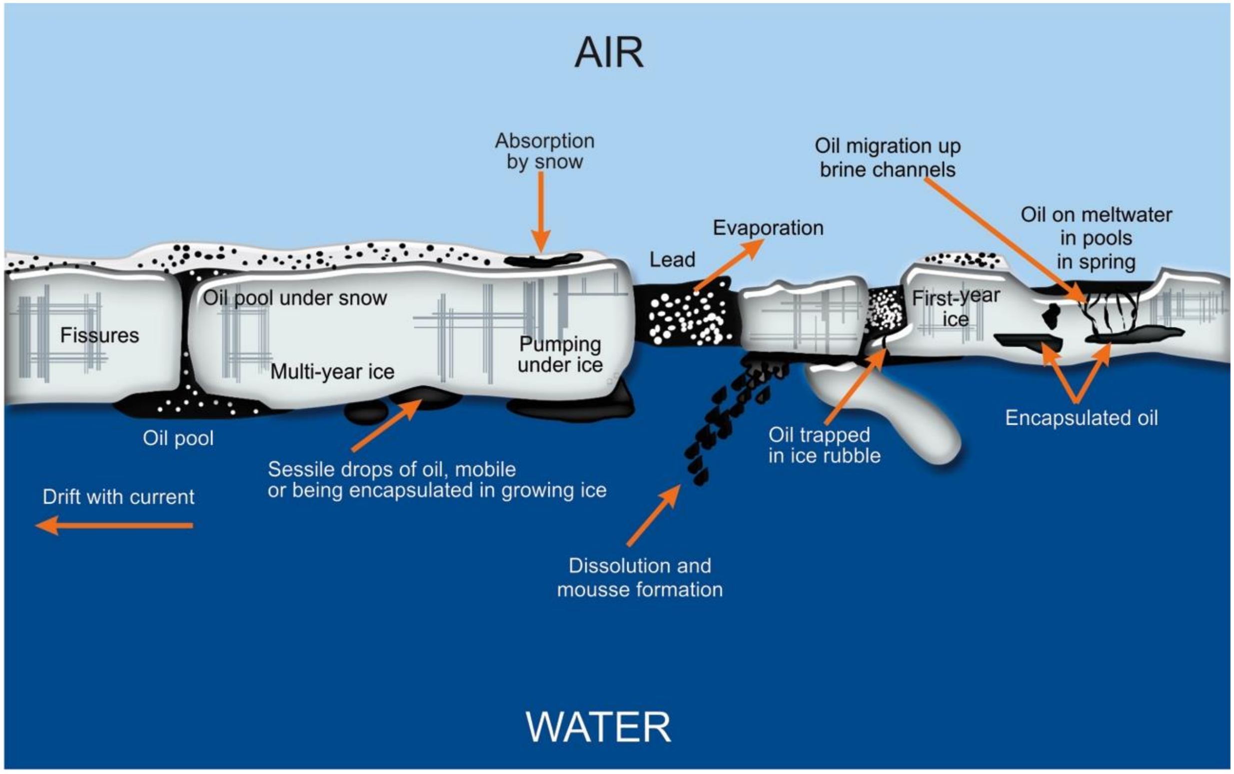


Figure 3-2. Oil and ice interactions at the water surface.

Ice data used as modelling inputs were obtained from the Canadian Ice Service (CIS; ECCC 2017) in weekly files spanning 2006 to 2012. These data were in the form of polygon data, with information on total ice concentration and stage of development. For each ice polygon, concentration codes were converted to concentration percentages. Average 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 were gridded at a resolution matching the habitat grid (0.0225°). A representative map depicting percentage of sea-ice coverage and thickness for the first week of February 2008 is presented (Figure 3-3).

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

<table>
<tr><th>CIS Sea-Ice Category or Sea-Ice Stage</th><th>Concentration</th><th>CIS Thickness Range (cm)</th><th>Model Applied Thickness (cm)</th></tr>
<tr><td>Ice Free</td><td>0%</td><td>n/a</td><td>n/a</td></tr>
<tr><td>Open Water</td><td>30%</td><td>n/a</td><td>50</td></tr>
<tr><td>Landfast Ice</td><td>100%</td><td>n/a</td><td>assumed full water depth</td></tr>
<tr><td>First year thick ice</td><td rowspan="9">Total concentration converted from tenths to percent ice cover</td><td>>120</td><td>120</td></tr>
<tr><td>First year medium ice*</td><td>70 – 120</td><td>95</td></tr>
<tr><td>First year thin ice</td><td>30 – 70</td><td>50</td></tr>
<tr><td>Young ice</td><td>10 – 30</td><td>20</td></tr>
<tr><td>Grey white ice</td><td>15 – 30</td><td>22.5</td></tr>
<tr><td>Grey ice</td><td>10 – 15</td><td>12.5</td></tr>
<tr><td>New ice</td><td><10</td><td>5</td></tr>
<tr><td>Icebergs</td><td>unknown</td><td>100</td></tr>
</table>

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

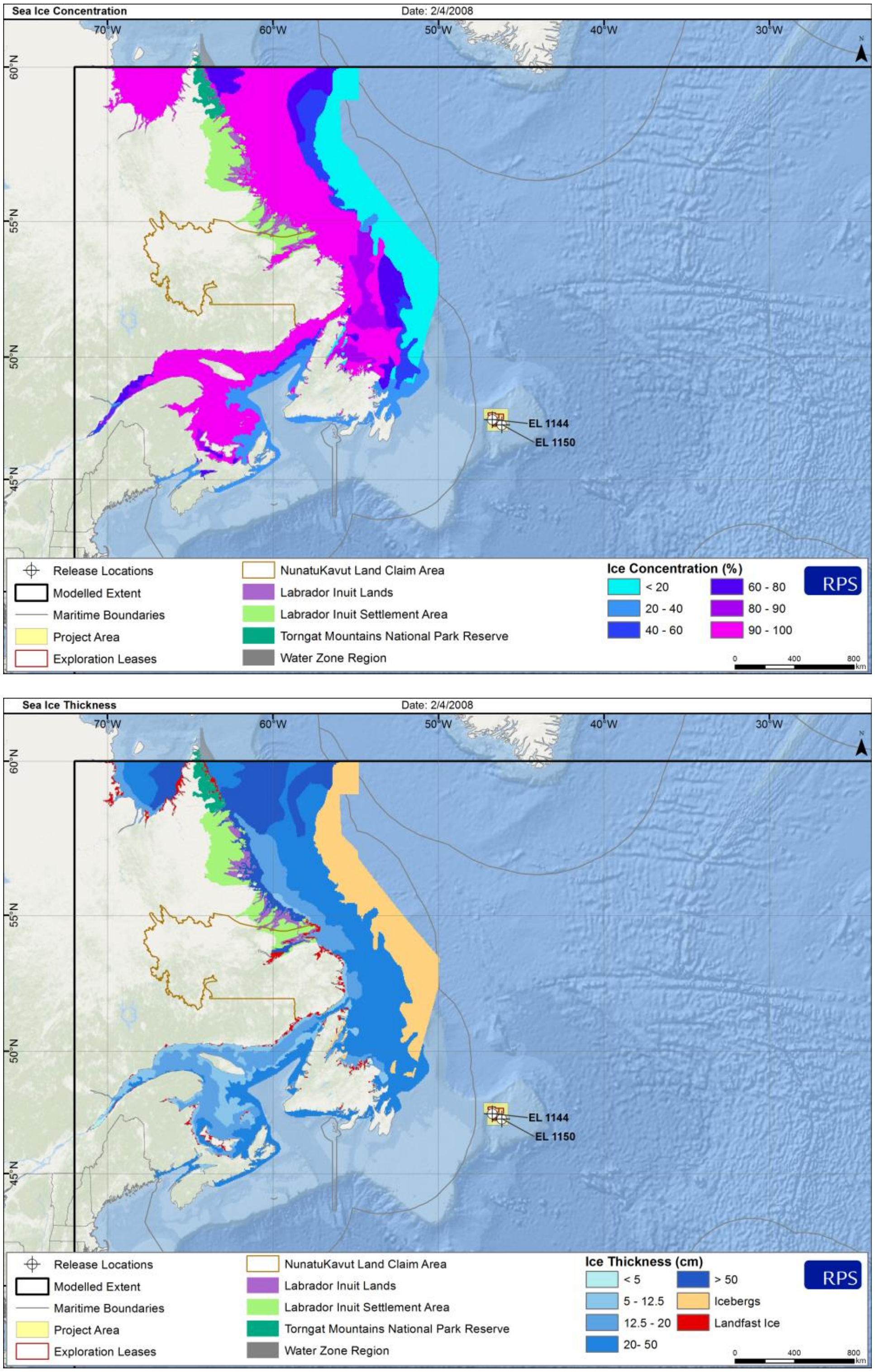


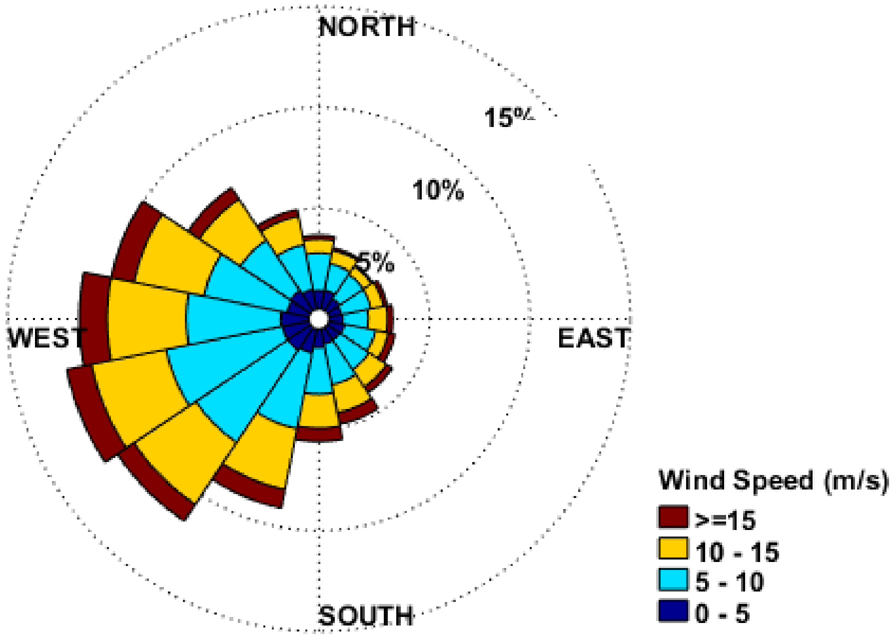
Figure 3-3. Representative percentage sea-ice coverage (top) and corresponding thickness (bottom) for the first week of February 2008.

3.4 Wind Data

Winds are one of the main physical forcings 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 travel long distances by wind transport.

Wind data for this study were obtained for the entire model domain (Figure 2-1) from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) product for 2006 through 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. 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 were also used as one of the main driving forces in the HYCOM hydrodynamic dataset used for modelling (see Section 3.5). The CFS time series acquired for this study was available at 0.5-degree horizontal resolution at 6-hourly intervals.

Averaged annual wind data at the EL 1144 and EL 1150 well sites are most frequently from the west-southwest direction (Figure 3-4) as part of prevailing Westerlies wind patterns. These winds would be expected to transport oil generally away from nearby shorelines further into the open ocean. Winter season winds are most frequently from the west and northwest with higher velocity than summer season winds, which typically come from the southwest (Figure 3-5). Spring and fall months 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. Monthly average wind speeds varied between 7 and 12 m/s while the 95^{th} percentile wind ranged from 12 to 20 m/s throughout the year, with highest speeds occurring during winter months (November-March) and lowest speeds during summer months (June-July) (Figure 3-6). 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).



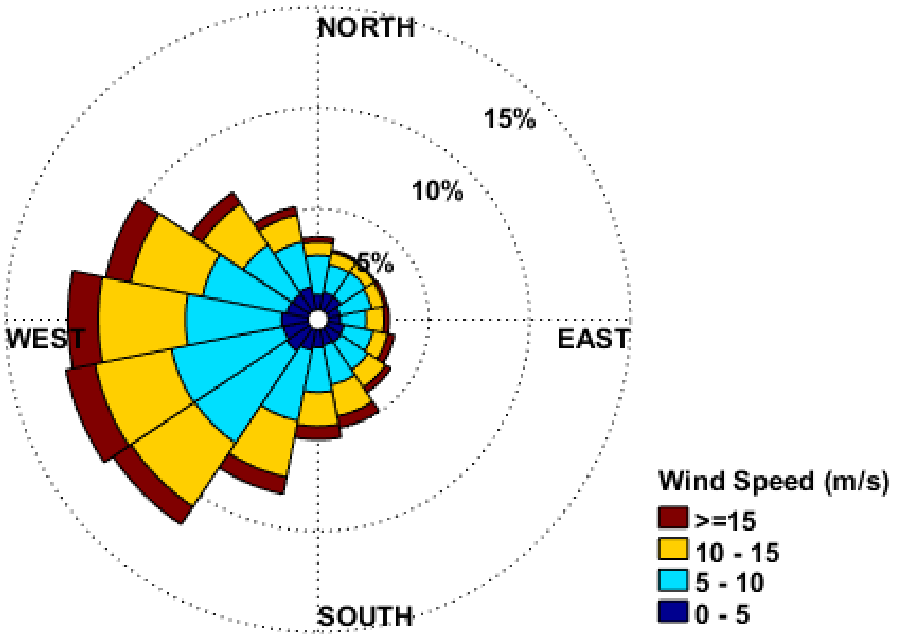


Figure 3-4. Annual CFS wind roses near the EL 1144 (top) and EL 1150 (bottom) well sites. Wind speeds are presented in m/s, using meteorological convention (i.e., direction wind is coming from).

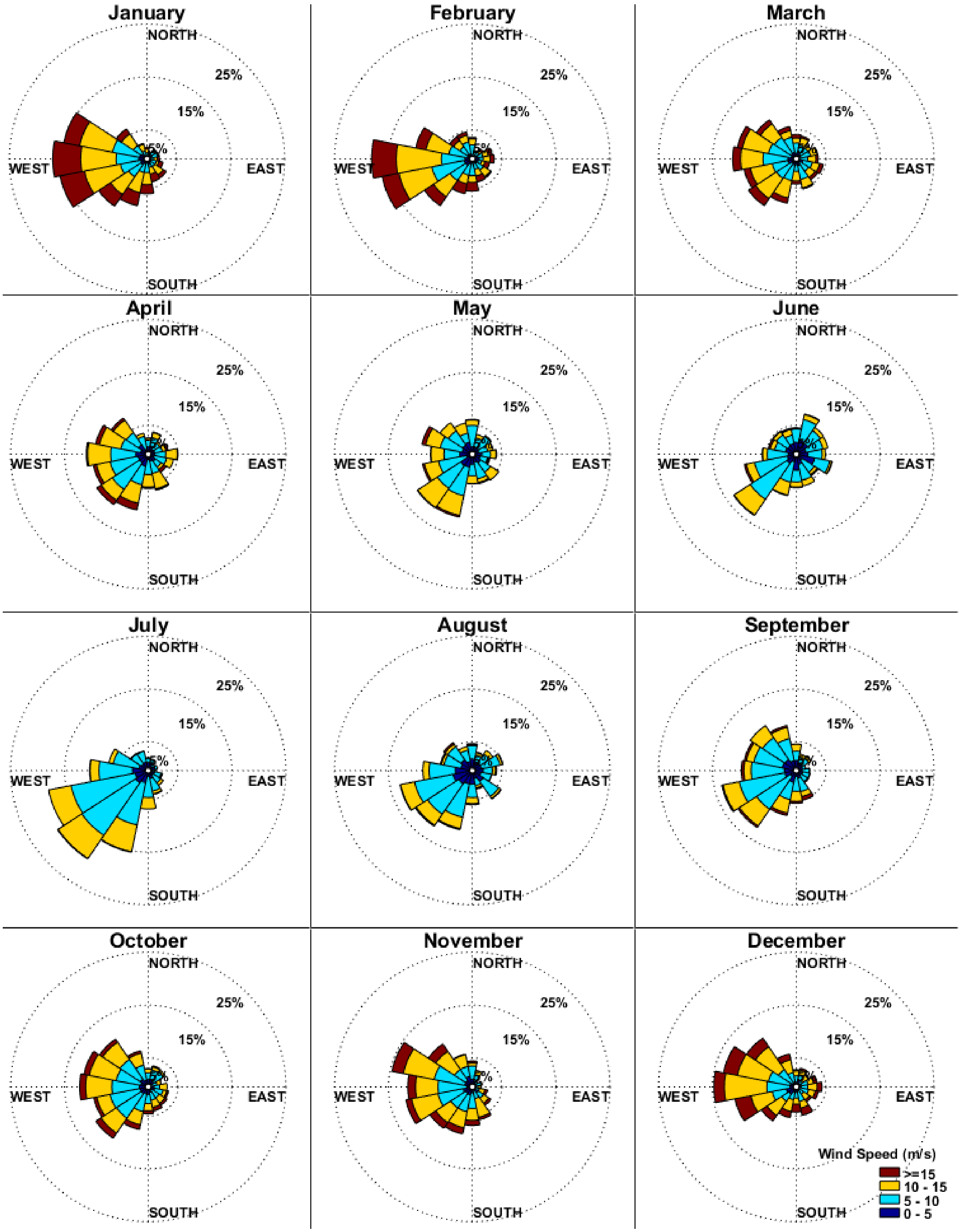


Figure 3-5. Monthly CFS wind roses near the EL 1144 Site. Wind speeds in m/s, using meteorological convention (i.e., direction wind is coming from). Because EL 1150 has similar patterns of seasonality it was not presented.

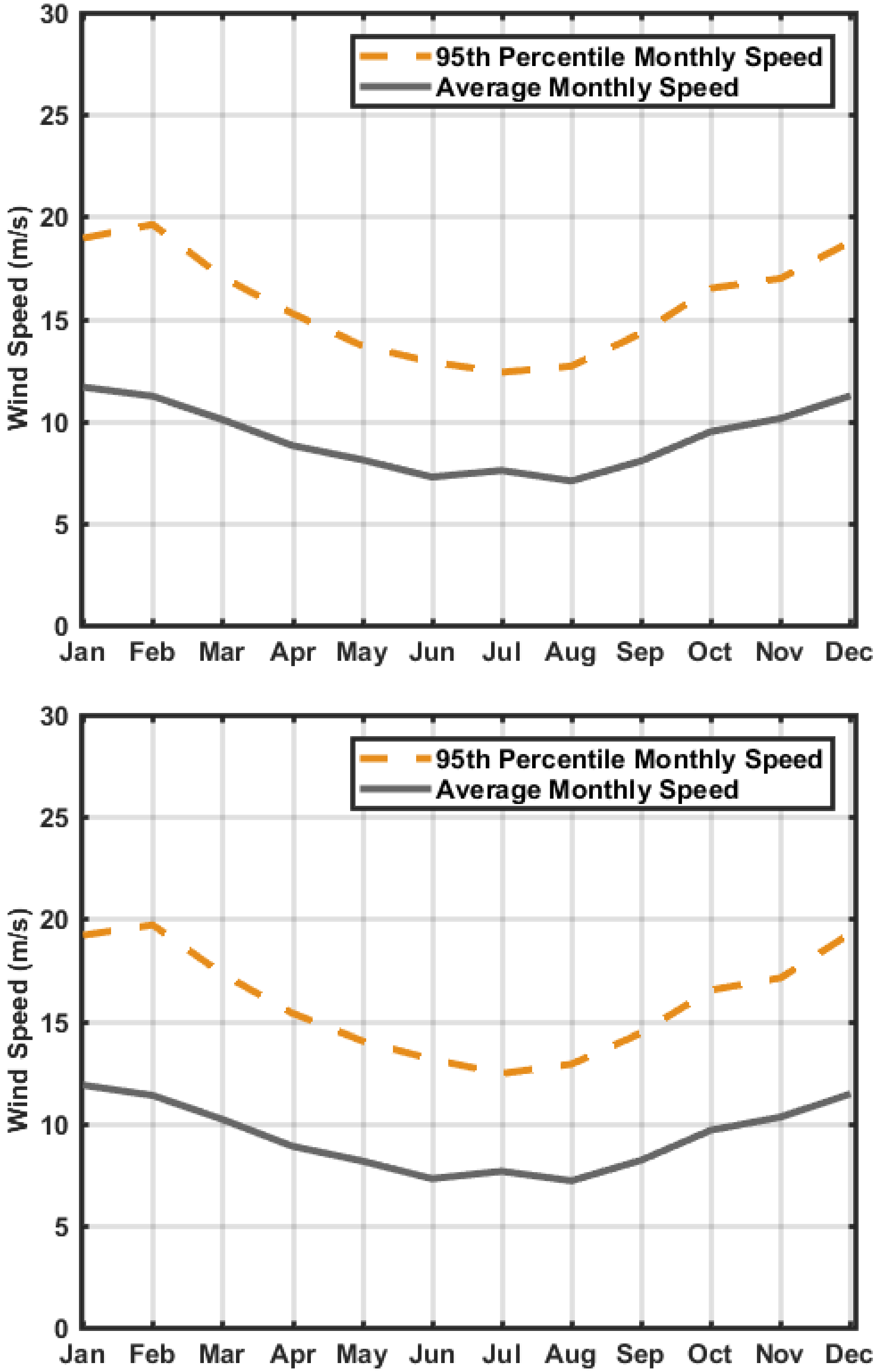


Figure 3-6. Average and 95th percentile monthly wind speeds near the EL 1144 (top) and EL 1150 (bottom) well sites.

3.5 Currents

In addition to winds, the second main forcing factor of oil spills are 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 3-8). This southerly current intensifies as waters funnel through the offshore branch, which follows the Flemish Pass along the 1,000 m contour between the Grand Banks and Flemish Cap. To a lesser extent, a portion of the Labrador Current flows through an inshore branch, which follows the Avalon Channel between Newfoundland and the Grand Banks. Over parts of the Grand Banks, currents can be generally weak and flow southward (Petrie and Isenor, 1985). Maximum current speeds in the upper 200 m of the water column range from 0.3-2.0 m/s (C-NLOPB, 2014). The strong southerly current dominates the yearly average flow, and winds may only account for approximately 10% of current variability in this region (Petrie and Isenor, 1985). South of the Flemish Pass, the Labrador Current mixes with the North Atlantic Current. The 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.

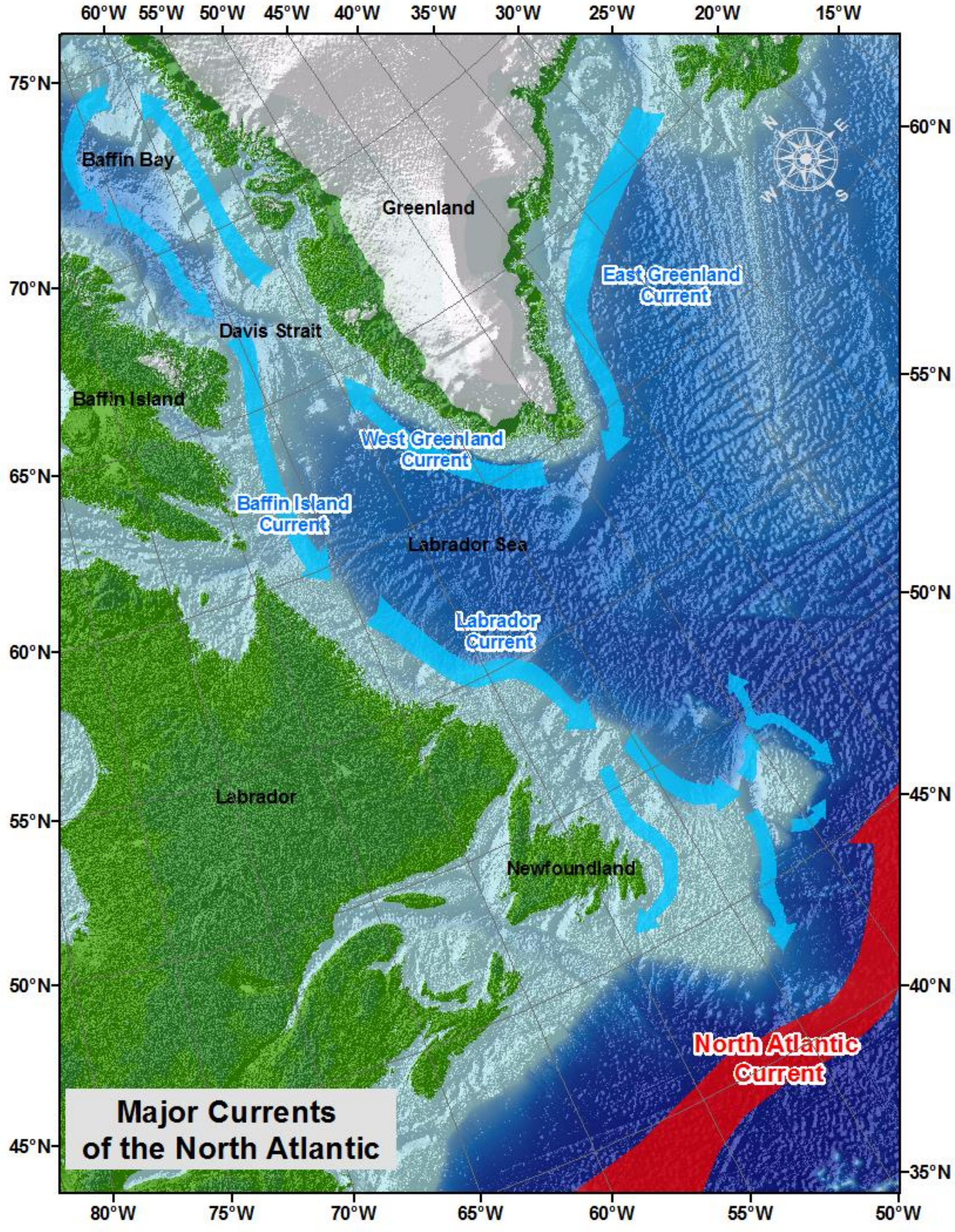


Figure 3-7. Large scale ocean currents in the Newfoundland region (USCG 2018).

Currents for the North Atlantic region were acquired from the HYCOM (HYbrid Coordinate Ocean Model) circulation model. HYCOM is a primitive-equation ocean general circulation model that evolved from the Miami Isopycnic-Coordinate Ocean Model (MICOM) (Halliwell, 2002; Halliwell et al., 1998, 2000; Bleck, 2002). MICOM is one of the premier ocean circulation models, following several validation studies (Chassignet et al., 1996; Roberts et al., 1996; Marsh et al., 1996). MICOM is used in numerous ocean climate studies (New and Bleck, 1995; New et al., 1995; Hu, 1996; Halliwell, 1997, 1998; Bleck, 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 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 water) 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., 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. 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 time steps must increase. Shorter time steps are required with higher spatial resolution data to account for the distance traveled in each time steps to ensure the spatial scale is resolved. As the number of cells for covering the same domain with higher resolution increases, consequently the amount of time required to model increases.

The HYCOM model leverages data assimilation technique through 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 U.S. Naval Research Laboratory BDB2 dataset. Surface forcing is derived from the Navy Operational Global Atmospheric Prediction System, which includes wind stress, wind speed, heat flux (using bulk formula), and precipitation.

For this study, daily HYCOM current data were obtained for the period January 2006 through December 2012 for the North Atlantic region (HYCOM, 2016). 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 the stochastic analysis. While this subset of data is not the most recent seven years of data, currents and winds in the study area would be representative of environmental conditions of 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 Figure 3-9) and direction offshore Newfoundland (Figure 3-9) in the model domain from 2006-2012 depict larger 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. While these figures present an average current speed and direction for visual purposes, oil transport was defined by the daily currents throughout each modelled simulation.

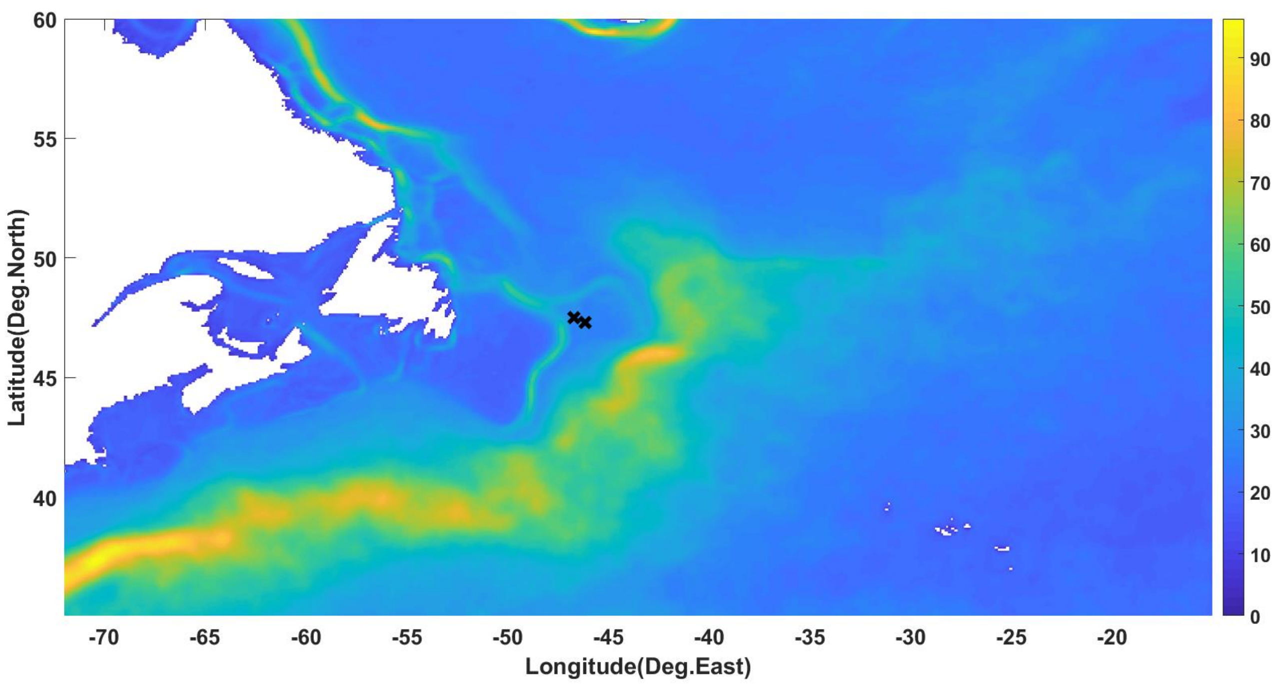


Figure 3-8. Average HYCOM surface current speeds (cm/s) off the coast of Newfoundland from 2006 – 2012. Black crosses represent the well locations.

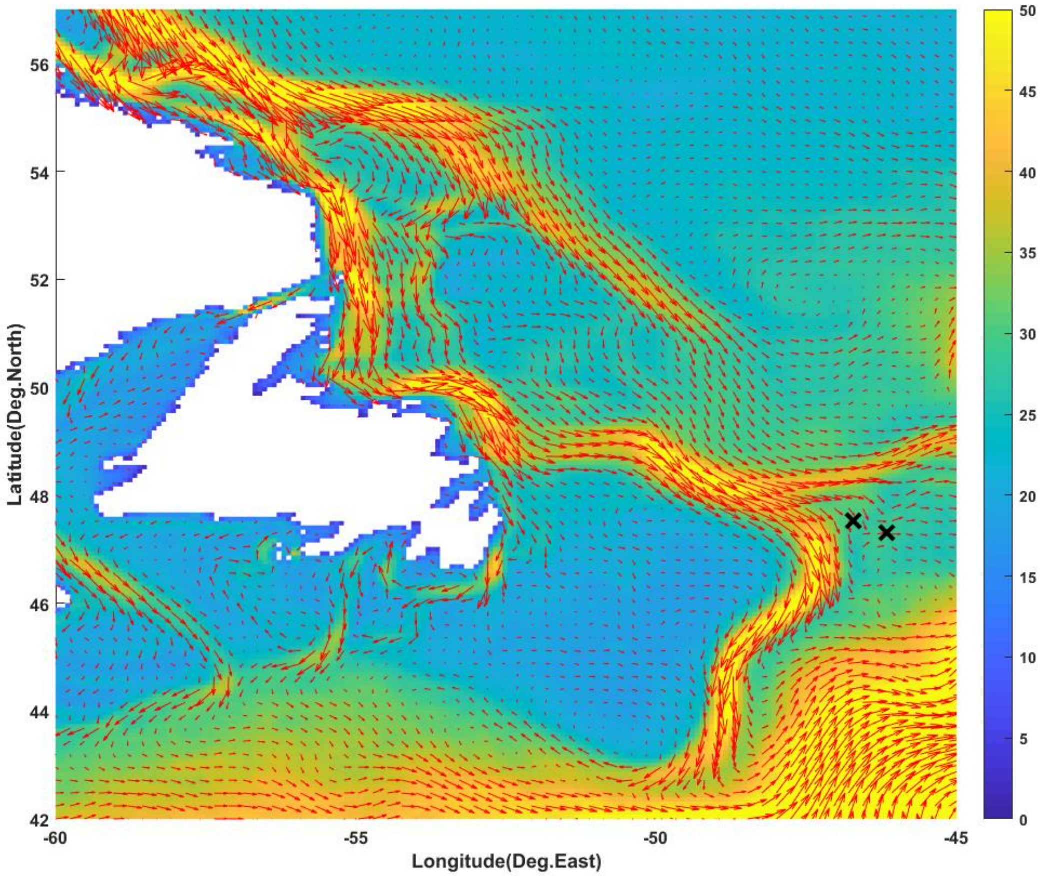


Figure 3-9. Averaged HYCOM surface current speed (cm/s) in color, and direction presented as red vectors around the Newfoundland coast, including portions of Labrador (2006-2012).

3.6 Water Temperature & Salinity

Temperature and salinity values throughout the water column influence a number of oil transport and fate calculations such as density and resulting buoyancy, evaporation, and others. Temperature and salinity data were obtained from the World Ocean Atlas (WOA) 2013 high-resolution dataset, Version 2, which is compiled and maintained by the U.S. National Oceanographic Data Center (Levitus et al., 2014). The WOA originated from the Climatological Atlas of the World Ocean (Levitus, 1982) and was updated with new data records in 1994, 1998, 2001 (Conkright et al., 2002), and 2013. These data records consist of observations obtained from various global data management projects. The dataset includes up to 57 depth bins from the sea surface to the seabed and include averaged yearly, seasonally, and monthly data over a global grid with a 1/4^{o} horizontal resolution. At both sites, the temperature sharply decreases with increasing depth and reaches the lowest value at approximately 75 m. Below this depth, the temperature starts to rise again and becomes relatively stable below 200 m. On the other hand, the salinity and density of the seawater increase with depth, with the surface 200 m having the largest degree of variability (Figure 3-10).

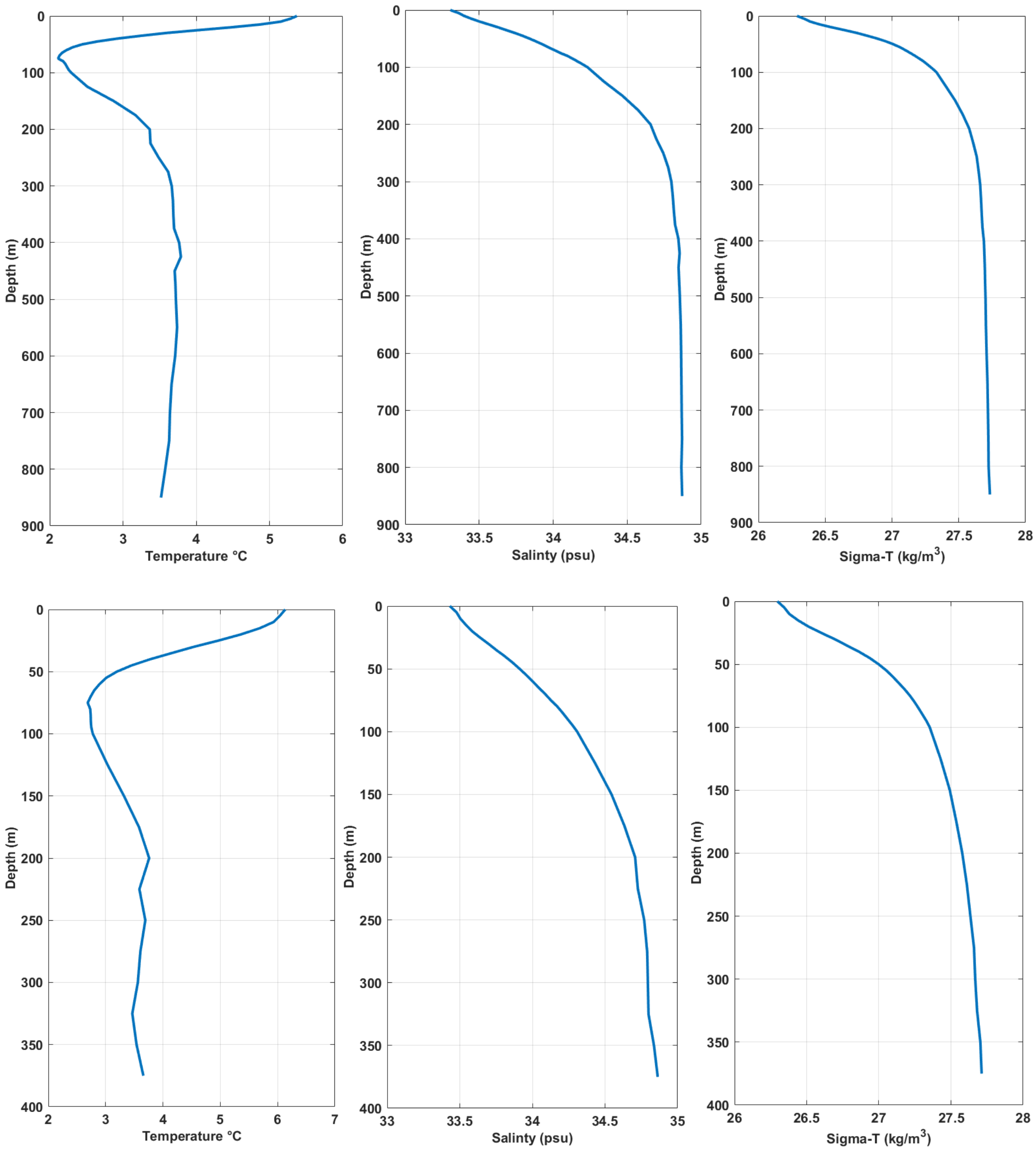


Figure 3-10. Annual water column profiles of temperature (left), salinity (middle) from WOA13, and corresponding density (right) represented as sigma-t in the vicinity of the release site EL 1144 (top), and EL 1150 (bottom). The density profile was generated based on the temperature and salinity profile using equations of state as published by UNESCO, 1981 (EOS – 80).

3.7 Blowout Model Scenarios and Results

The nearfield model OILMAPDeep was used to predict the initial droplet size distribution associated with subsurface blowouts of BdN crude oil at two different release locations. 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 release depth ranged from 378 m to 1,137 m between the two identified release locations. 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 scenarios simulated for this study, the oil was assumed not to be treated with dispersant. The energy of the release is a function of the volumetric flow rate and discharge orifice size, with higher energy releases occurring as greater volumes pass through smaller openings more quickly.

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

(1) EL 1144 Example Well Site –120-day release of BdN, through a 31.37 cm (12.35-inch) orifice at a depth of 1,137 m and rate of 29,254 m^3/d (184,000 bpd)
(2) EL 1150 Example Well Site– 120-day release of BdN, through a 31.37 cm (12.35-inch) orifice at a depth of 378 m and rate of 7,042 m^3/d (44,291 bpd)

The predicted droplet size distribution was represented by seven discrete size bins for each modelled release scenario at the EL 1144 and EL 1150 example well sites (Table 3- 1). The non-uniform spacing between the droplet size bins is the result of the non-linear functionality of droplet size distribution. Each of the seven bins were determined such that an equal proportion of the released oil by mass (14.29%) was within each bin. Differences in release volume, duration, and depth of release resulted in different droplet size distributions for each of the two modelled releases.

Oil droplets rise through the water column at rates based on drag, calculated using their diameter (treated as a sphere) and the buoyancy, and the density difference between the oil and the water, which varies with changing temperature and salinity by depth (Figure 3-10). Rise times for oil to reach the surface varied between minutes to many hours, depending on droplet size and depth of release. Rise time estimates are approximated, based on the initial droplet size, initial droplet density, and bottom water density, neglecting dispersion, dissolution, and degradation (which were tracked within the oil spill model and modified the rise rates). The longest rise times were associated with the smallest droplets and deepest release depths, with some rise times exceeding a day.

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

Median Droplet Size (d_{50}) in Each of Seven Equal-Mass Bins, by Diameter (µm)	
EL 1144 Example Well BdN Crude Oil (184,000 bpd, 120-day release)	**EL 1150 Example Well BdN Crude Oil (44,291 bpd, 120-day release)**
221	485
505	1,109
629	1,380
758	1,662
914	2,004
1,144	2,510
2,012	4,413

4 Model Results

4.1 Stochastic Analysis Results

Stochastic analyses characterize results from many tens to hundreds of individual modelled releases. This study included modelling 171 individual releases for 160 days over the course of seven years of environmental data at the EL 1144 and EL 1150 example well sites to capture the natural variability in the environment. In total, two stochastic analyses were conducted based upon these two release locations and one release duration.

Because ice cover can affect the trajectory and fate of oil, individual model runs were separated into two groups based upon the specific time periods modelled that included ice cover or ice-free conditions. 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 years. 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" analyses (90 modelled releases), while those releases with a majority of days experiencing periods with sea-ice coverage are referred to as "winter" analyses (81 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.

The figures presented in the stochastic modelling results section illustrate the possible spatial extent of surface floating oil, water column concentrations of dissolved hydrocarbons, and shoreline contact including both the probabilities and associated minimum times to threshold exceedance (Table 4-1) for the hypothetical release scenarios. The probability maps define the area of potential exposure and the associated probability with which sea surface oil, water column contamination, or shoreline oil are expected to exceed the specified thresholds at any point of time throughout the 160-day modelled duration. The colored contours in the stochastic maps signify the boundary for given percentiles of areas that may experience oil at or above the specified threshold for each release scenario. Darker color contours denote areas that are more likely to exceed the specified threshold, while lighter color contours are less likely. Note that the lightest mint-green line represents areas where oil may exceed the specified threshold in only 1% of release 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%. The area between this contour and the next (10%) has between a 1-10% probability of exceeding the threshold, given a release of the modelled scenario 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 did occur. Therefore, probability contours should be interpreted as "In the unlikely event of a release, the probability that any one specific area may experience contamination above the specified threshold is X%." Stochastic figures do not imply that the entire contoured area would be covered with oil in the event of a single release, nor do they provide any information on the quantity of oil in a given area. Additionally, these figures do not provide the likelihood of a blowout occurring in any given year. Rather, these stochastic figures denote the probability of oil exceeding identified thresholds at any modelled time step (over 160 days), for each point within the modelled domain, assuming a release were to occur at some point in time.

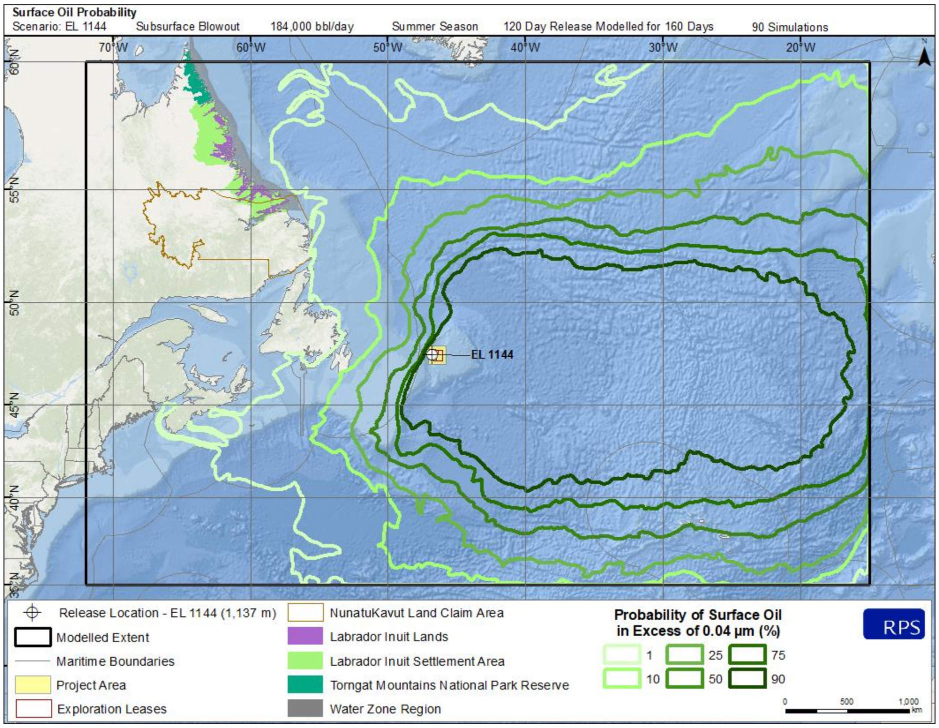
The stochastic maps depicting water column contamination by dissolved hydrocarbon concentrations do not specify the depth at which the threshold exceedance occurs. The maps depict the vertical maximum at any time during or after the release. Thus, images do not imply that the entire water column (i.e., from surface to bottom) will experience a concentration above the threshold, but rather a concentration 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 together to read: “There is X% probability that oil is predicted to exceed the identified threshold at a specific location, and this exceedance could occur in as little as Y days.”

The Exclusive Economic 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 (81 or 90 modelled simulations), two scenarios would be required to exceed the same threshold in the annual analysis (171 modelled simulations) due to a greater number of modelled releases in the annual set of runs being analyzed. Figures depicting stochastic results are provided for surface oil thickness >0.04 µm, dissolved hydrocarbon contamination >1 µg/L, and shoreline contact >1g/m^2 for annual, summer, and winter scenarios for the EL 1144 and EL 1150 example well sites (Figure 4-1 through Figure 4-18).

4.1.1 EL 1144 Example Well Release Site



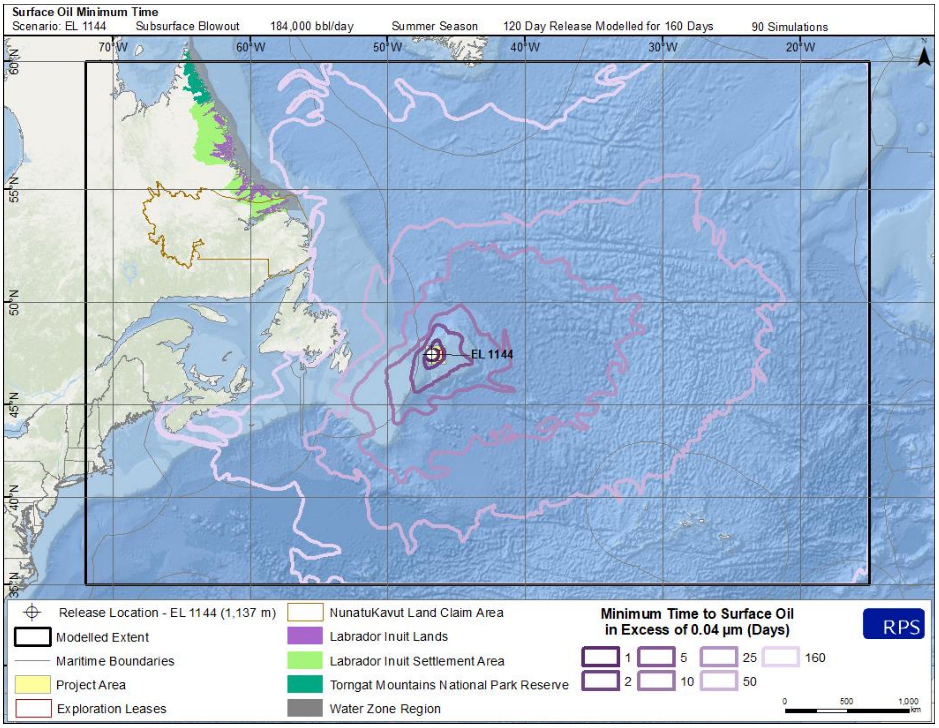
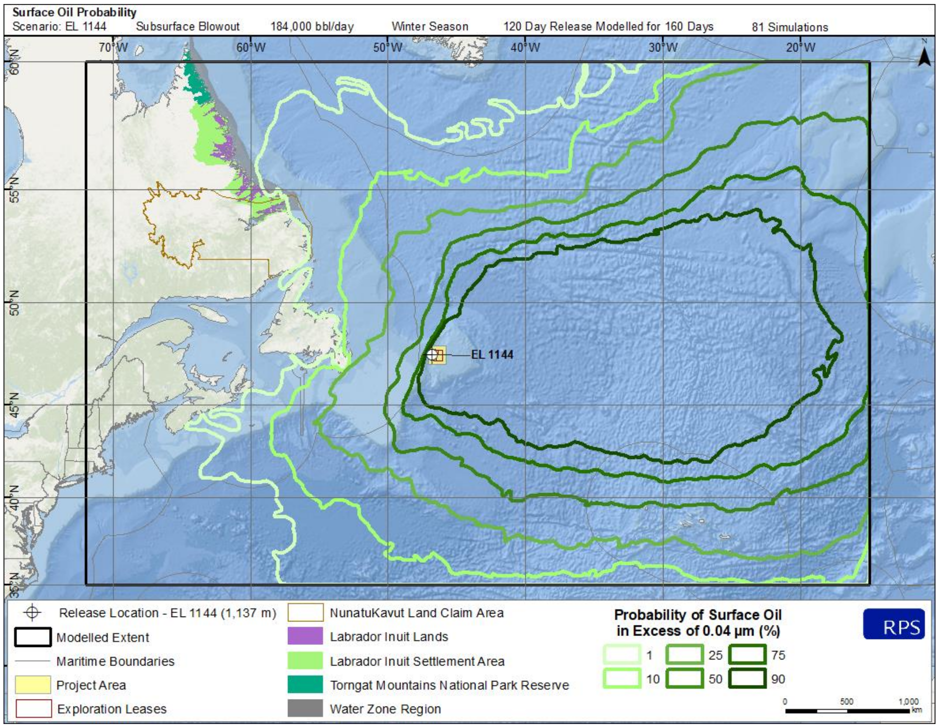


Figure 4-1. Summer probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1144 example well site.



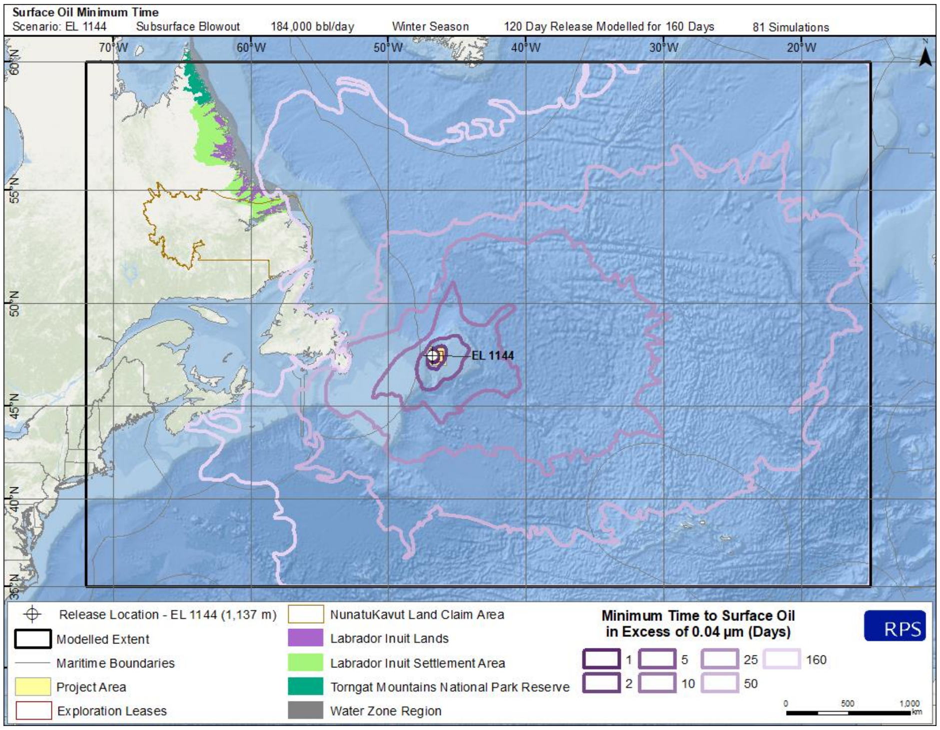


Figure 4-2. Winter probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1144 example well site.

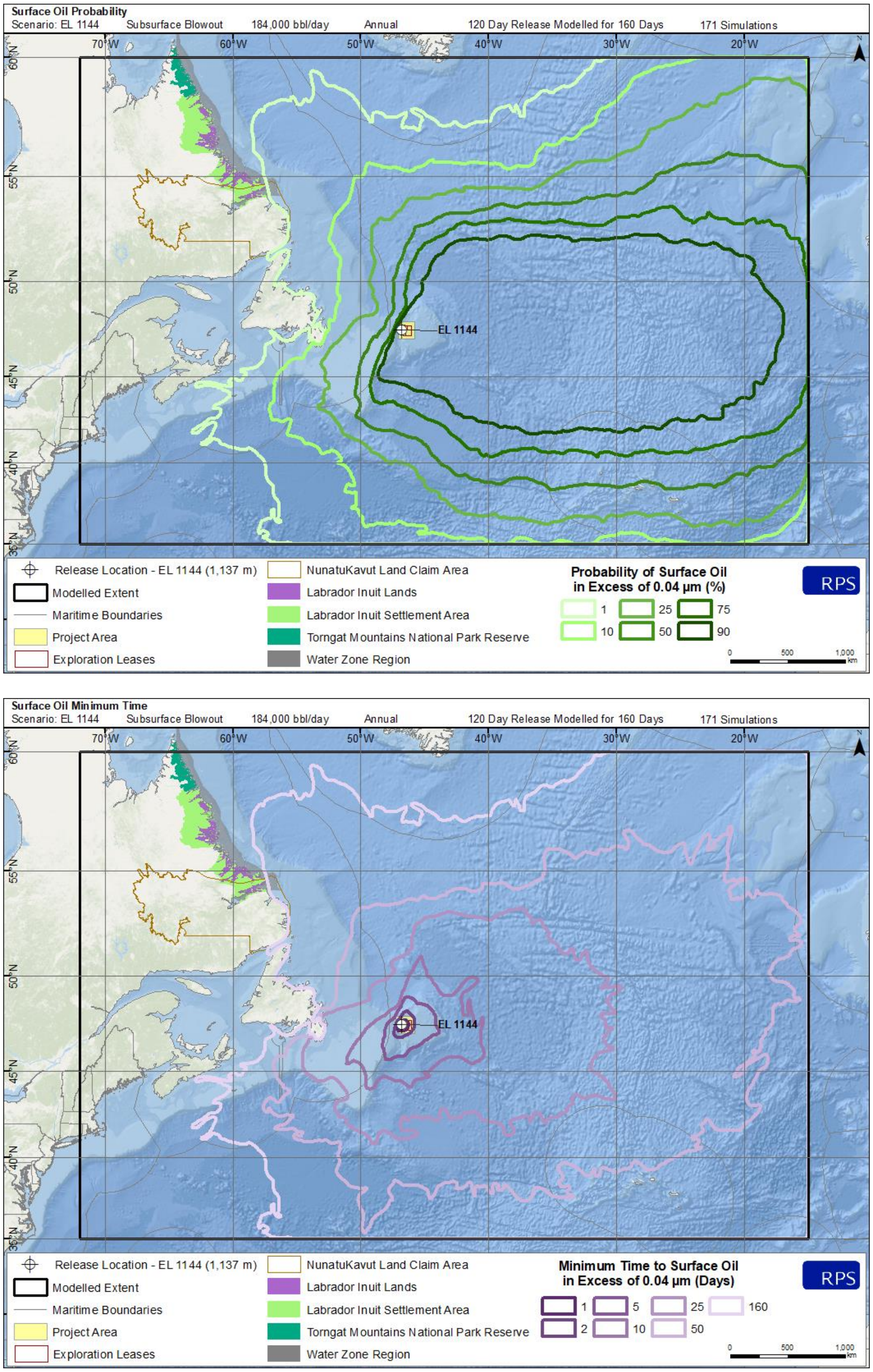


Figure 4-3. Annual probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1144 example well site.

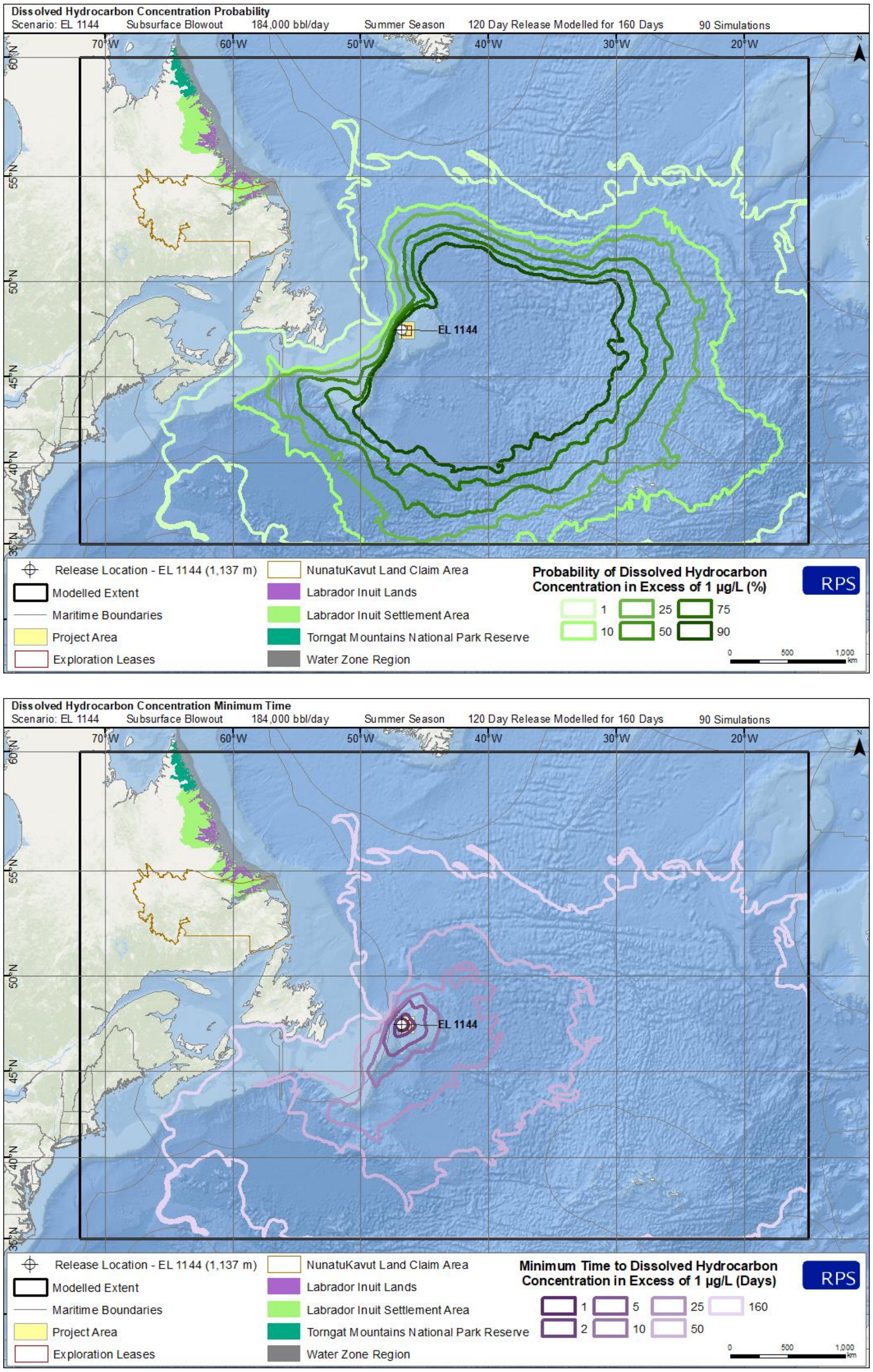
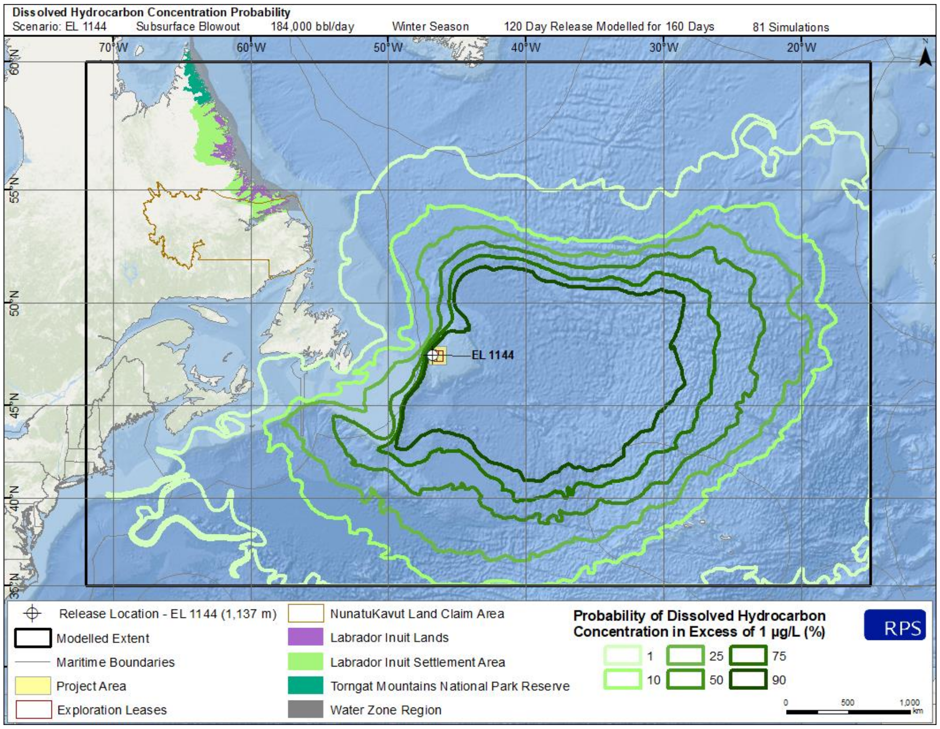


Figure 4-4. Summer probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1144 example well site.



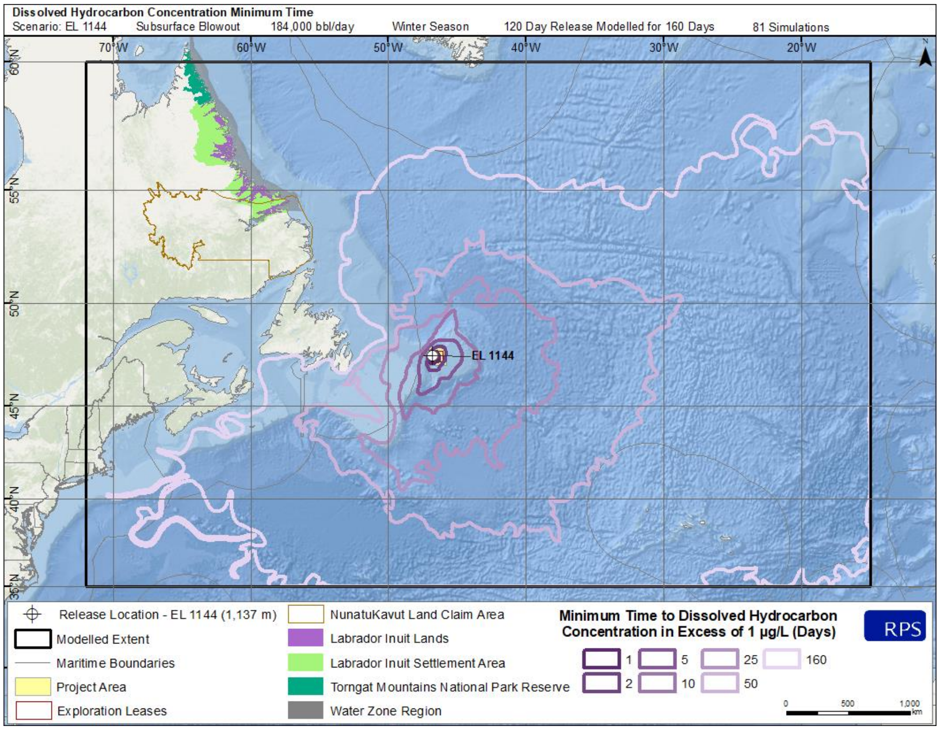


Figure 4-5. Winter probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1144 example well site.

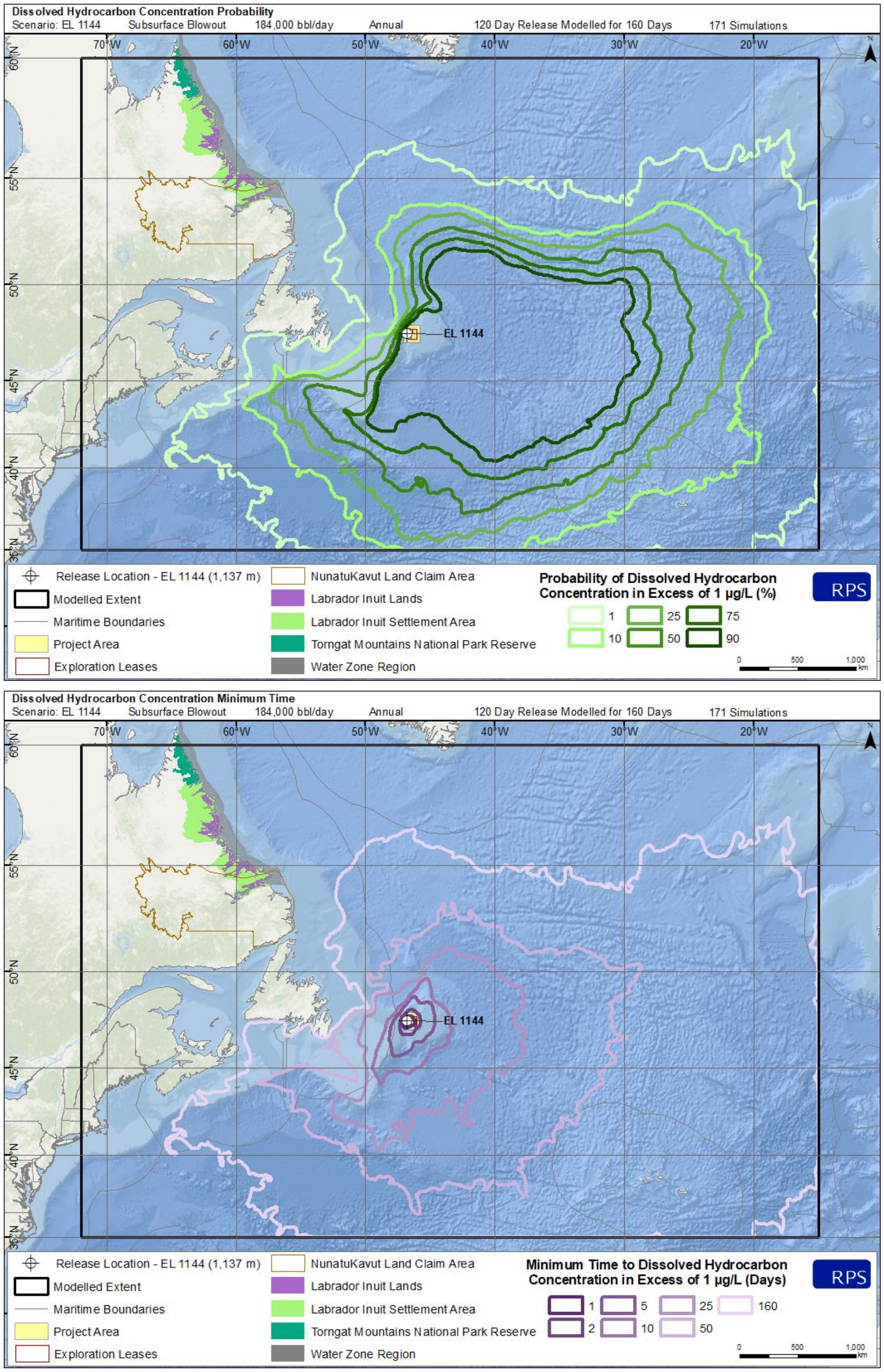
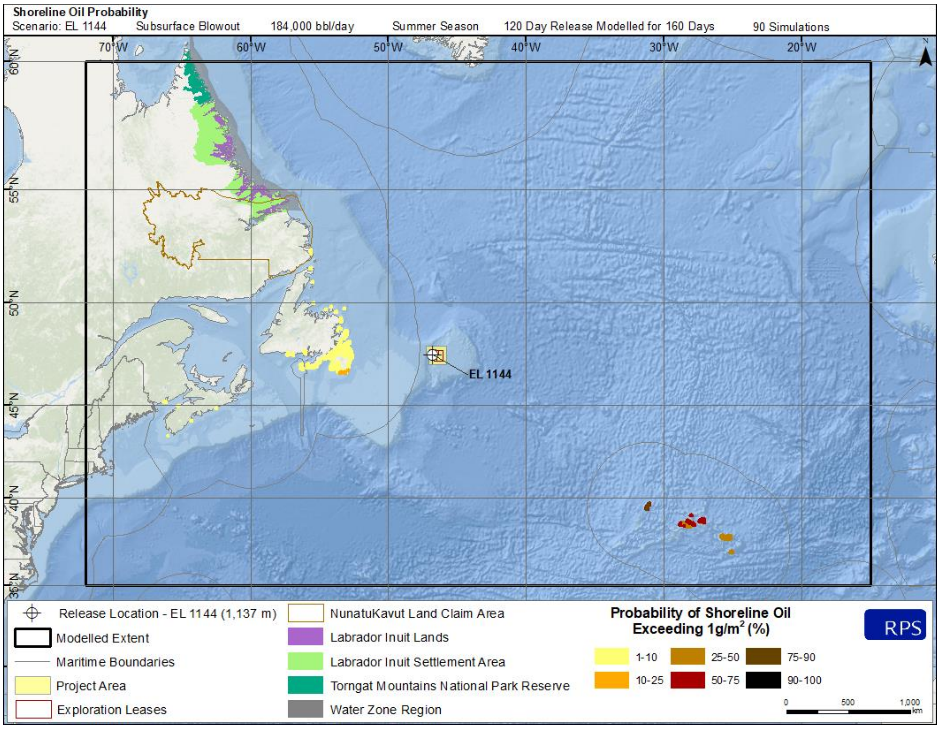


Figure 4-6. Annual probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1144 example well site.



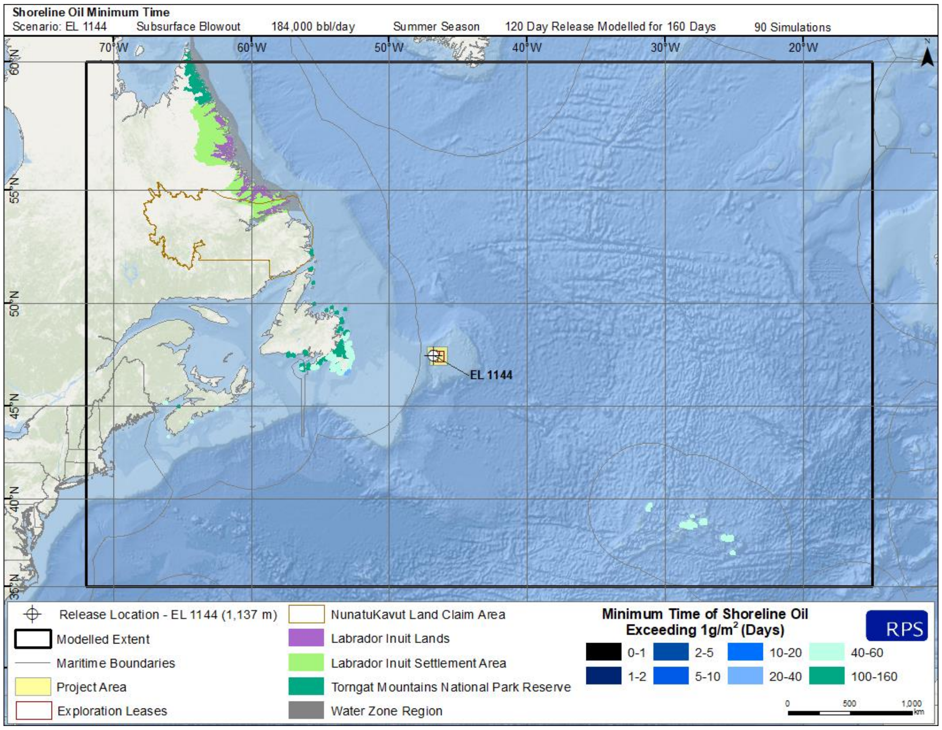


Figure 4-7. Summer probability of shoreline contact >1 g/m2 (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1144 example well site.

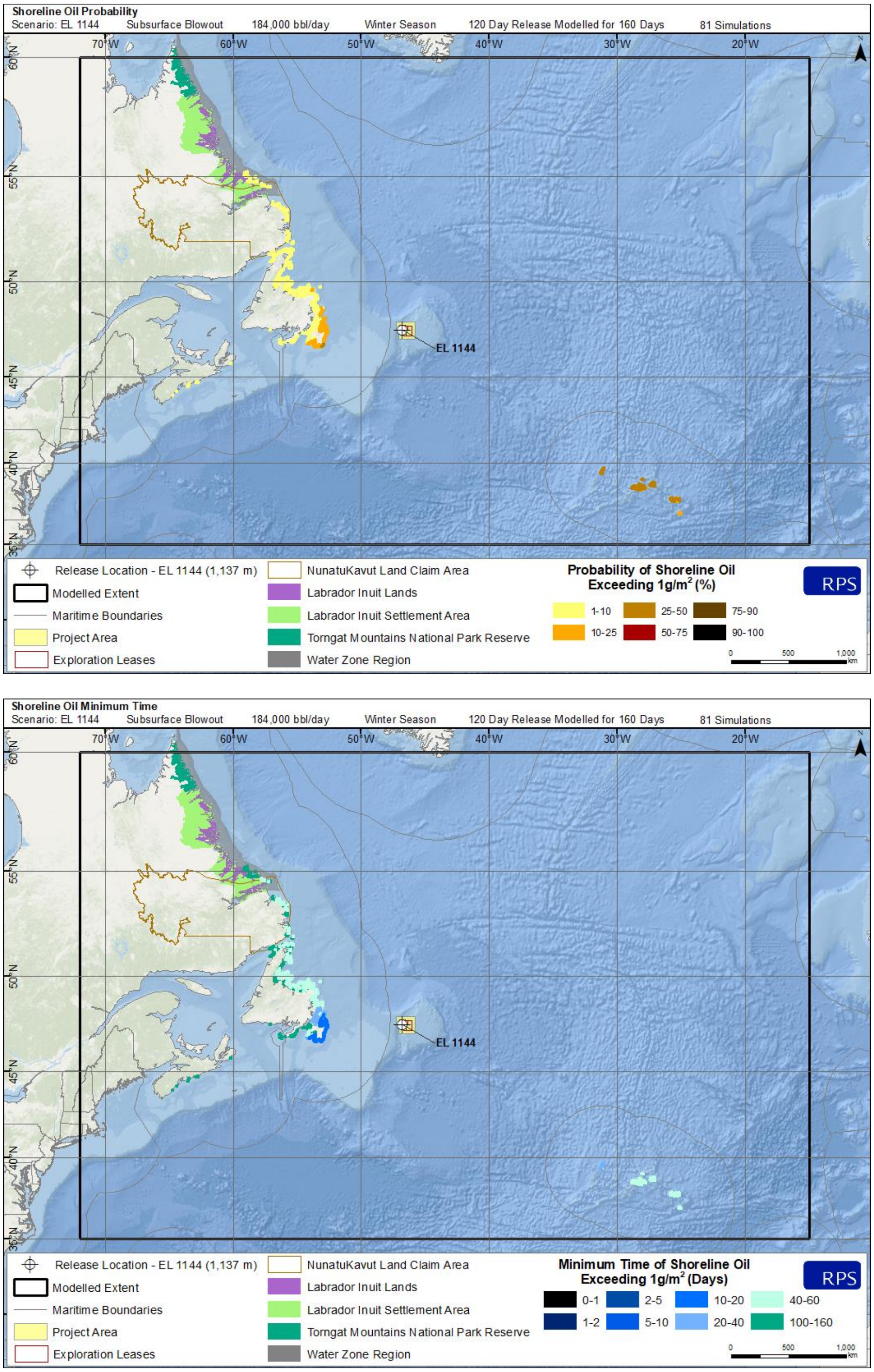


Figure 4-8. Winter probability of shoreline contact >1 g/m2 (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1144 example well site.

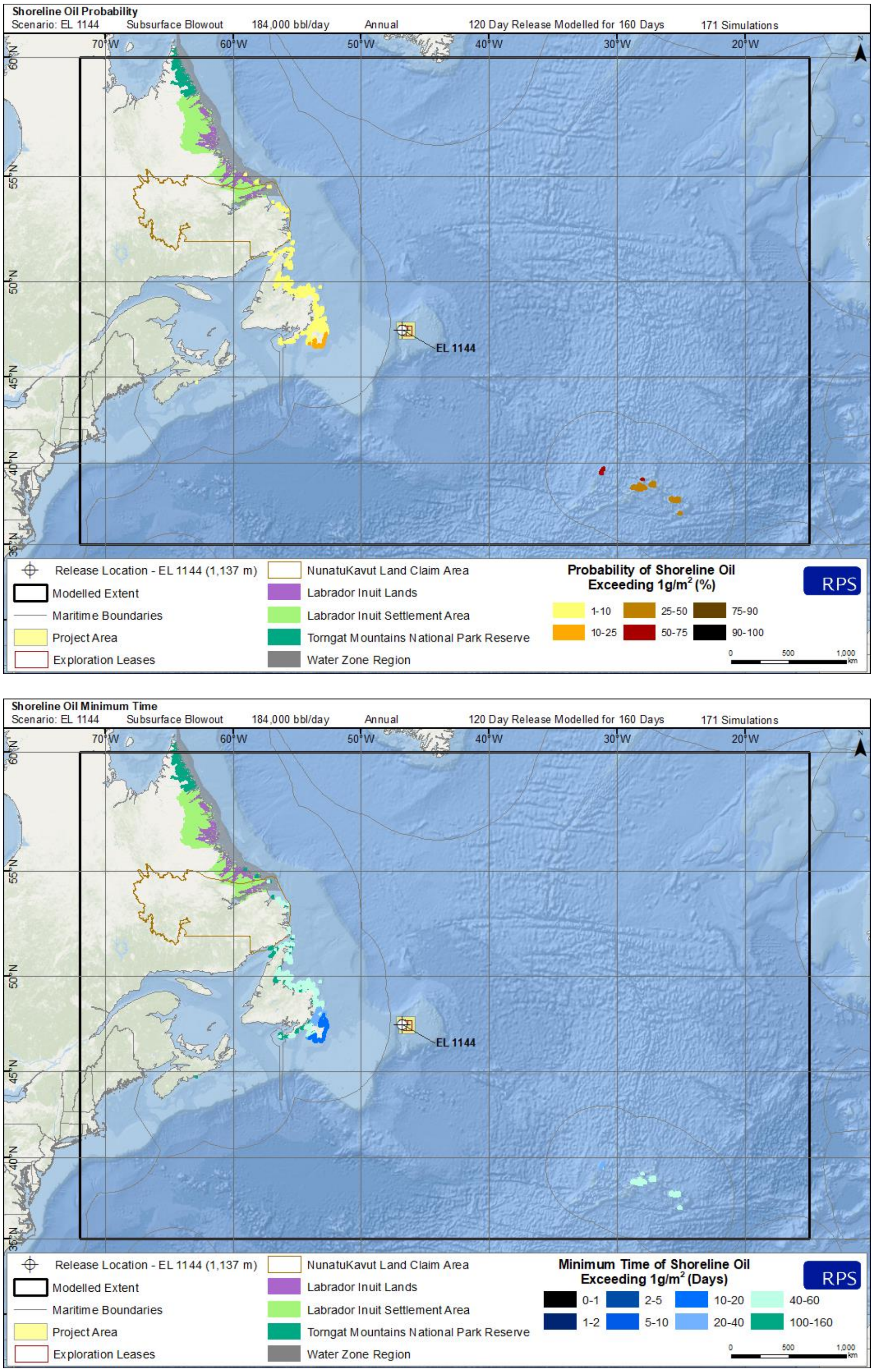


Figure 4-9. Annual probability of shoreline contact >1 g/m2 (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1144 example well site.

4.1.2 EL 1150 Example Well Release Site

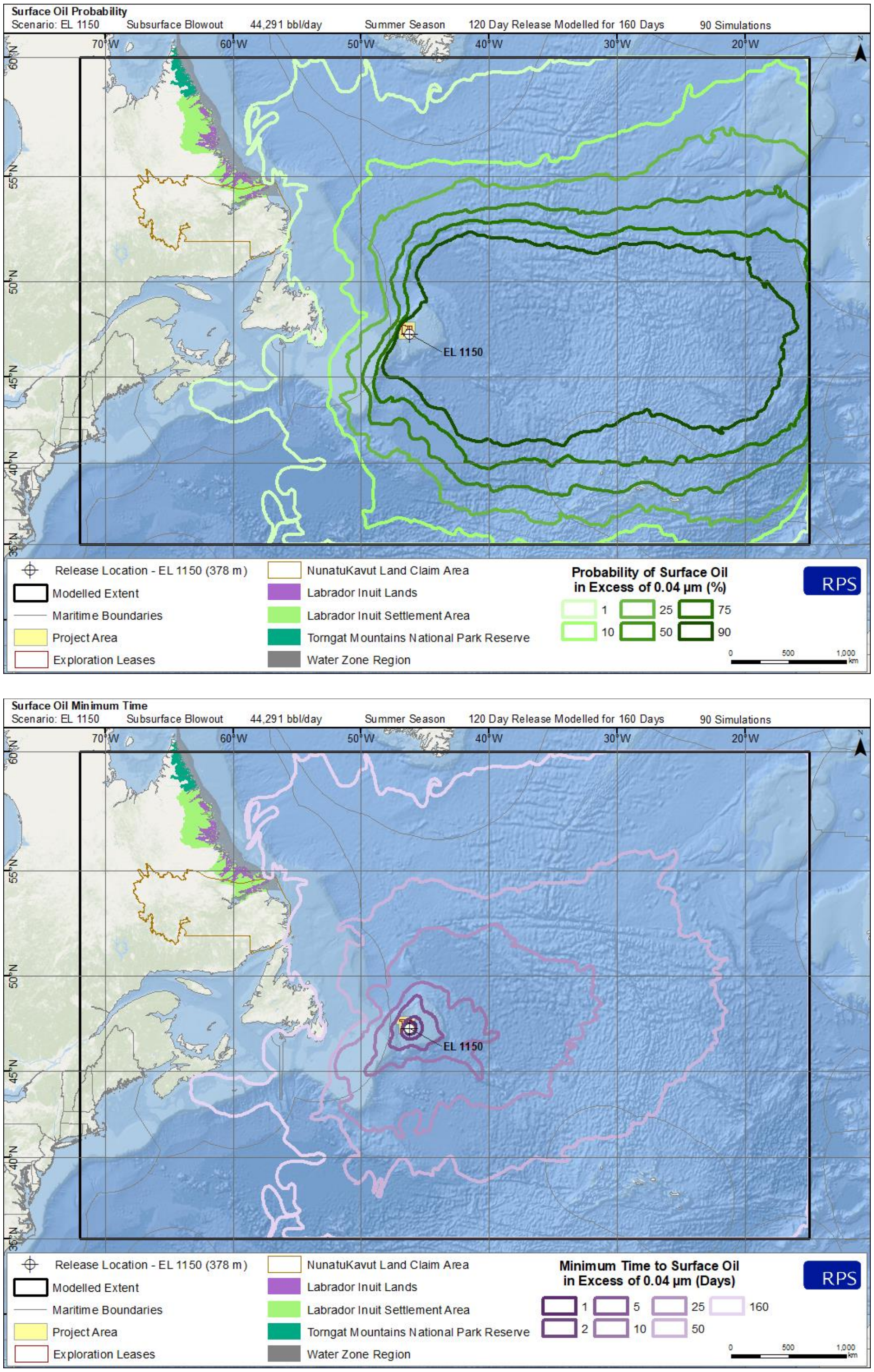
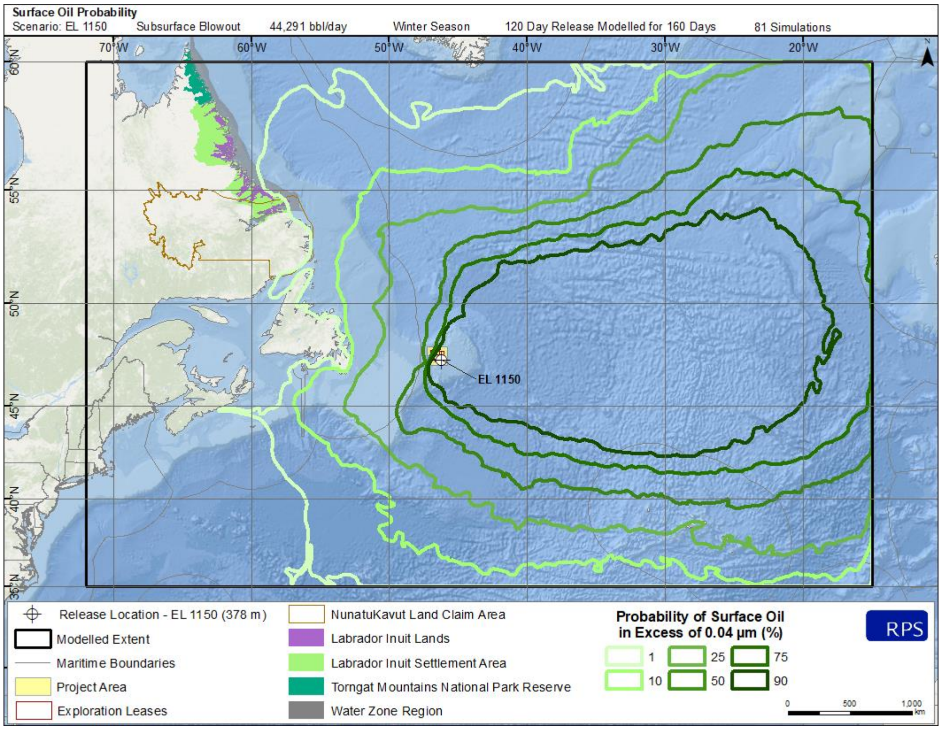


Figure 4-10. Summer probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1150 example well site.



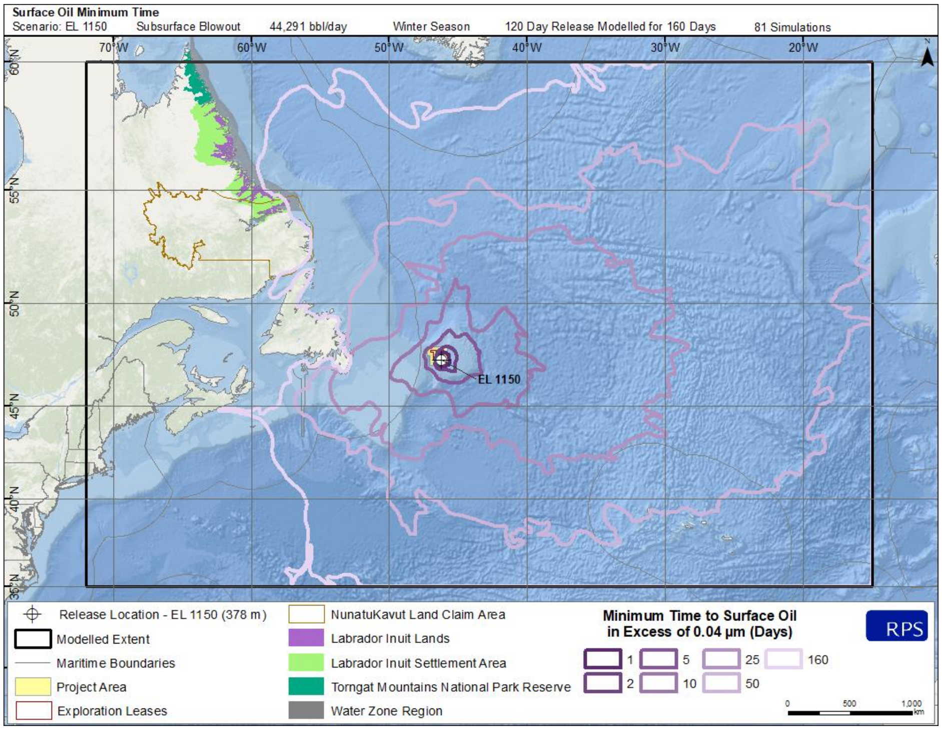
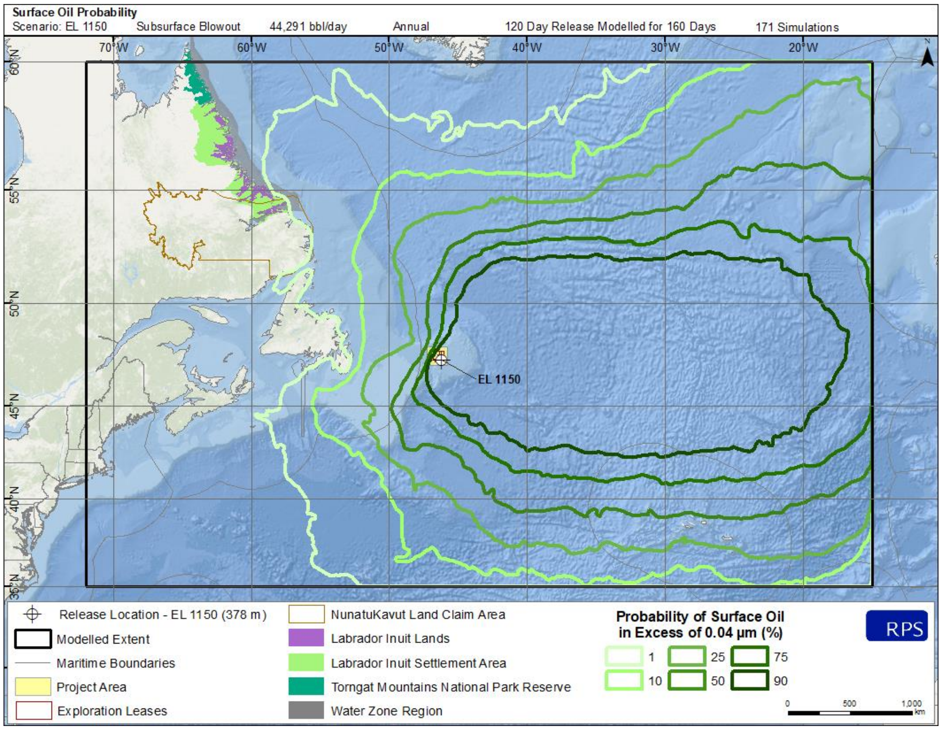


Figure 4-11. Winter probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1150 example well site.



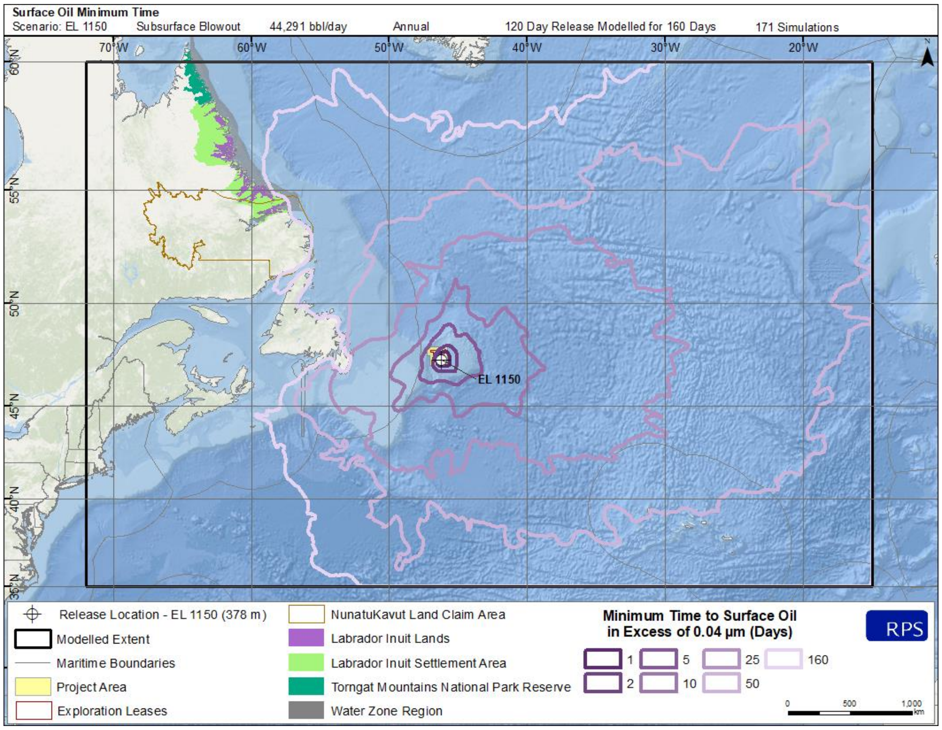
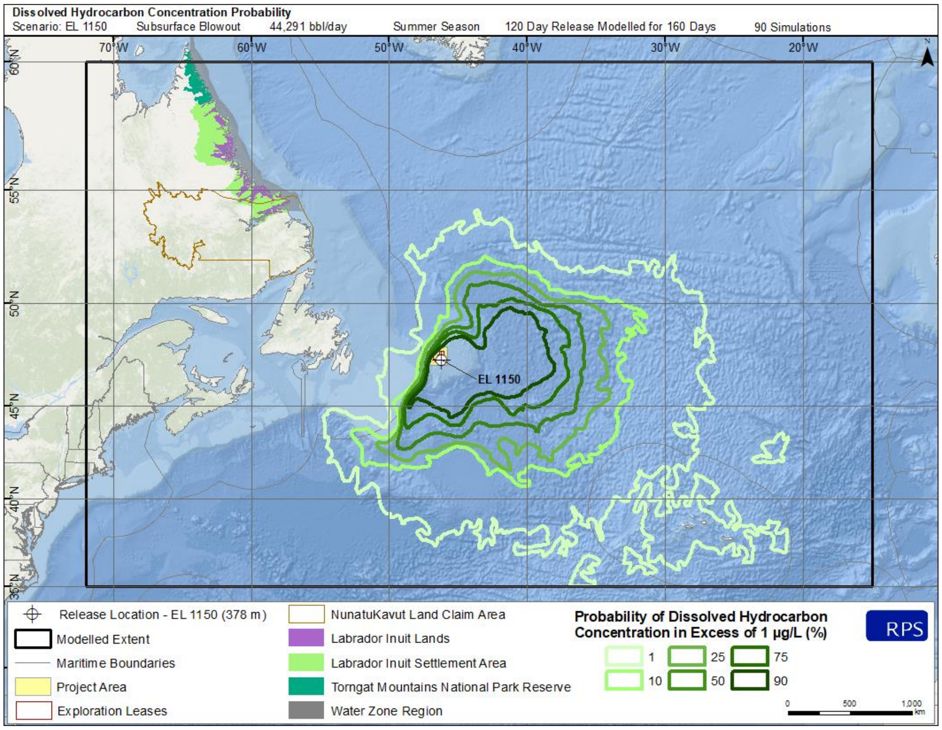


Figure 4-12. Annual probability of surface oil thickness >0.04 µm (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1150 example well site.



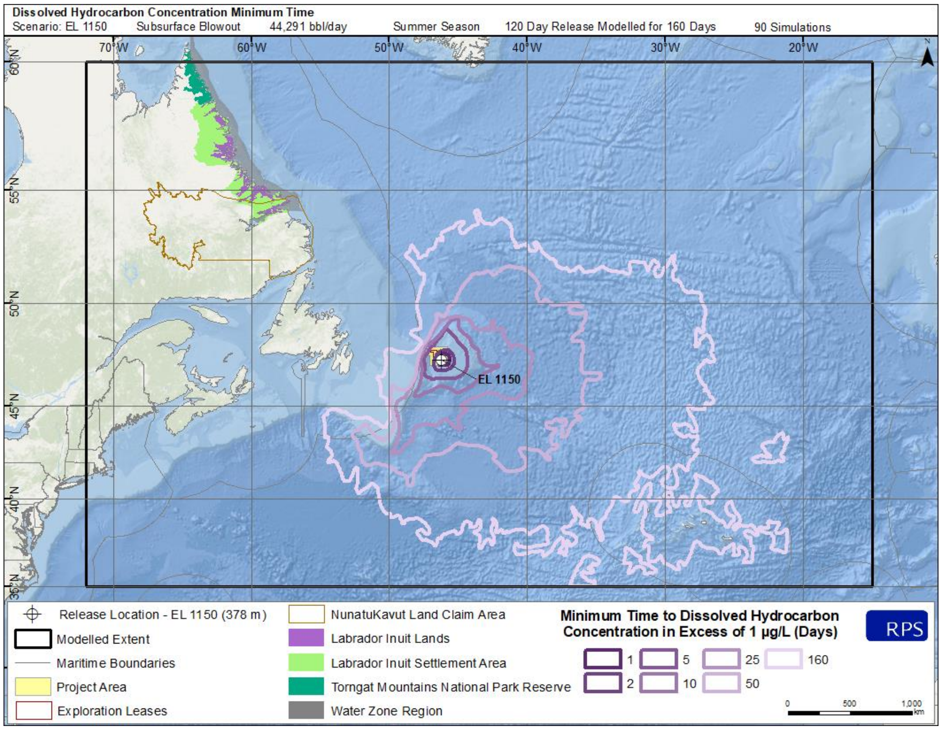


Figure 4-13. Summer probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1150 example well site.

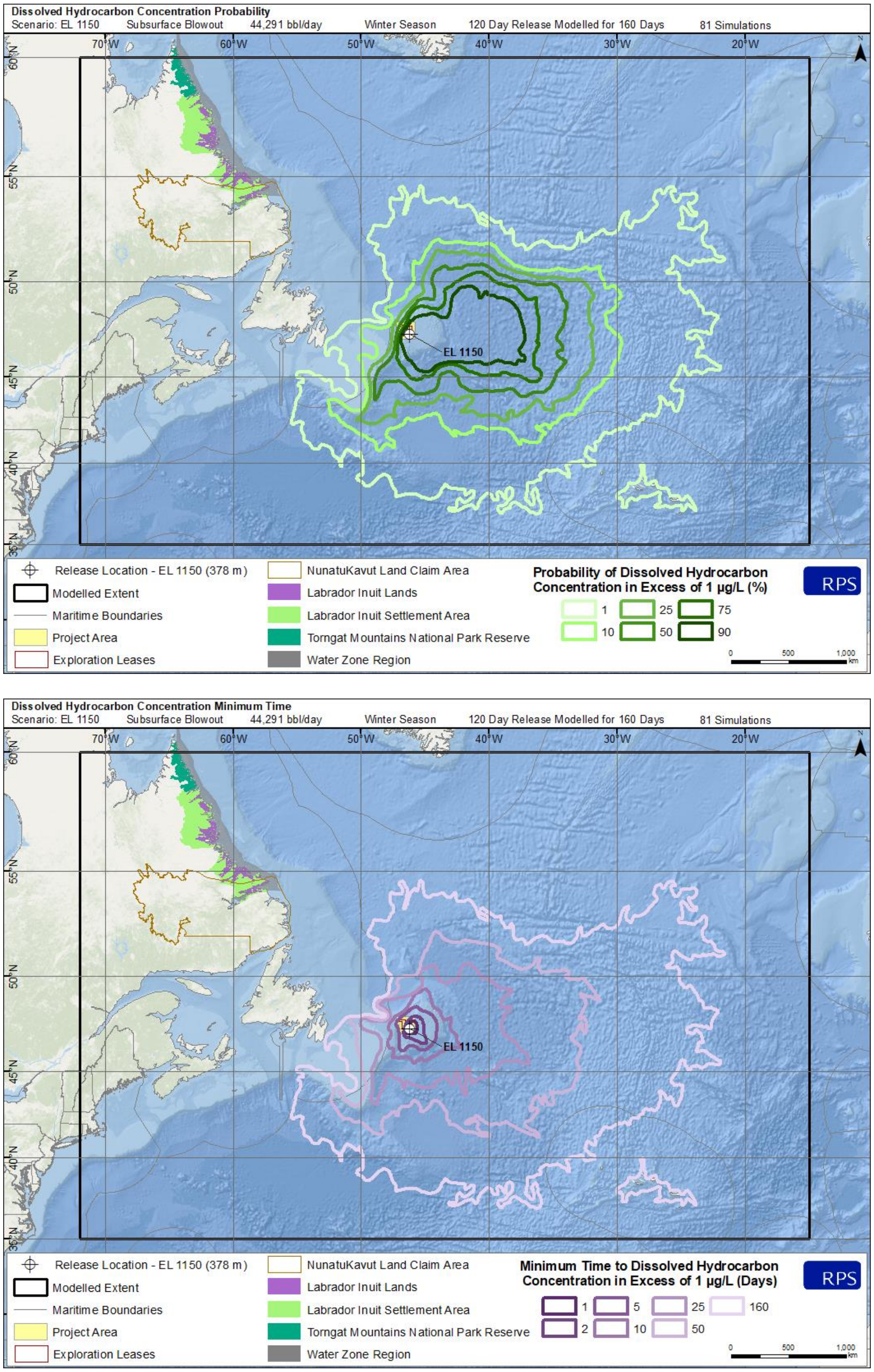
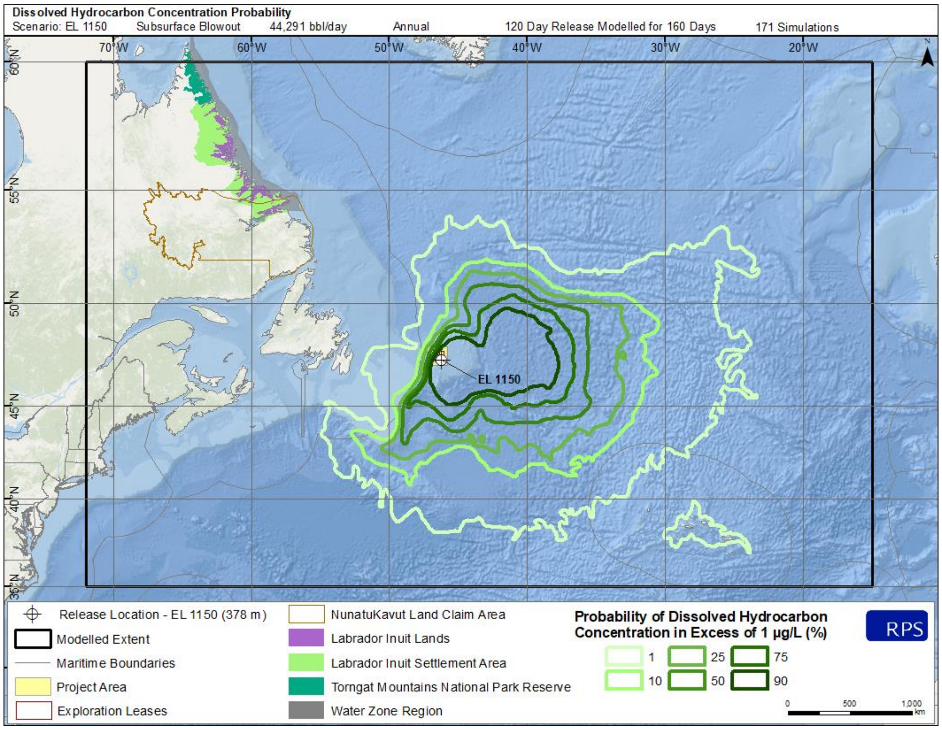


Figure 4-14. Winter probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1150 example well site.



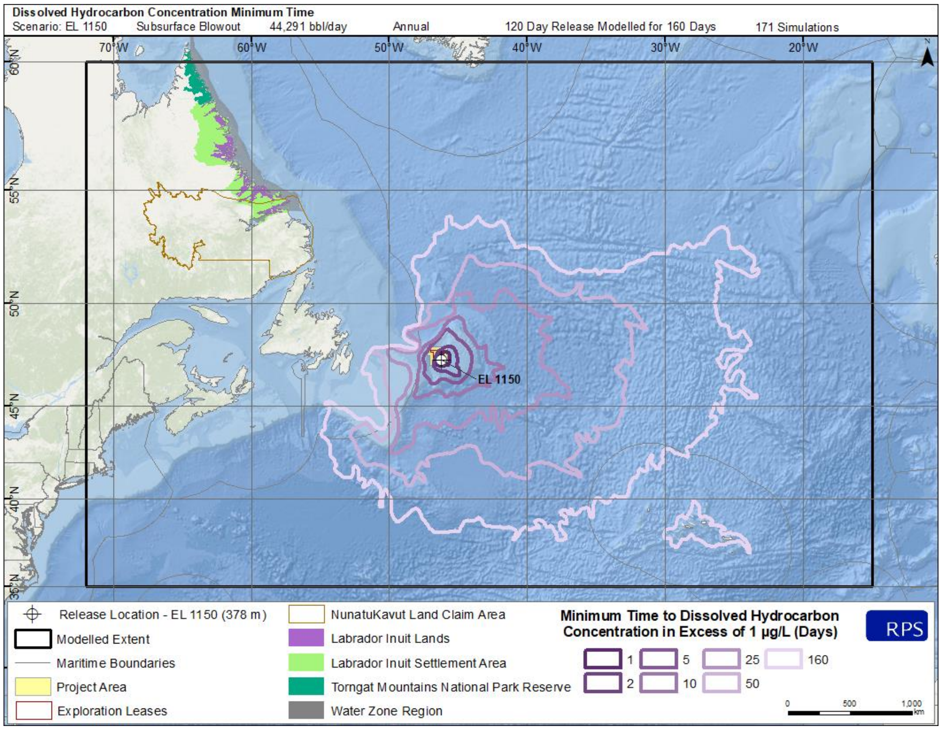
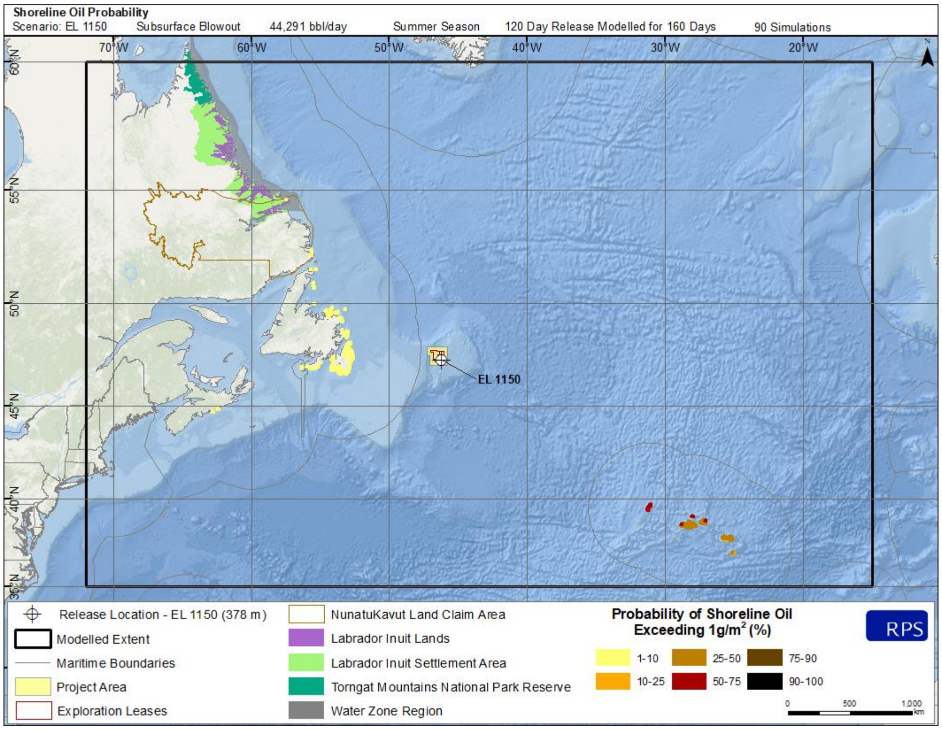


Figure 4-15. Annual probability of dissolved hydrocarbon concentrations >1 µg/L at some depth in the water column (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1150 example well site.



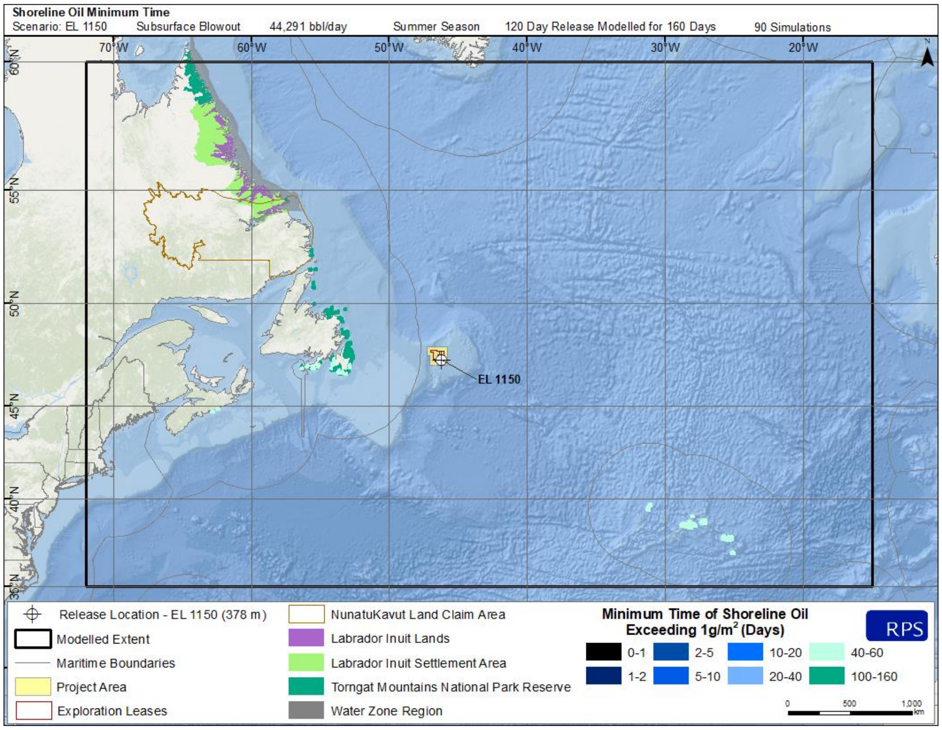
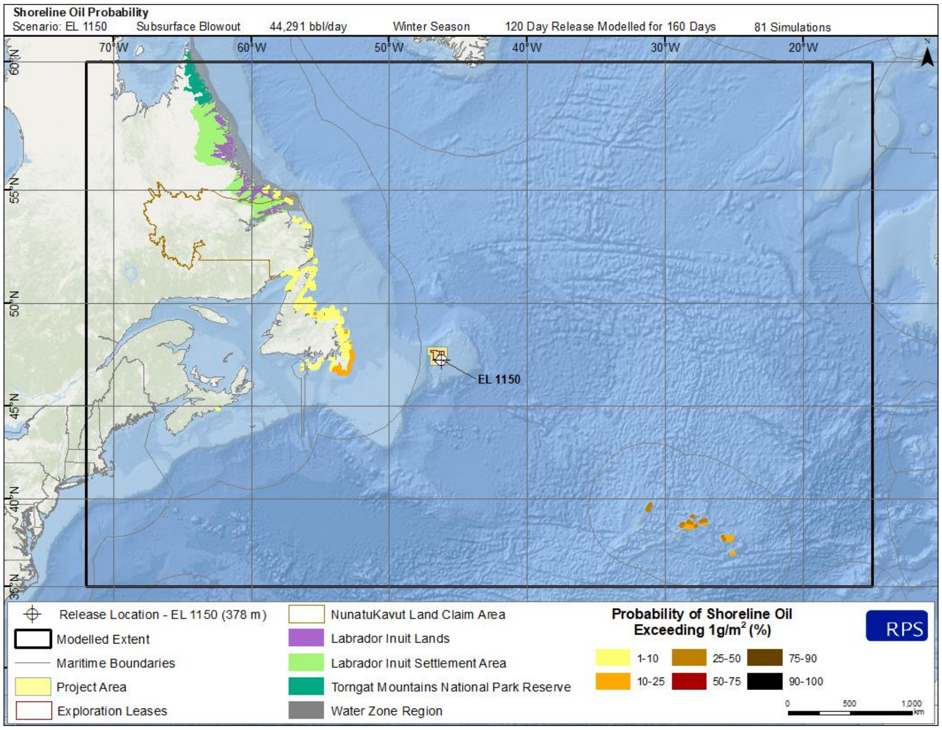


Figure 4-16. Summer probability of shoreline contact >1 g/m2 (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1150 example well site.



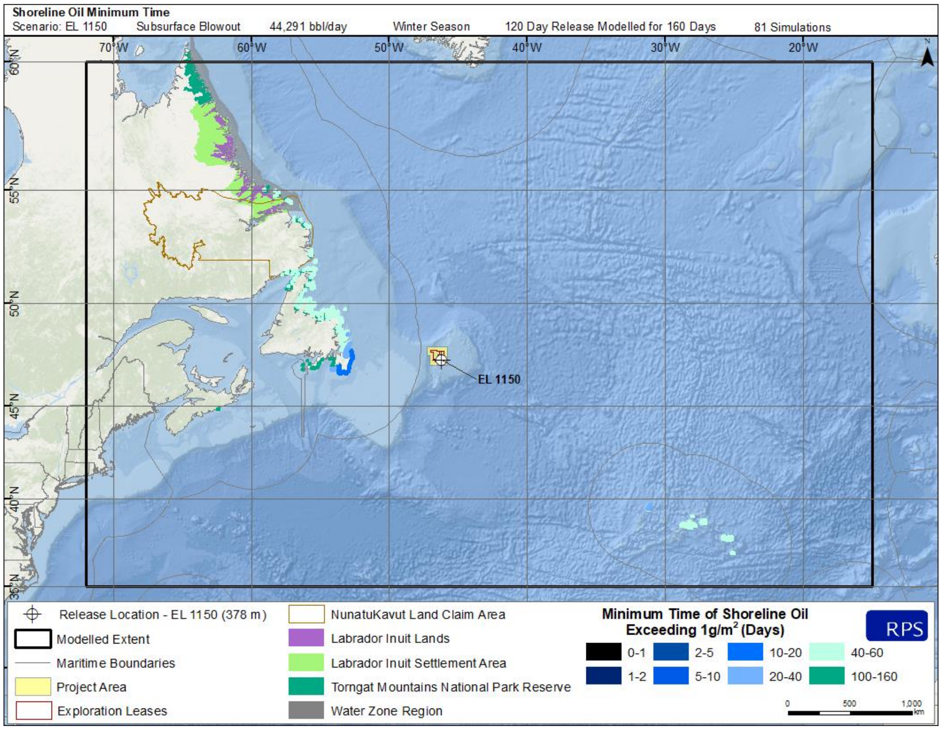
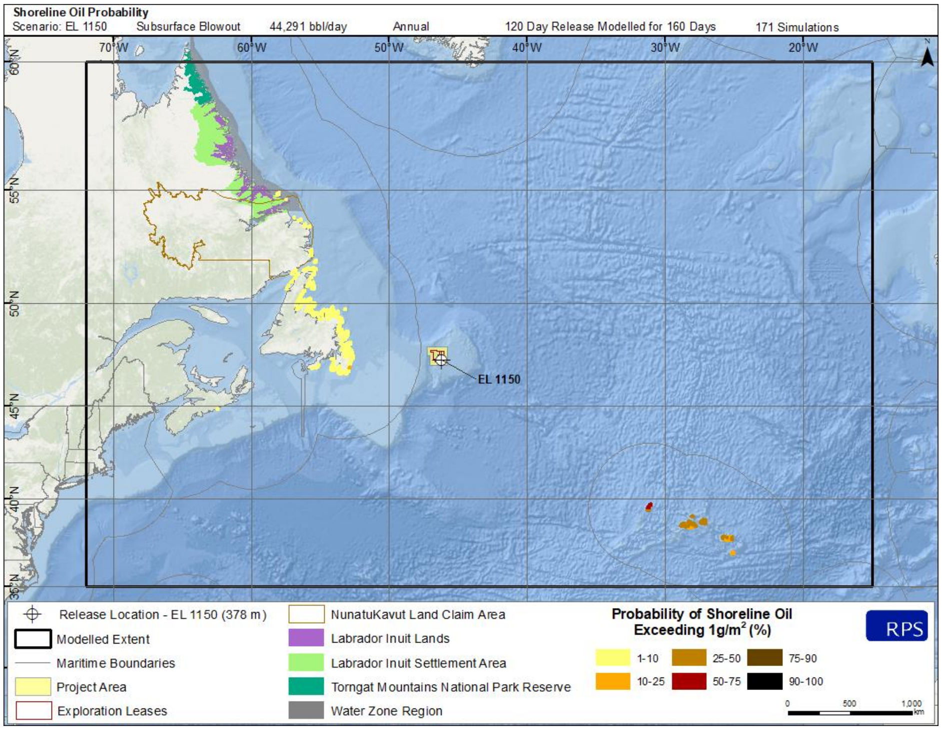


Figure 4-17. Winter probability of shoreline contact >1 g/m2 (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1150 example well site. No shoreline contact was predicted for this scenario.



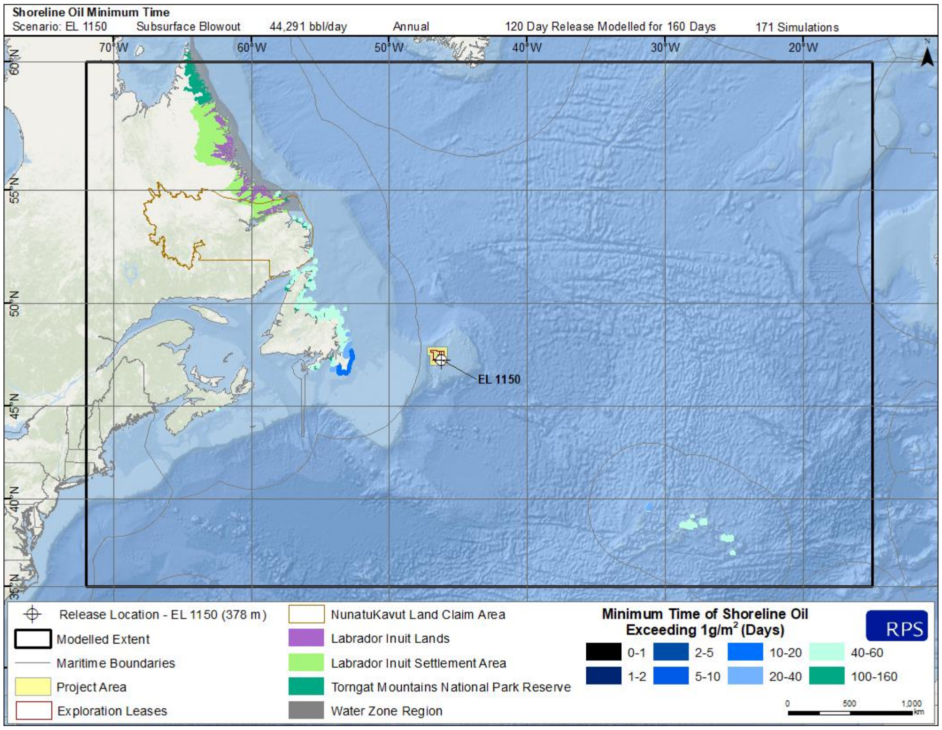


Figure 4-18. Annual probability of shoreline contact >1 g/m2 (top) and minimum time to threshold exceedance (bottom) resulting from a 120-day subsurface blowout at EL 1150 example well site. No shoreline contact was predicted for this scenario.

4.1.3 Summary of Stochastic Results

A total of 171 individual model runs were conducted for the statistical analysis for each modelled release at the EL 1144 and EL 1150 hypothetical example well release sites, representing subsurface blowouts (120-day) in waters offshore of Newfoundland. The two 120-day releases were modelled for a total of 160 days at the EL 1144 (1,137 m) and EL 1150 (378 m) example well sites to represent the amount of time required to mobilize a MODU and drill a relief well to stop a subsurface release. This study is a follow on to the original modelling report "Trajectory Modelling in Support of the Nexen Energy ULC Flemish Pass Exploration Drilling Project (2018-2028)" authored on January 26, 2018, which investigated shorter release durations (30-day subsurface blowouts) contained through the use of a "Capping Stack" technology. In addition, this modelling study included a larger model domain than the previous assessment.

For both example well sites, 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, with a smaller portion extending to the north and south of release sites. Much lower probabilities of threshold exceedance are predicted landward or west of the releases (Figure 4-1 through Figure 4-6; Figure 4-10 through Figure 4-15). Releases were predicted to impact Canadian, US, and Portuguese waters with potential threshold exceedance occurring in the Canadian, US, and Portuguese EEZs. In many cases, oil contamination above the identified threshold was predicted beyond the extent of the model domain, primarily to the east and to a much lesser extent to the south. In these scenarios, the environmental forcing mechanisms (i.e., wind and currents) and timeframe modelled (160 days) allowed for a very small portion of the total release made up of highly weathered oil (>50 days old) to be transported outside of the model domain.

The hypothetical 120-day release at the EL 1144 example well site (see figures in Section 4.1.1) was predicted to lead to a larger stochastic surface oil probability footprint, where oil was predicted to exceed the 0.04 µm thickness threshold in >1% of releases, when compared to the release at the EL 1150 example well site (Table 4-1). The difference in the size of the predicted footprints was due to the larger release volume of 22,080,000 bbl associated with the modelled release at EL 1144, when compared to the 5,314,920 bbl release modelled at EL 1150. Note that the highly conservative 0.04 µm surface oil thickness threshold is an average surface oil thickness over the modelled grid cell that corresponds with an observed surface slick that would be both patchy and discontinuous within the region (Table 2-2). The >90% probability footprints for surface oil threshold exceedances were predicted to extend approximately 2,000 km to the south and east of EL 1144 for surface oil and 1,200-1,500 km for in water contamination, with respective total areas of 2,236,000 km^2 and 133,600 km^2 (Figure 4-1 through Figure 4-6; Table 4-1). For the EL 1150 example well site, the >90% probability of surface oil extents were predicted to be closer to 2,000 km to the east with a total area of 2,069,000 km^2, and water column contamination extents reached closer to 500-600 km with a total area of 23,960 km^2 (Figure 4-10 through Figure 4-15; Table 4-1). Predicted differences between the seasonal threshold exceedance footprints were minor for each release location, with a slightly larger surface oil exceedance for >90% footprints in the summer, due to calmer winds, which resulted in less entrainment and therefore more surface oil (Table 4-1). Shoreline oiling probabilities were predicted to be higher along the Canadian coast and the Azores with a release at EL 1144, which was located closer to shore than the EL 1150 example well site (Figure 4-7 through Figure 4-9 and Figure 4-16 through Figure 4-18). Shoreline oiling probabilities from both example well releases are highest along the Azores in the summer, due to prevailing westerlies, while probabilities were highest along the Canadian coast in the winter, due to more variable winds during winter storms.

General findings for the lowest probability contours were very similar for the EL 1144 and EL 1150 example well sites. This is representative of the same underlying metocean conditions providing information on the presence or absence of oil. However, the hypothetical releases at the EL 1144 example well site had a release volume that was over four times larger than that of EL 1150, resulting in much larger predicted areas with between 10% and 90% likelihood that a threshold would be exceeded (Table 2-1 and Table 4-3).

As stated previously, stochastic figures do not imply that the entire contoured area would be covered with oil in the event of a single release, nor do they provide any information on the quantity of oil in each area. The large threshold exceedance footprints in annual results are not the expected exposure from any single release of oil, but rather areas where there is >1% probability that exposure above the threshold could occur, based on the combination of either 171 (annual), 90 (summer), or 81 (winter) individual releases analyzed together.

The oil predicted to make contact with shorelines would be expected to be highly weathered, as even the minimum time estimates for first shoreline oil exposure ranged from approximately 15-51 days (Table 4-2). This was associated with oil that was predicted to reach the shores of Newfoundland. The oil that did make its way to shore would likely be patchy and discontinuous. Although release sites were closer to the Newfoundland and Labrador coastlines, the highest potential for shoreline oiling was predicted to occur along the Azores, primarily due to the prevailing westerlies (winds blowing to the east) and surface currents. However, for both Labrador and the Azores, oil was predicted to be extremely weathered by the time it reached shorelines. The shortest amount of time for oil to reach the Azores was 45 days and for Labrador was 68 days.

Table 4-1. Summary of threshold exceedance information predicted at each example well site (EL 1144 and EL 1150) for surface, water column, and shoreline oil within the modelled domain are provided by season (annual, winter, summer). Predicted areas (km2) exceeding for surface and water column are provided for the >1%, 10%, or 90% likelihood of exposure to oil contours. The predicted length (km) of shoreline susceptible to exposure by oil is provided at 6 separate contour intervals.

Stochastic Scenario Parameters				Areas Exceeding Threshold (km^2)		
Component and Threshold	Scenario	Example Well Site	Probability Contour or Bin*	Annual Results	Winter (ice cover)	Summer (ice-free)
Surface Oil >0.04 µm, on average	120-day release	EL 1144 (184,000 bpd)	1%	8,211,000	8,371,000	8,339,000
			10%	7,003,000	7,208,000	6,657,000
			90%	2,236,000	2,205,000	2,532,000
		EL 1150 (44,291 bpd)	1%	8,152,000	8,309,000	8,304,000
			10%	6,733,000	6,877,000	6,483,000
			90%	2,069,000	2,053,000	2,328,000
Water Column Dissolved Hydrocarbons >1 µg/L at some depth within the water column	120-day release	EL 1144 (184,000 bpd)	1%	726,800	763,600	709,200
			10%	468,000	468,800	463,800
			90%	133,600	130,900	149,700
		EL 1150 (44,291 bpd)	1%	280,700	315,800	120,200
			10%	128,800	139,200	87,810
			90%	23,960	24,620	25,530
				Lengths Exceeding Threshold (km)		
Shoreline Oil >1 g/m^2, on average	120-day release	EL 1144 (184,000 bpd)	1 - 5%	1,668	1,245	629
			5 - 15%	455	1,048	317
			15 - 25%	110	345	60
			25 - 50%	473	331	335
			50 - 75%	60	-	188
			75 - 100%	-	-	14
		EL 1150 (44,291 bpd)	1 - 5%	1,603	1,006	450
			5 - 15%	266	1,144	46
			15 - 25%	253	308	161
			25 - 50%	276	133	340
			50 - 75%	18	-	69
			75 - 100%	-	-	-

*Bins are based on stochastic probabilities; for example, 2,236,000 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 EL 1144 over the entire modelled duration.

Table 4-2. Shoreline contamination probabilities and minimum time for oil exposure exceeding 1 g/m^2 for all shorelines, Labrador shorelines, and the Azores.

Scenario	Example Well Release Site	Scenario Timeframe	Average Probability of Shoreline Oil Contamination (%)	Maximum Probability of Shoreline Oil Contamination (%)	Minimum Time to Shore (days)*	Maximum Time to Shore (days)
All Shorelines†						
120-day release	EL 1144 (184,000 bpd)	Annual	1	63	15	146
		Winter	1	48	15	160
		Summer	1	77	34	160
	EL 1150 (44,291 bpd)	Annual	9	56	15	141
		Winter	9	41	15	159
		Summer	19	70	51	160
Labrador, CA						
120-day release	EL 1144 (184,000 bpd)	Annual	2	2	83	130
		Winter	2	2	83	160
		Summer	1	1	159	159
	EL 1150 (44,291 bpd)	Annual	2	2	68	136
		Winter	3	3	68	156
		Summer	1	1	159	160
Azores, PT						
120-day release	EL 1144 (184,000 bpd)	Annual	36	36	61	83
		Winter	27	27	45	111
		Summer	44	44	51	103
	EL 1150 (44,291 bpd)	Annual	32	32	45	89
		Winter	20	20	45	115
		Summer	26	26	51	110

*Note that the shoreline of Newfoundland, specifically the Avalon Peninsula is the first location that is predicted to have oil strand on shorelines.

4.2 Deterministic Analysis Results

Six individual trajectories of interest were selected from the stochastic ensemble of results for the deterministic analysis (see Table 2-5 in Section 2.3). The deterministic trajectory and fate simulations provided an estimate of the oil's transport through the environment as well as its physical and chemical behavior for a specific set of environmental conditions. The 95th percentile "worst case" results for surface oil exposure, shoreline length exposure, and water column dissolved hydrocarbon concentrations were identified from the stochastic model scenarios for each site. These representative deterministic simulations tend to maximize the predicted effects from the suite of stochastic simulations in an effort to bound the upper range of predicted effects in a "credible worst case" scenario.

The following sections contain figures corresponding to each identified representative case and tables summarizing the areas exceeding specified thresholds (Table 2-2). During modelling, components of oil were tracked as floating surface oil, entrained droplets of oil, dissolved hydrocarbon constituents, and stranded shoreline oil. The figures provided display the cumulative footprint of all oil experienced by a region over the entire 160-day duration of modelling. Therefore, the footprints are much larger than the amount of oil predicted to be present in a region at any given point in time. This concept is illustrated in Figure 4-19, which portrays average surface oil thickness in each grid cell at five specific time steps (days 2, 10, 50, 100, and 160) during the 95th percentile shoreline oil case, and in Figure 4-20, which portrays the cumulative footprint (maximum value over 160 days) of average surface oil thickness experienced at each grid cell over all of the individual modelled time steps (30 minute interval over 160 days). The remaining figures in this report display the cumulative footprints of oil exposure over the entire model duration.

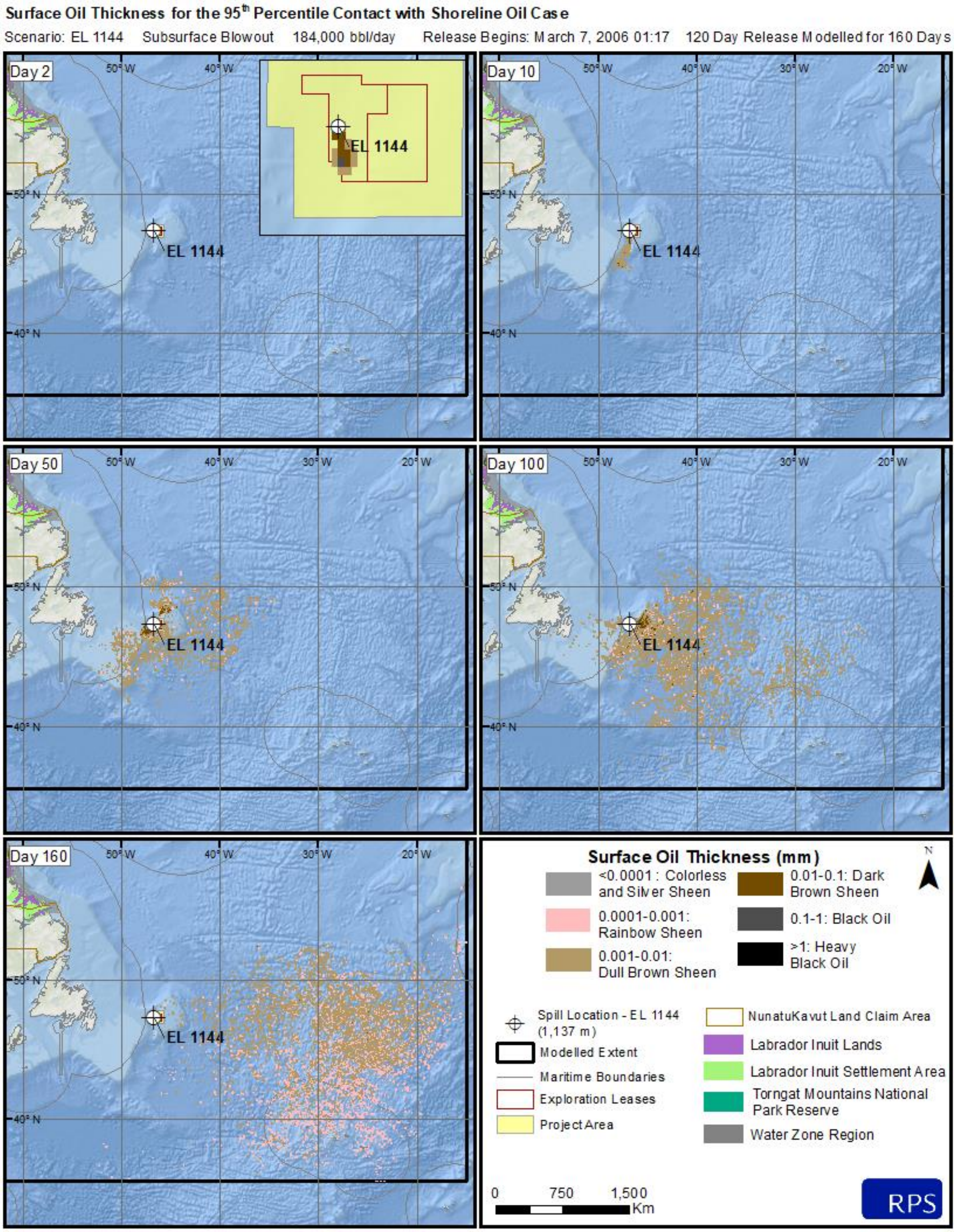


Figure 4-19. Average surface oil thickness for the 95th percentile surface oil exposure case of a 120-day blowout at the EL 1144 example well site at days 2, 10, 50, 100, and 160 to illustrate the variation in size of the surface oil footprint over the course of the model duration.

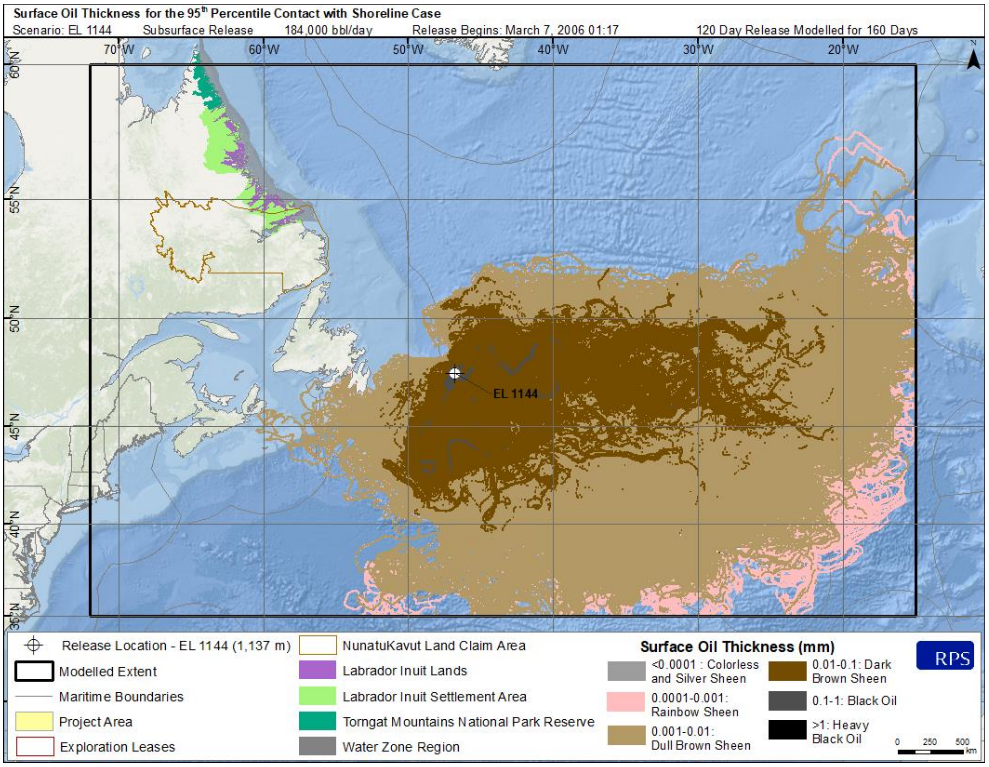


Figure 4-20. Average surface oil thickness for the 95th percentile shoreline oil exposure case of a 120-day blowout at the EL 1144 example well site to illustrate the much larger size of the cumulative surface oil footprint over the entire model duration, compared to the size of the surface oil footprint on any one day or time step (Figure 4-19).

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

1. **Mass Balance Plots**: Illustrate the predicted weathering and fate of oil for a specific run over the entire model duration as a fraction of the oil released up to that point. Components of the oil tracked over time include the amount of oil on the sea surface, the total entrained hydrocarbons in the water column, the amount of oil in contact with the shore, 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.
3. **Water Column Dissolved Hydrocarbon Concentration Maps**: Depict the predicted footprint of the vertical maximum water column concentration of dissolved hydrocarbons over all modelled time steps for an individual release simulation. Dissolved hydrocarbons are the

constituents of the oil with the greatest potential to affect water column biota. Only concentrations above 1 µg/L for the representative cases are displayed.

4. **Water Column Total Hydrocarbon Concentration Maps:** Depict the predicted footprint of the vertical maximum water column concentration of total hydrocarbons over all modelled time steps for an individual release simulation. Only concentrations above 1 µg/L for the representative cases are displayed.
5. **Shoreline and Sediment Total Hydrocarbon Concentration Maps:** Depict the predicted total mass of oil (per unit area as g/m^2) deposited onto the shoreline and on sediments.

4.2.1 Surface Oil Exposure Cases

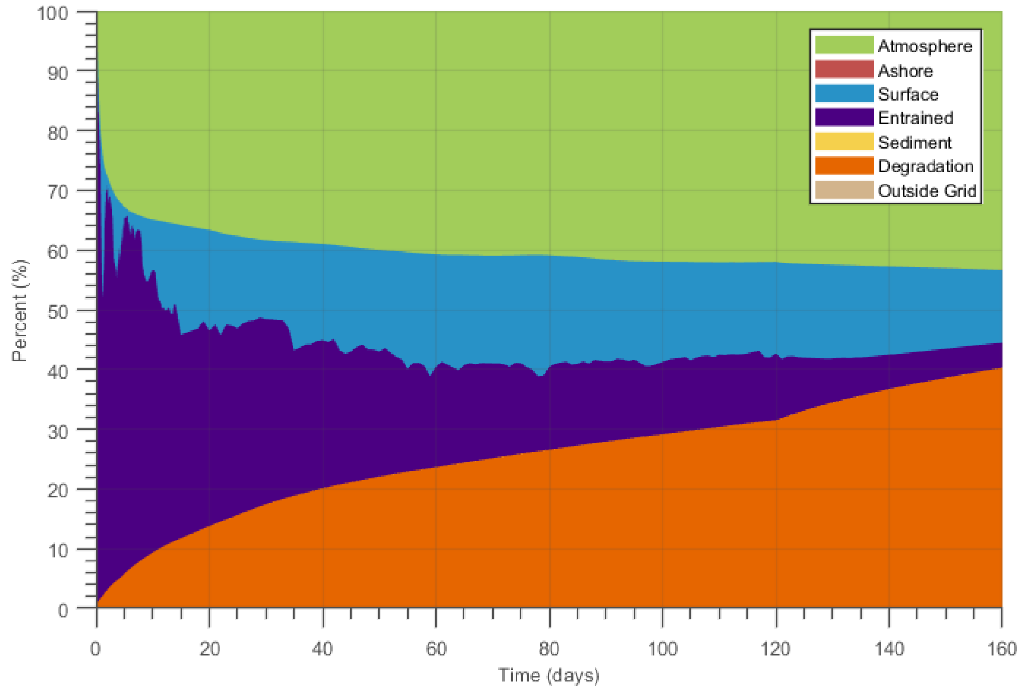
Results for the identified 95th percentile scenarios for floating surface oil exposure >0.04 µm for the 120-day releases at the EL 1144 and EL 1150 example well sites are provided. Note that the modelled release dates for the representative scenarios at each site differed (Table 2-5). The 120-day release at the EL 1144 example well site was modelled for 160 days spanning mid-October 2009 through March 2010, while at the EL 1150 example well site it spanned early-February through June 2008 (Table 2-5). For both sites, the released oil was predicted to rise rapidly to the surface where it was transported by surface winds and currents to the east, south, and north (Figure 4-22). Although surface oil was transported in a similar direction for both releases (even with the different start dates and underlying environmental forcing), the extent of surface oiling was larger at EL 1144 when compared to EL 1150 due to the larger volume of oil released at EL 1144. Variable weather events within the first 10 days of both simulations resulted in a large amount of variability in the amount of oil to surface and entrained within the water column (Figure 4-21). During calmer events, oil rose to the surface forming slicks, while during windier periods, surface breaking waves were formed which entrained surface oil into the water column. Surfaced oil was predicted to evaporate quickly, ultimately totaling approximately 45% of the total release, while the amount degraded increased through time totaling approximately 35-40% of the release.

The thickest oil was predicted to be within several kilometers of the release locations as black oil and dark brown sheen (Figure 4-22). Predicted visual appearance of surface oil following both releases for the vast majority of the cumulative maximum footprints was predominantly in the dark brown sheen to dull brown sheen range due to the light and low viscosity nature of the BdN crude oil. At EL 1144 example well site, small amounts of black oil were predicted to travel upwards of 100 km from the release site, while for EL 1150, the thickest surface oil predicted was in the range of a dark brown sheen. The thicker oil at EL 1144 was the result of the larger release volume. Similarly, thicker oil was predicted over broader areas for the larger modelled blowout at the EL 1144 example well site due to the larger release volume, when compared to the EL 1150 example well site. It is important to note that these scenarios were identified as some of the largest predicted surface oil footprints formed (95th percentile) out of all (171) of the 160-day simulations. At the furthest extents, some rainbow sheen was predicted. It is important to note that oil at any single snapshot in time would not appear as continuous like these cumulative maximum figures but would be both patchy and discontinuous.

The combined effects of a subsurface release and the entrainment of surface oil into the water column by high winds, which induced surface breaking waves, were predicted to result in concentrations of dissolved and total hydrocarbons in the water column that exceeded the identified thresholds of concern (Figure 4-23; Figure 4-24; Table 2-2). Due to the larger release volume, the 120-day release at the EL 1144 example well site was predicted to result in larger footprints of dissolved hydrocarbons and total hydrocarbon concentrations (THC), when compared to the EL 1150 example well site.

Both representative 95th percentile surface oil cases were predicted to result in oil contacting shorelines (Figure 4-25). Shoreline oiling was predicted along the shores of Newfoundland and the Azores in concentrations >500 g/m^2 for the release at EL 1144. For the EL 1150 release, shoreline oiling was generally predicted to be at lower concentrations (<500 g/m^2) and only along portions of the Azores. Oiling of the sediment was predicted to occur primarily at the lowest threshold concentration levels (<0.01 g/m^2) for both releases, with slightly higher concentrations accumulating to the west of the EL 1150 site and to the west and southeast of the EL 1144 site (Figure 4-25).

At the end of the 160-day simulations of 95th percentile surface oil exposure cases at the EL 1144 and EL 1150 example well sites, 43- 47% of the released oil was predicted to evaporated into the atmosphere, up to 40% degraded, <13% remained floating on the water surface, 4% remained entrained in the water column, <2% was transported outside the modelled domain, 0.01% adhered to suspended sediment, and 0.01% contact shorelines (Figure 4-21 and Table 4-3).



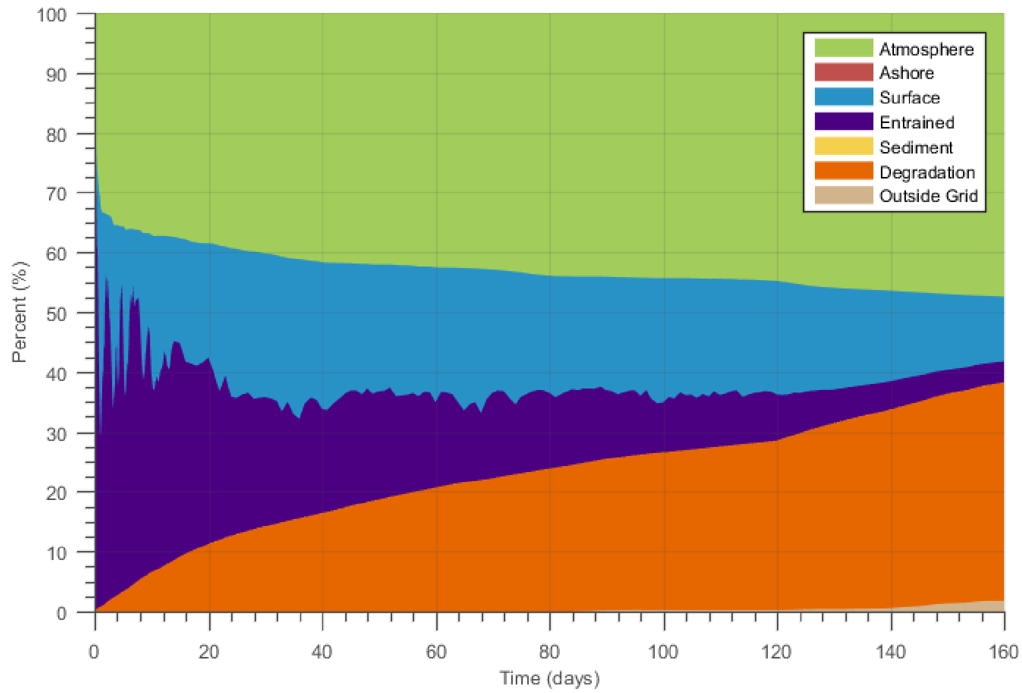


Figure 4-21. Mass balance plots of the 95th percentile surface oil thickness cases resulting from a 120-day blowout at the EL 1144 (top) and the EL 1150 (bottom) example well sites.

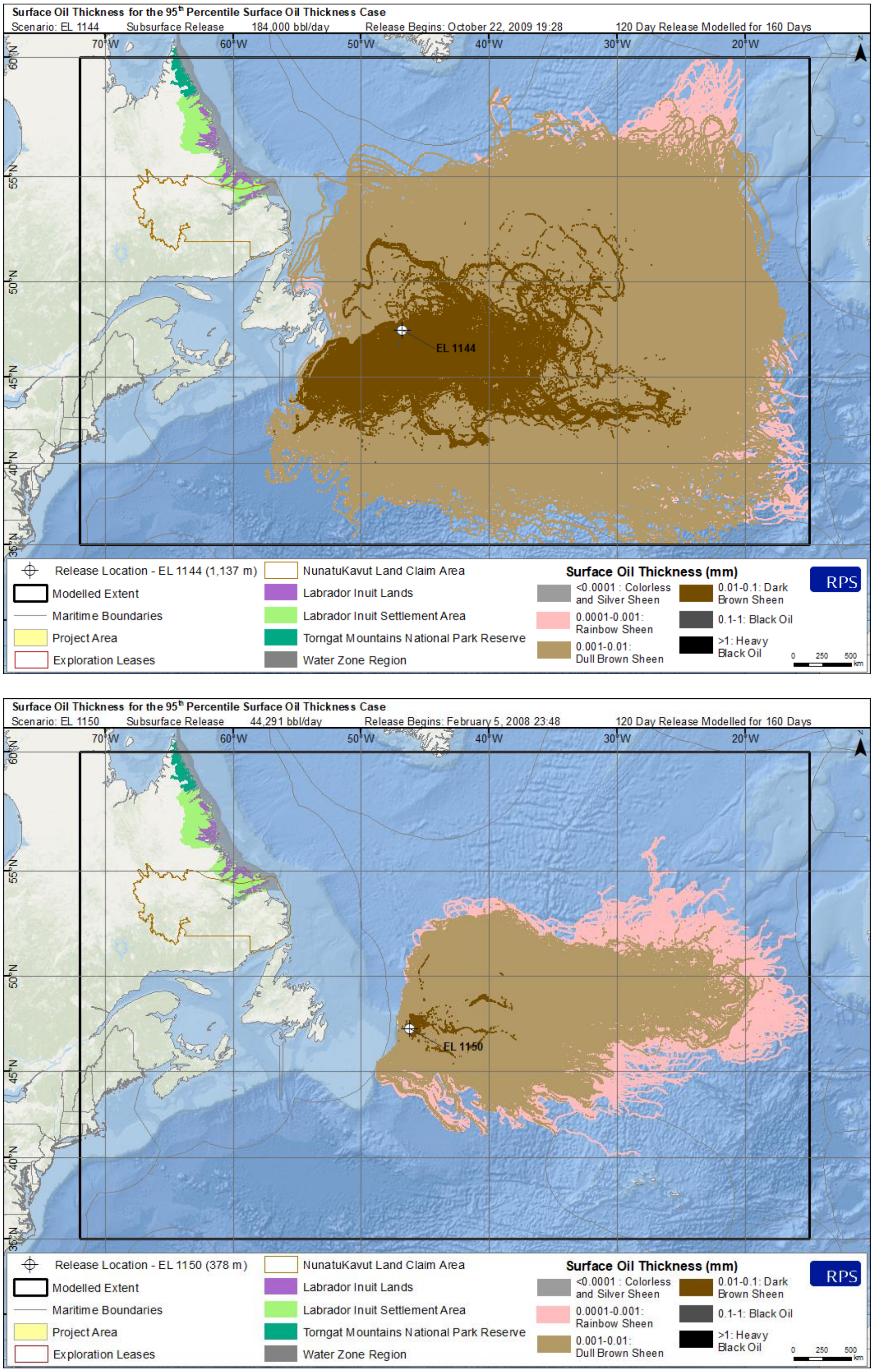
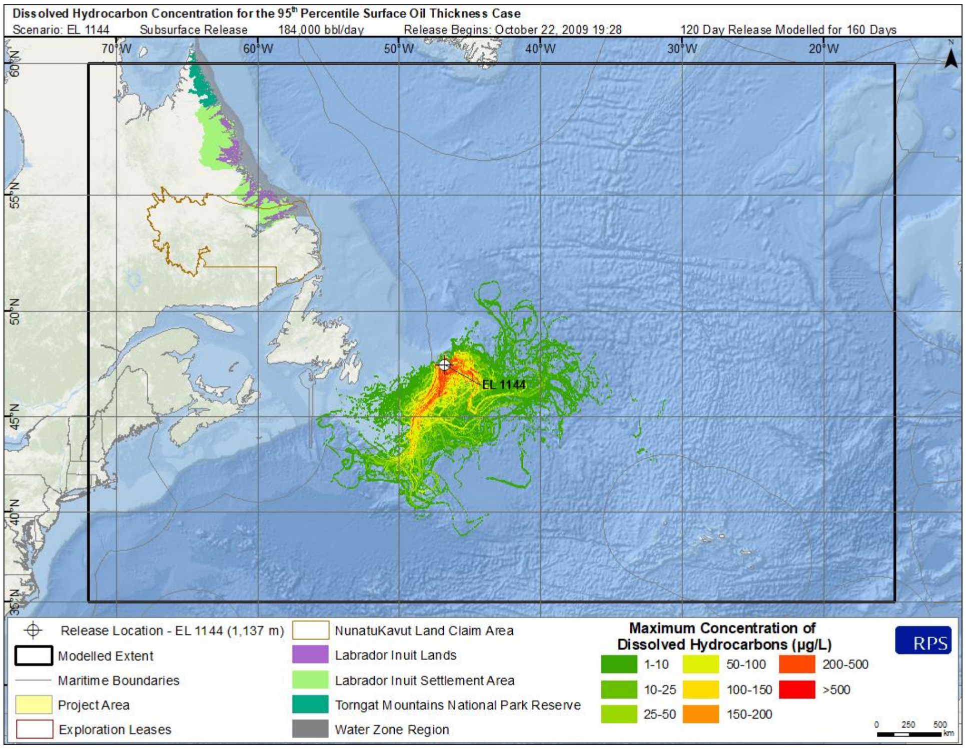


Figure 4-22. Representative scenario for 95th percentile average surface oil thickness resulting from a 120-day subsurface blowout at the EL 1144 (top) and the EL 1150 (bottom) example well sites.



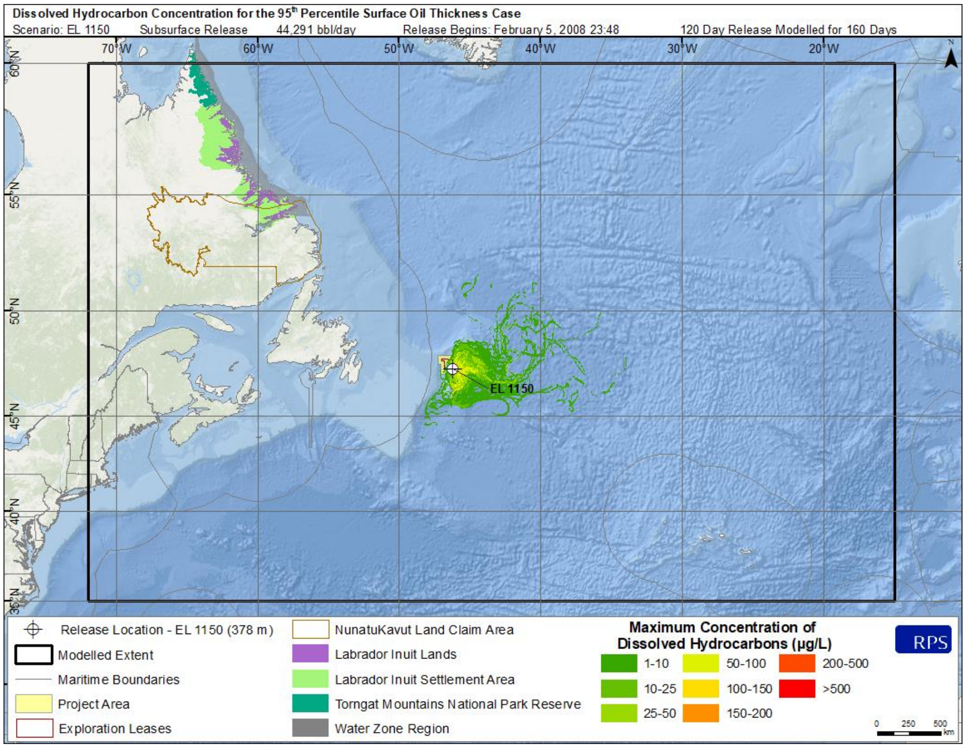


Figure 4-23. Maximum dissolved hydrocarbon concentration at any depth in the water column for the 95th percentile surface oil thickness case resulting from a 120-day subsurface blowout at the EL 1144 (top) and EL 1150 (bottom) example well sites.

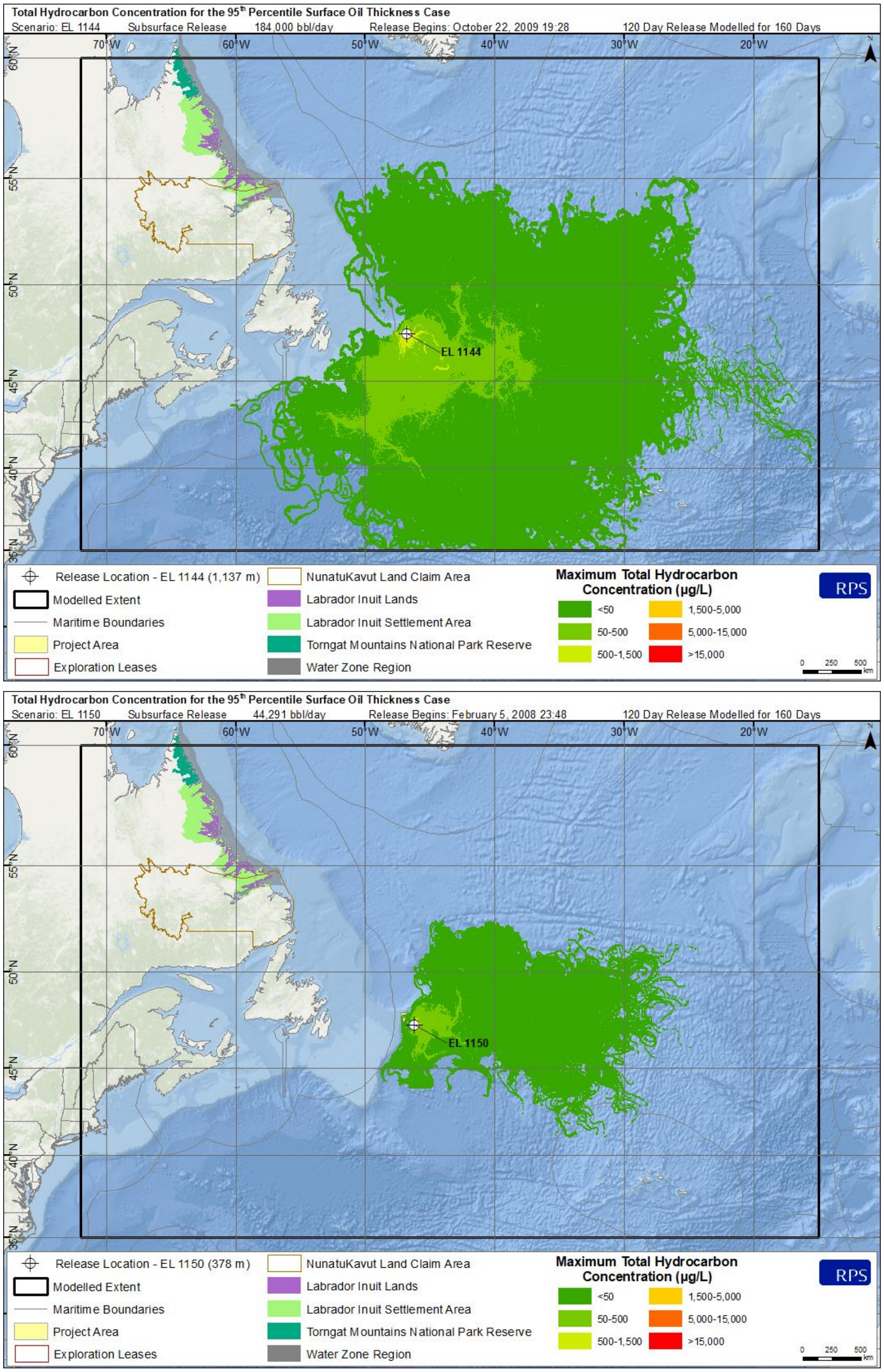


Figure 4-24. Maximum total hydrocarbon concentration (THC) at any depth in the water column for the 95th percentile surface oil thickness case resulting from a 120-day subsurface blowout at the EL 1144 (top) and EL 1150 (bottom) example well sites.

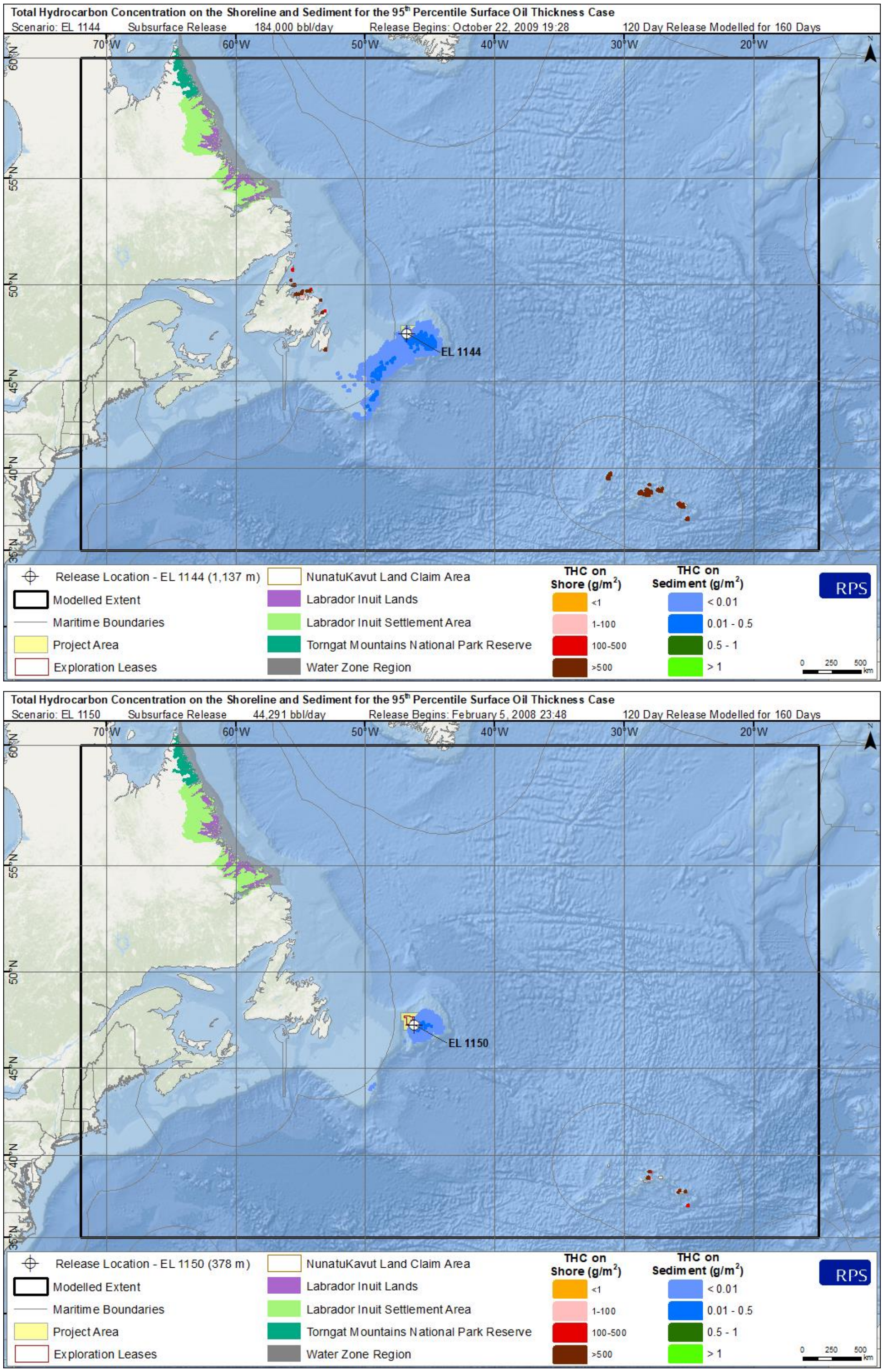


Figure 4-25. Total hydrocarbon concentration (THC) on the shore and sediment for the 95th percentile surface oil thickness case resulting from a 120-day subsurface blowout at the EL 1144 (top) and EL 1150 (bottom) example well sites.

4.2.2 Water Column Exposure Cases

Results for the identified 95th percentile water column exposure cases for the 120-day releases at the EL 1144 and EL 1150 example well sites are provided below. As previously noted, the modelled release dates for each scenario differed from one another and from the surface cases. Each of the trajectories in the stochastic analysis represented a different start date and associated environmental conditions (e.g. wind and current speed and direction), which resulted in different outcomes. The 120-day release modelled for 160 days at the EL 1144 example well site spanned mid-June through late-December 2012, while at the EL 1150 example well site it spanned late-May through October 2009 (Table 2-5).

Similar to the 95th percentile surface exposure cases, predicted surface oil thickness levels for the EL 1144 release site were higher (black oil) than those predicted at EL 1150 due to the larger release volume at EL 1144 (Figure 4-27). However, the majority of the predicted cumulative maximum surface oil extent was in the range of a dark brown and dull brown sheen for EL 1144 and dull brown to rainbow sheen for EL 1150.

The combined effects of the modelled subsurface releases and the entrainment of surface oil from wind-induced surface breaking waves into the water column were predicted to result in both dissolved and total hydrocarbon concentrations in the water column that exceeded the identified thresholds of concern (Figure 4-28; Figure 4-29; Table 2-2). Concentrations of dissolved and total hydrocarbons were predicted to be highest around the modelled release sites, dissipating as contaminants dispersed and were transported away from the release location where they continued to evaporate to the atmosphere, dissolve, disperse/dilute within the water column, and degrade. As total hydrocarbons represent the sum of the dissolved phase (i.e., soluble fraction making up approximately 1% of the whole oil) and the particulate phase (i.e., whole oil droplets) within the water column, THC was predicted to have a larger footprint and a higher concentration than the dissolved phase. The EL 1144 example well site was predicted to have higher concentrations and a larger cumulative footprint, compared to that of the EL 1150 example well site, due to the release volume being over four times larger at EL 1144. Due to the winds and currents in the area at the modelled times, concentration exceedances were predicted to the east, south, and north of the release locations (Figure 4-28 and Figure 4-29). While the highest concentrations of THC were predicted near the release location at the trap height (see Section 3.7), the majority of the predicted THC concentrations outside of a few kilometer radius from the release locations were within a few tens of meters of the surface. This result was due to the majority of the predicted THC deriving from entrained oil from wind-induced surface breaking waves, which occurs in the upper water column (i.e. mixed layer depth).

Shoreline oiling from the 95th percentile water column exposure cases from both release sites was predicted along the Azores at concentrations >500 g/m^2 (Figure 4-30). The magnitude and extent of both shoreline and sediment oiling was smaller at the EL 1150 release site, when compared to EL 1144, due to the smaller modelled release volume at EL 1150.

At the end of the 160-day water column exposure simulations at the EL 1144 and EL 1150 example well sites, 48-51% of the released volume was predicted to evaporate into the atmosphere, 34-37% degraded, <10% was predicted to remain floating on the water surface, 5-6% remained entrained in the water column, <1% was transported outside the modelled domain, 0.01% adhered to suspended sediment, and 0.02% contacted the shore (Figure 4-26 and Table 4-3).

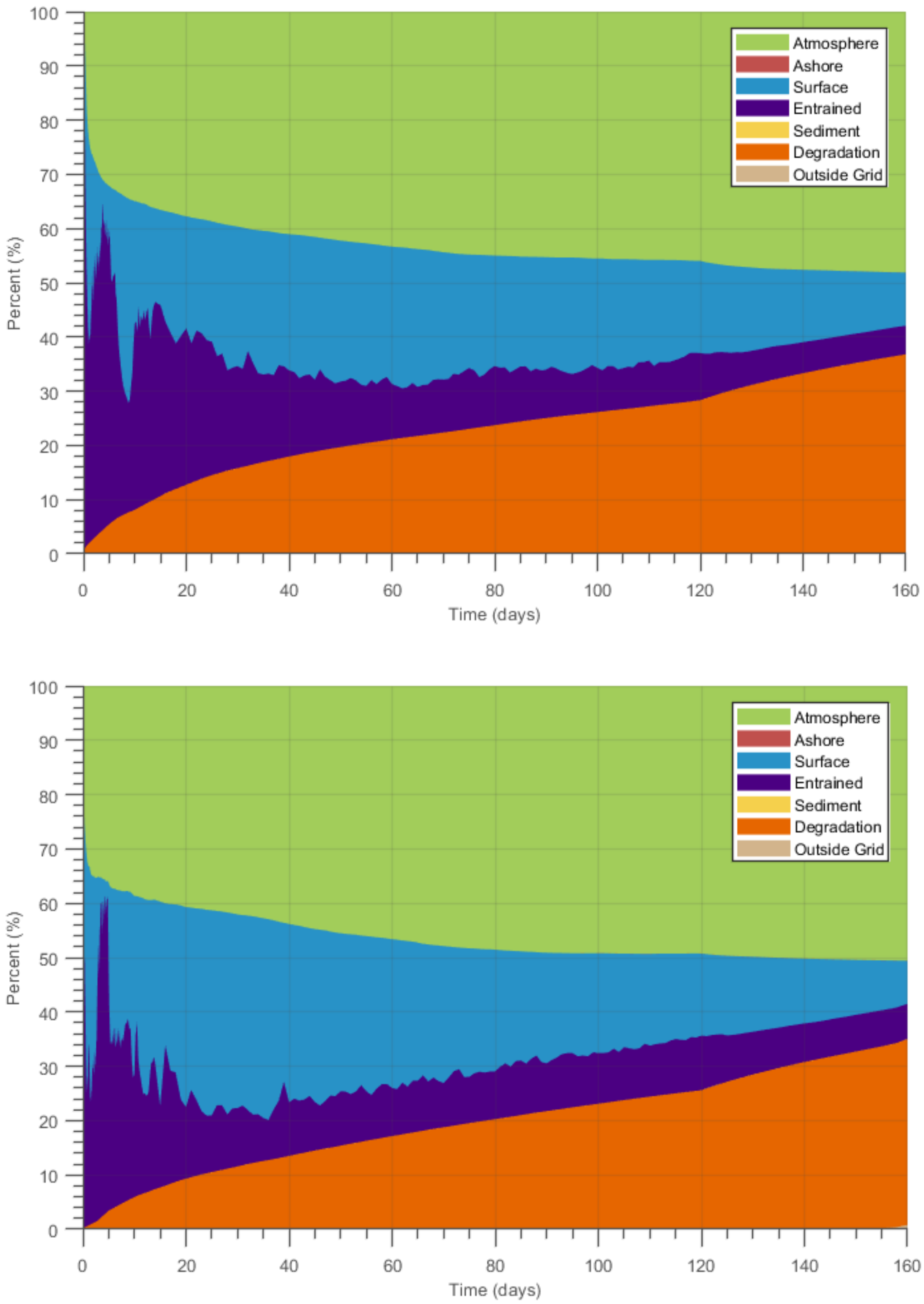


Figure 4-26. Mass balance plots of the 95th percentile water column contamination cases resulting from a 120-day blowout at the EL 1144 (top) and the EL 1150 (bottom) example well sites.

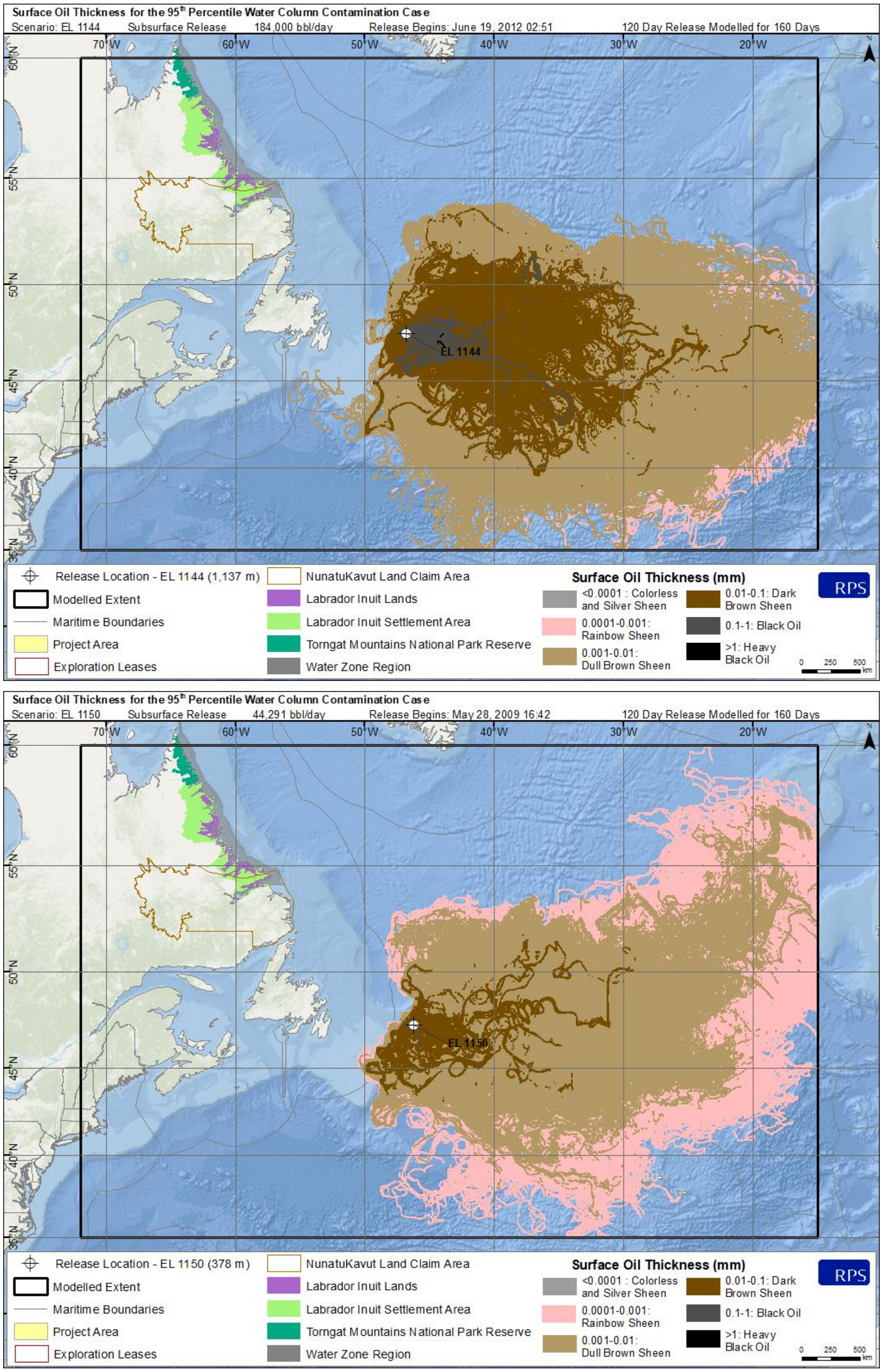


Figure 4-27. Surface oil thickness for the 95th percentile water column contamination case resulting from a 120-day subsurface blowout at the EL 1144 (top) and EL 1150 (bottom) example well sites.

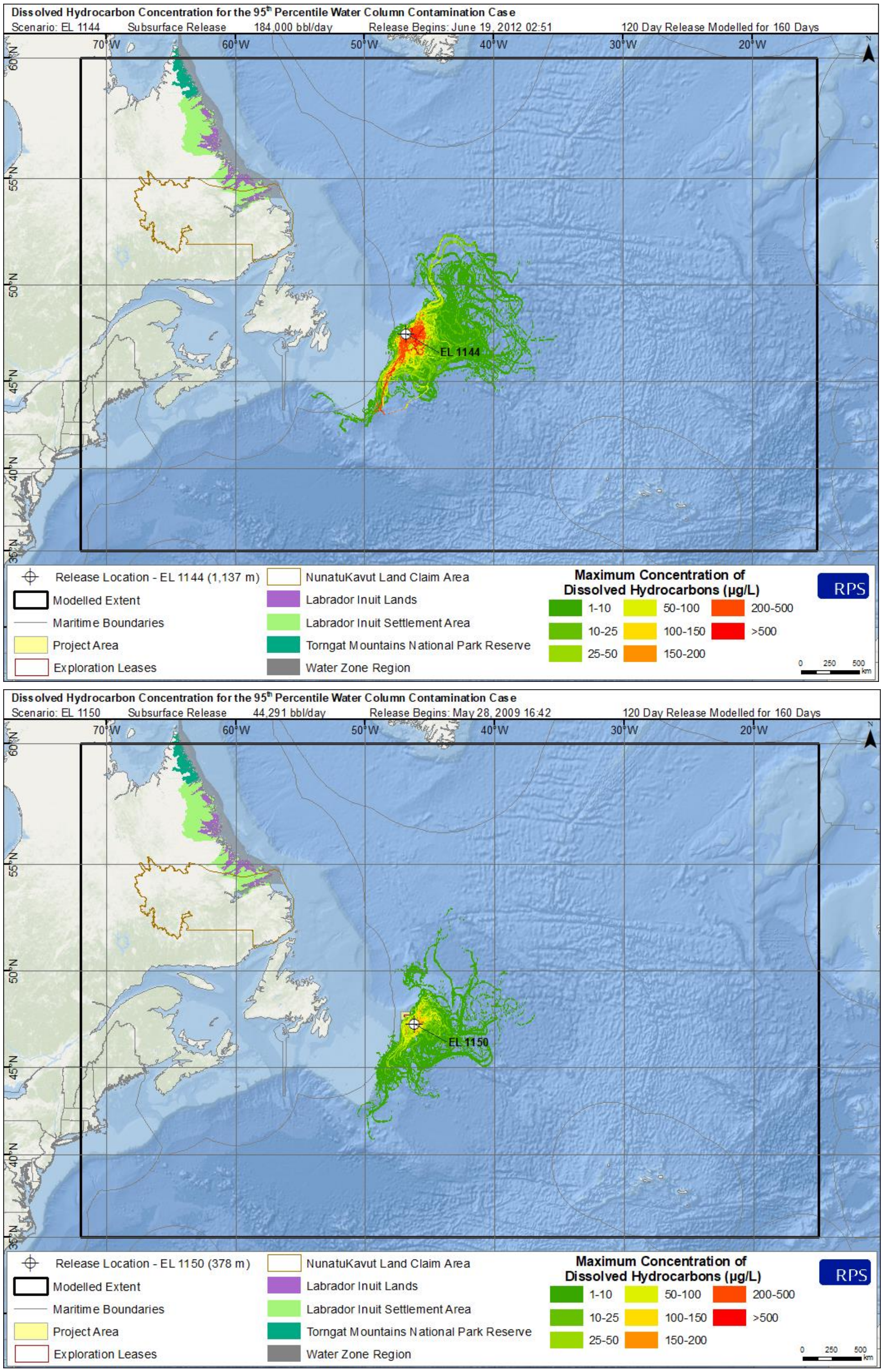


Figure 4-28. Maximum dissolved hydrocarbons at any depth in the water column for the 95th percentile water column contamination case resulting from a 120-day subsurface blowout at the EL 1144 (top) and EL 1150 (bottom) example well sites.

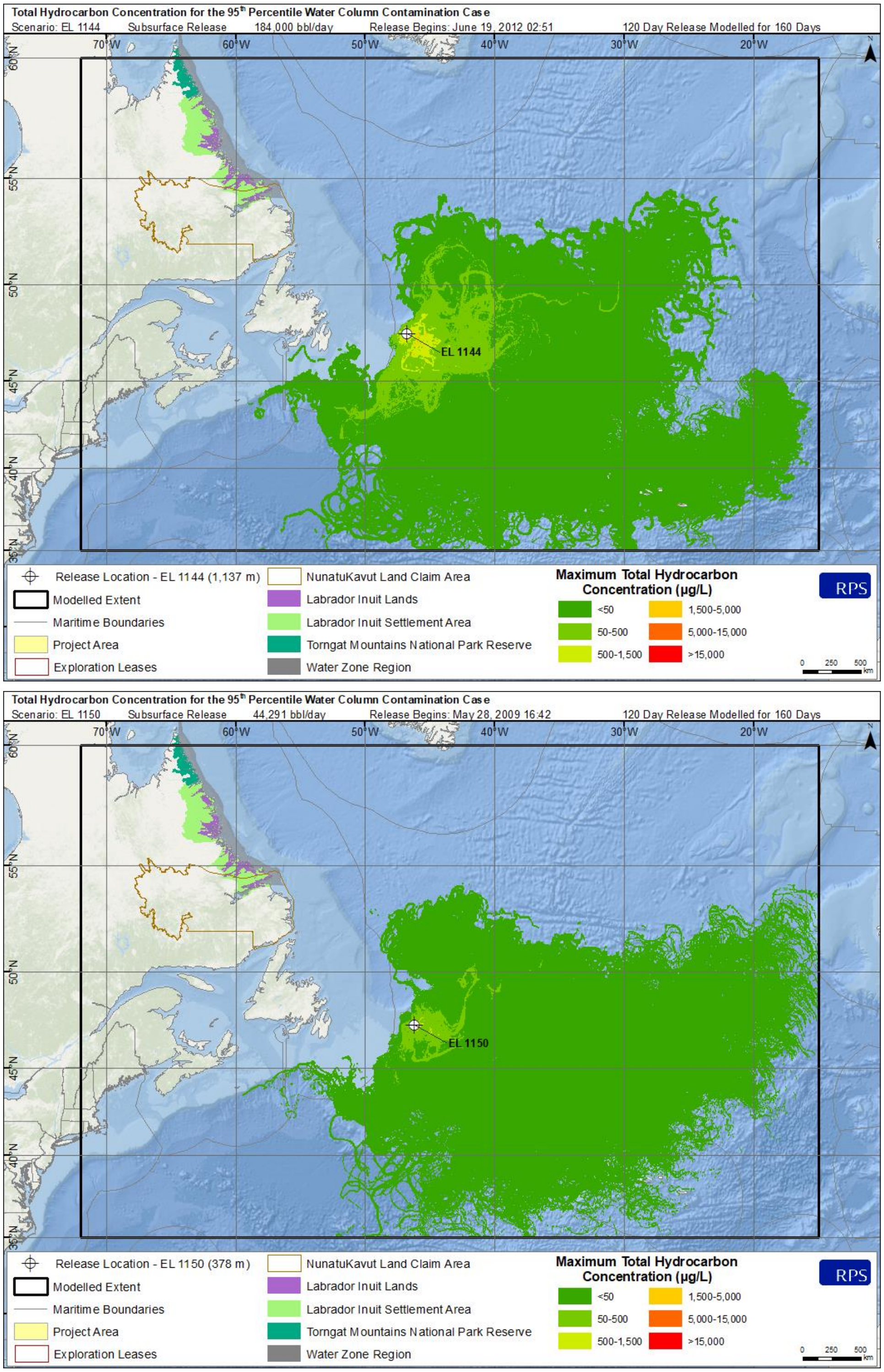


Figure 4-29. Maximum total hydrocarbon concentration (THC) at any depth in the water column for the 95th percentile water column contamination case resulting from a 120-day subsurface blowout at the EL 1144 (top) and EL 1150 (bottom) example well sites.

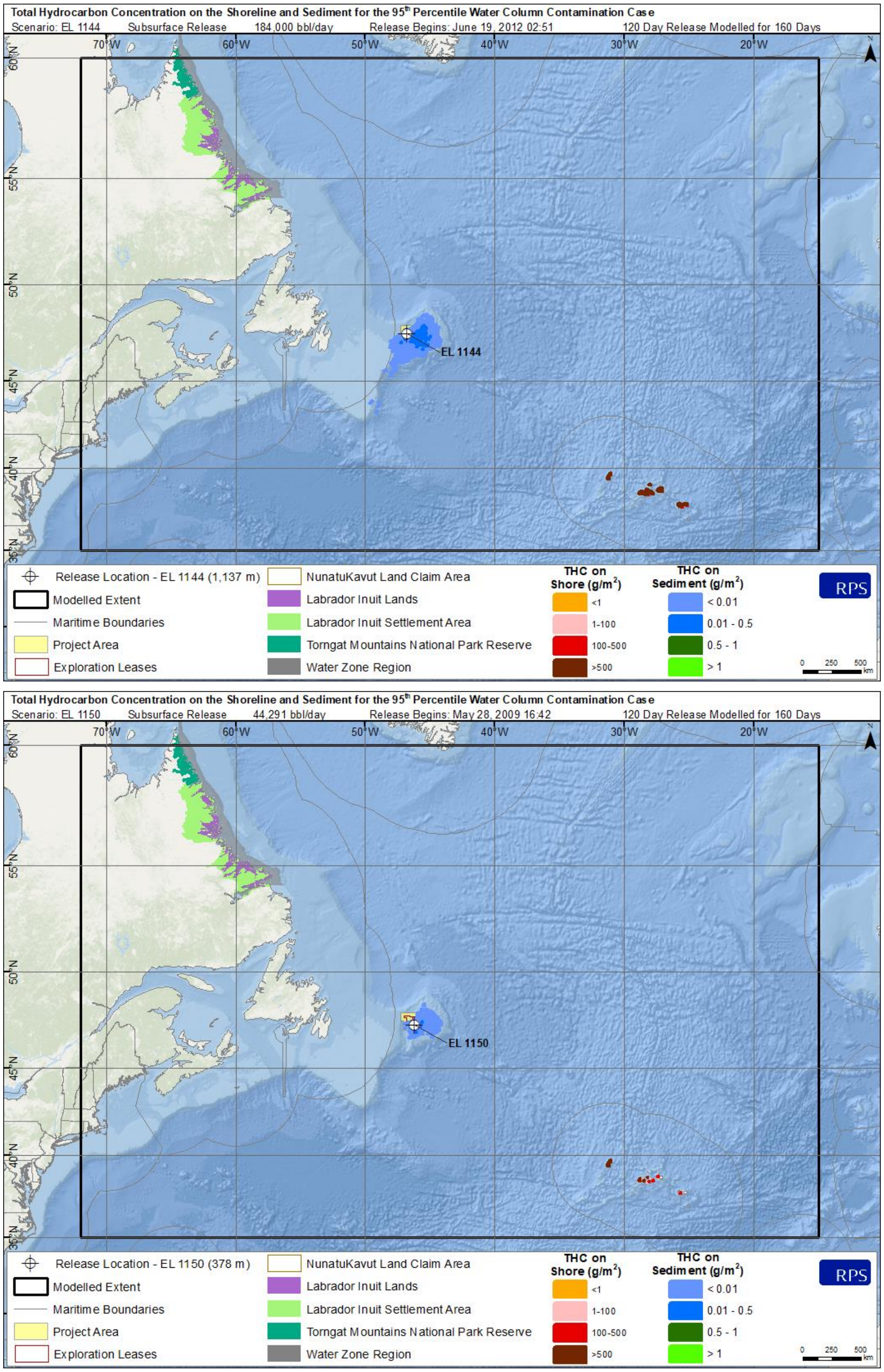


Figure 4-30. Total hydrocarbon concentration (THC) on the shore and sediment for the 95th percentile water column contamination case resulting from a 120-day subsurface blowout at the EL 1144 (top) and EL 1150 (bottom) example well sites.

4.2.3 Shoreline Exposure Cases

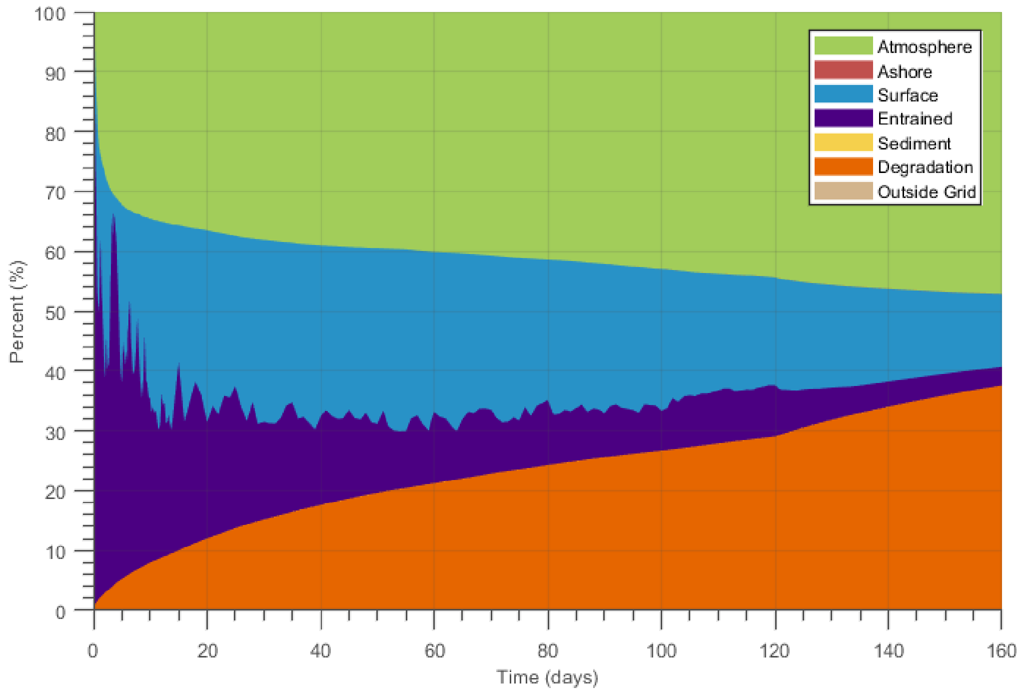
Results for the identified 95th percentile shoreline exposure cases for the releases at the EL 1144 and EL 1150 example well sites are provided below. The 120-day release at the EL 1144 example well site that was modelled for 160 days spanned early-March through August 2006 (Table 2-5). Although only approximately 0.03% of released oil was predicted to be transported to shorelines, oil was predicted to make contact with the southern coastlines of Newfoundland (mainly the Avalon Peninsula) and the Azores in concentrations exceeding 500 g/m^2 (Figure 4-35), which exceeds both socioeconomic (1 g/m^2) and ecological (100 g/m^2) thresholds. The 95th percentile shoreline exposure case for the 120-day release at the EL 1150, which was modelled for 160 days between mid-July and December 2006, resulted in predicted shoreline oiling to the east of the release site along the Azores in concentrations >500 g/m^2 (Figure 4-35). The minimum predicted time for oil to contact shorelines for the modelled release at EL 1144 was 81 days into the release for the shores of Newfoundland, 111 days for the Azores, and no oil was predicted to reach the shores of Labrador following the modelled 120-day releases. For EL 1150, oil was only predicted to contact the shores of the Azores, 80 days into the modelled release. In general, the oil that was predicted to reach any shoreline was expected to be highly weathered, patchy, and discontinuous. For each of the simulations, the longer it took oil to make contact with shorelines, the more highly weathered it became from processes such as evaporation and degradation.

For the 95th percentile shoreline exposure case at EL 1144, a small portion of the surface oil were predicted to be transported to the west and southwest before making contact with shorelines of Newfoundland (Figure 4-34). The largest portion of oil was transported to the east, where a small fraction ultimately made contact with the shoreline of the Azores. For the 95th percentile shoreline exposure case at EL 1150, surface oil was predominantly transported towards the east, before making contact with the Azores. Because of the increased size of the release at EL 1144, the extent and oil thickness on the surface was predicted to be larger than for the release at EL 1150. Surface oil thickness during the EL 1144 release was primarily predicted to consist of dull brown and some dark brown sheens. However, small regions of predicted black oil were present to the west and south of the EL 1144 release site. As mentioned above, surface oil footprints from the release at EL 1150 was predicted to be smaller in area and magnitude and consisting of mostly thinner, dull brown and rainbow sheens (Figure 4-32).

Within the water column, oil was predicted to be transported to the southwest of the EL 1144 and EL 1150 release sites. Higher concentrations of the more ecologically harmful, dissolved hydrocarbons were predicted to be transported further distances at the EL 1144 release, when compared to EL 1150 due to the larger volume of oil being released at EL 1144 (Figure 4-33). The extent of the maximum total hydrocarbon concentration within the water column, however, was predicted to be larger for the EL

1150 release (Figure 4-34). This larger footprint of low concentration is due to wind induced entrainment of surface slicks over a larger area.

At the end of the 160-day simulations at EL 1144, approximately 47% of the oil was predicted to evaporate into the atmosphere, 37% degraded, 12% was predicted to remain on the water surface, 3% remained entrained within the water column, up to 0.2% was transported outside of the model domain, ≤0.01% adhered to suspended sediment, and 0.03% made contact with the shore (Table 4-3). At the end of the 160-day simulations at EL 1150, approximately 50% of the oil evaporated into the atmosphere, 34% degraded, 7% was predicted to remain on the water surface, 7% remained entrained within the water column, <2% was transported outside of the model domain, <1% made contact with the shore, and 0.01% adhered to suspended sediment (Table 4-3).



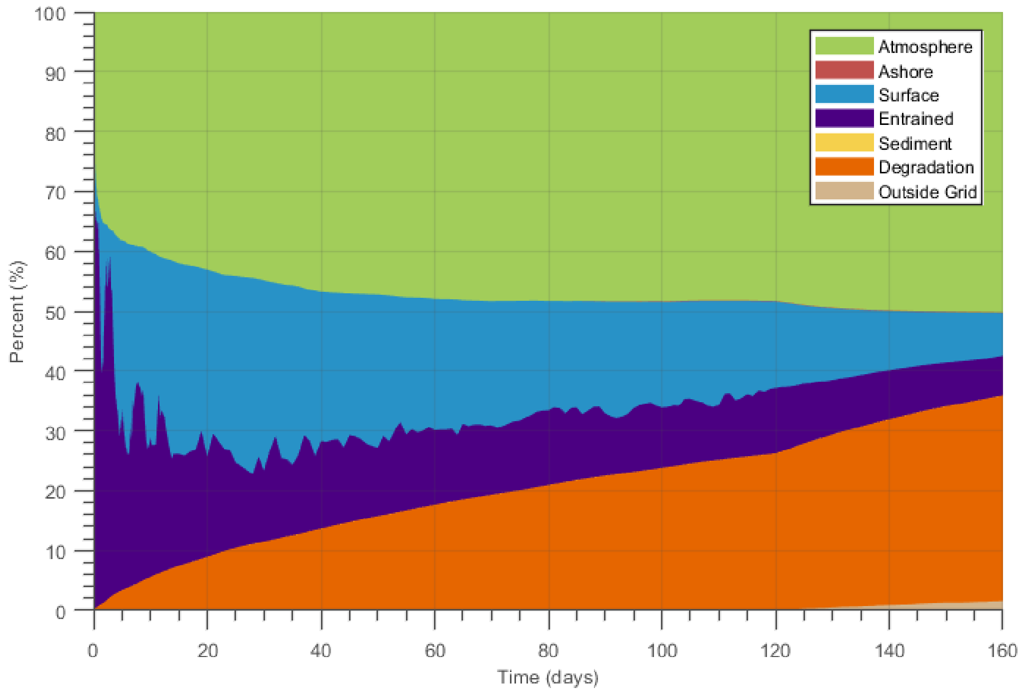
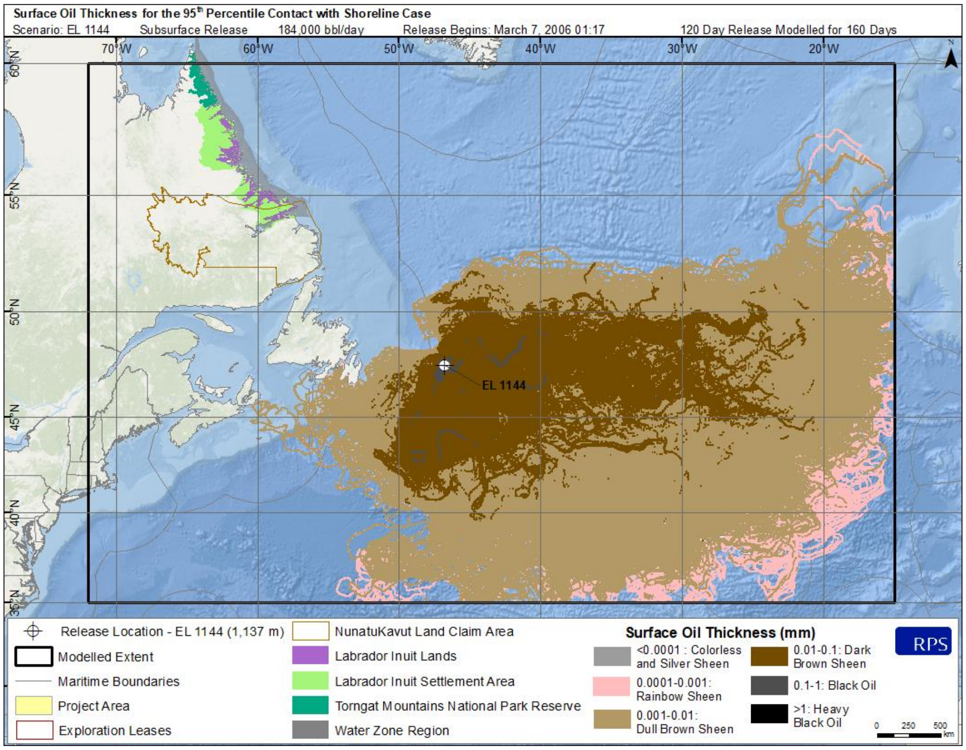


Figure 4-31. Mass balance plots of the 95th percentile shoreline contact case resulting from a 120-day blowout at the EL 1144 (top) and the EL 1150 (bottom) example well sites.



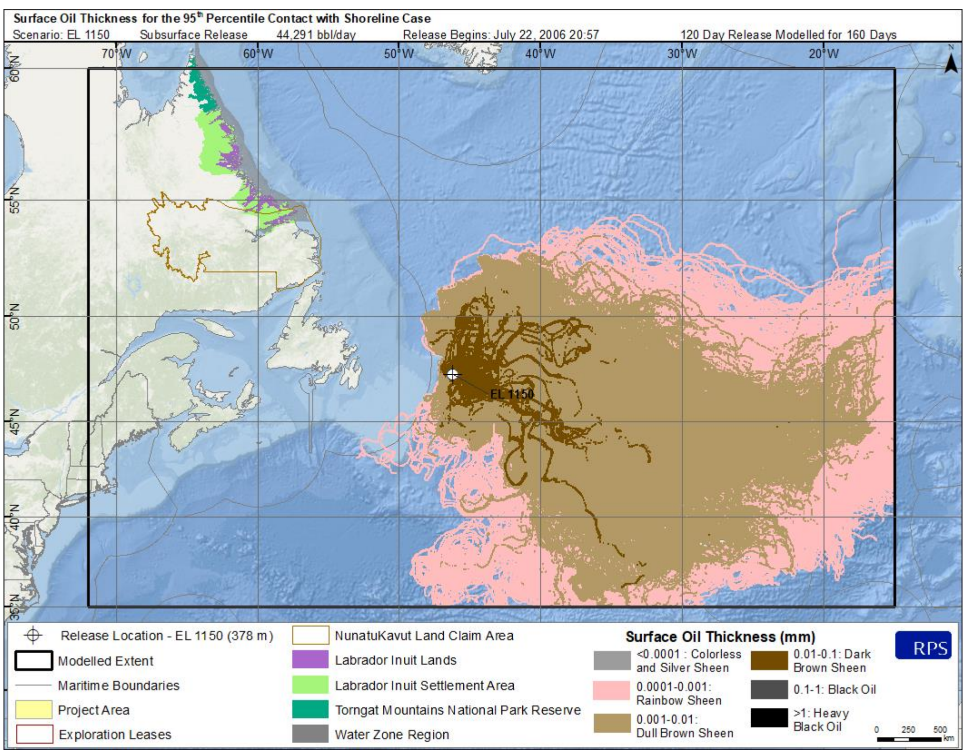


Figure 4-32. Surface oil thickness for the 95th percentile contact with shoreline case resulting from a 120-day subsurface blowout at the EL 1144 (top) and EL 1150 (bottom) example well sites.

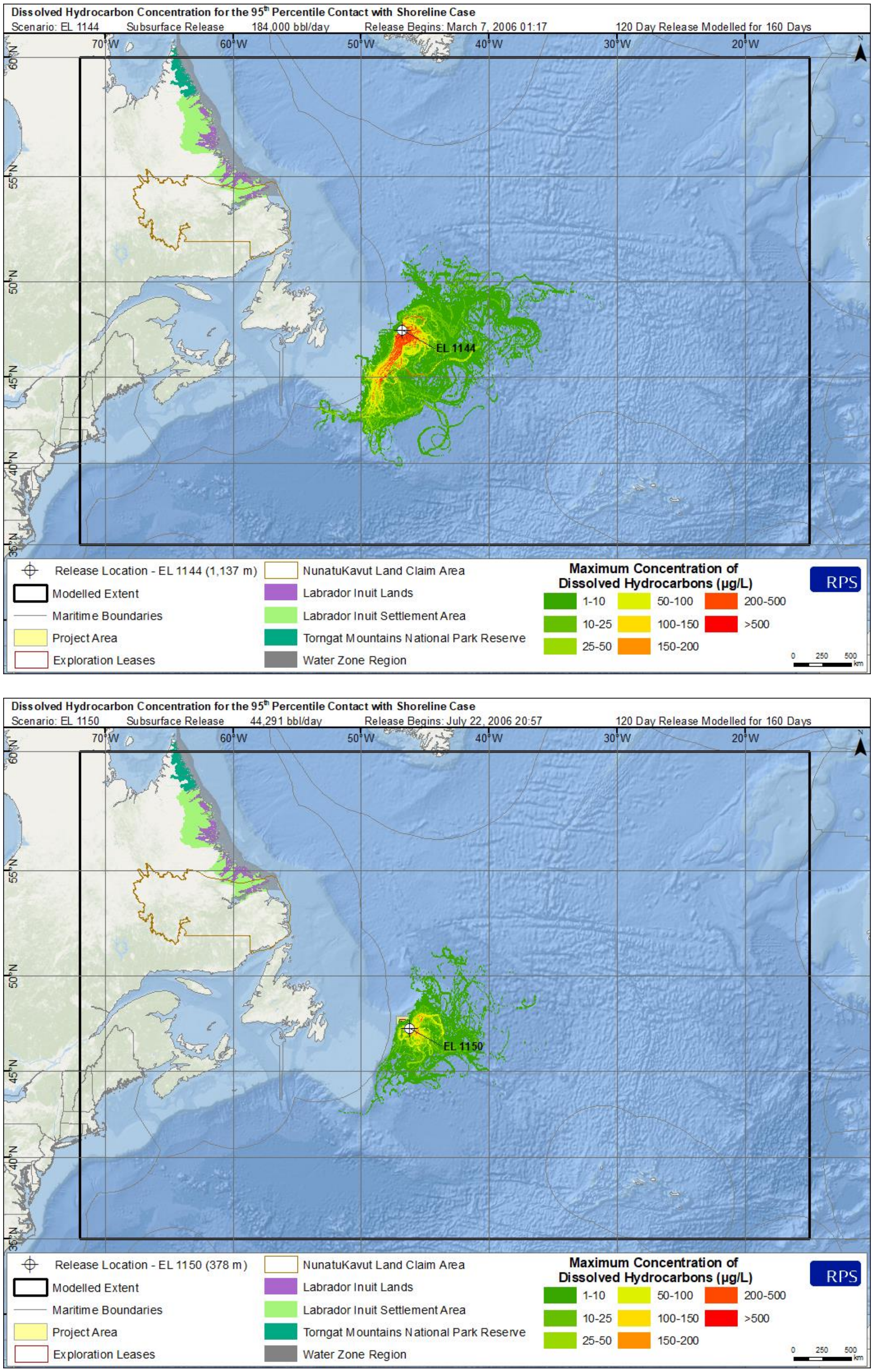
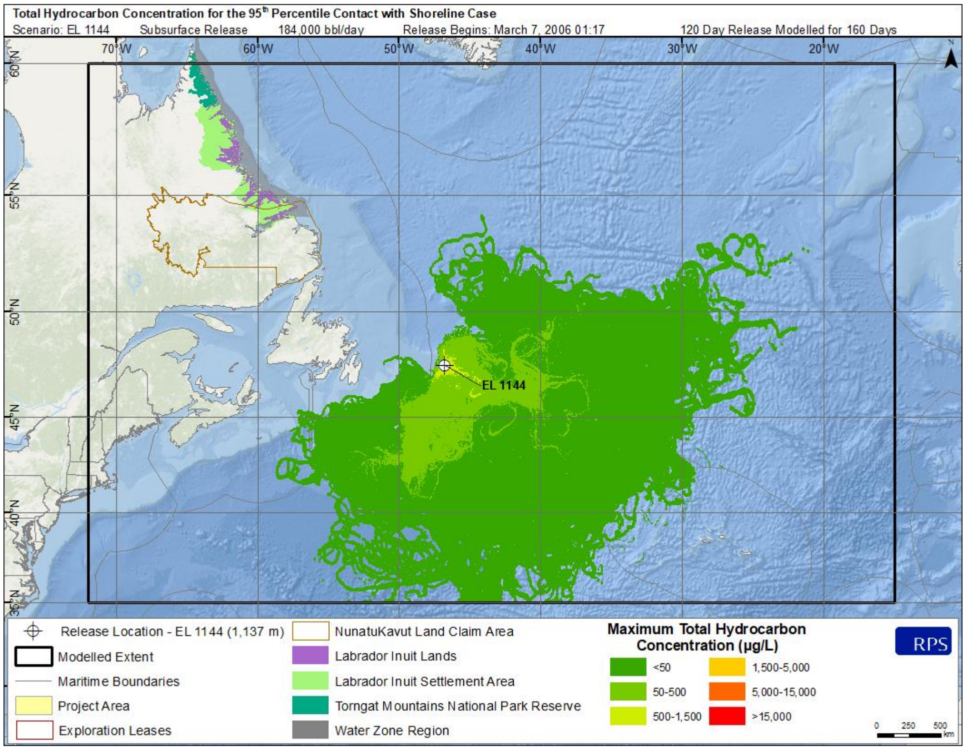


Figure 4-33. Maximum dissolved hydrocarbons at any depth in the water column for the 95th percentile contact with shoreline case resulting from a 120-day subsurface blowout at the EL 1144 (top) and EL 1150 (bottom) example well sites.



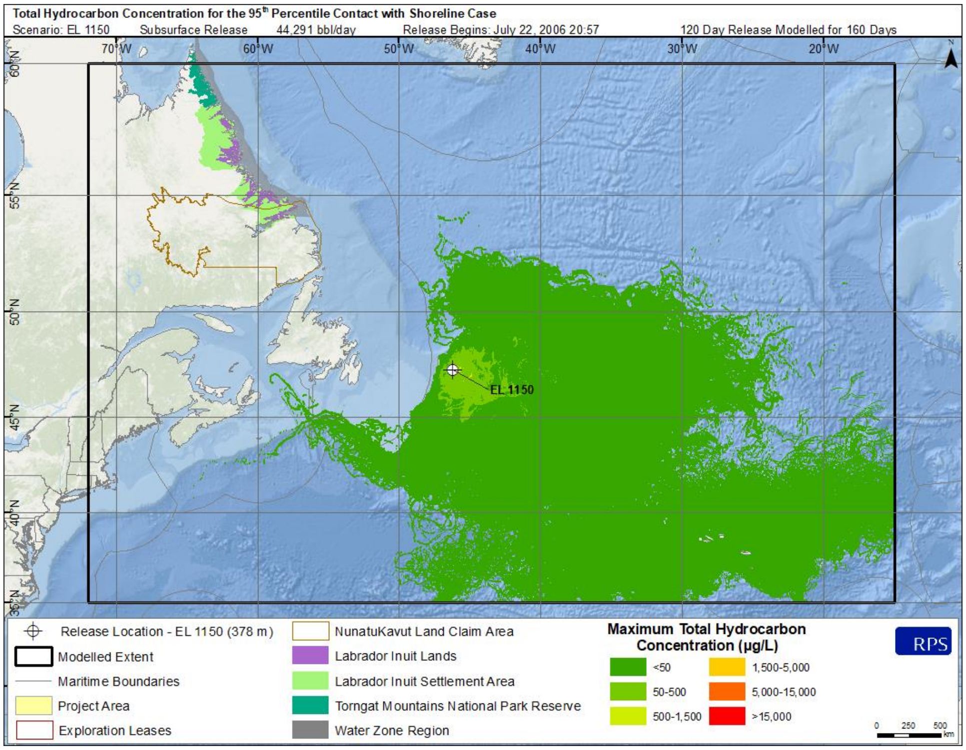
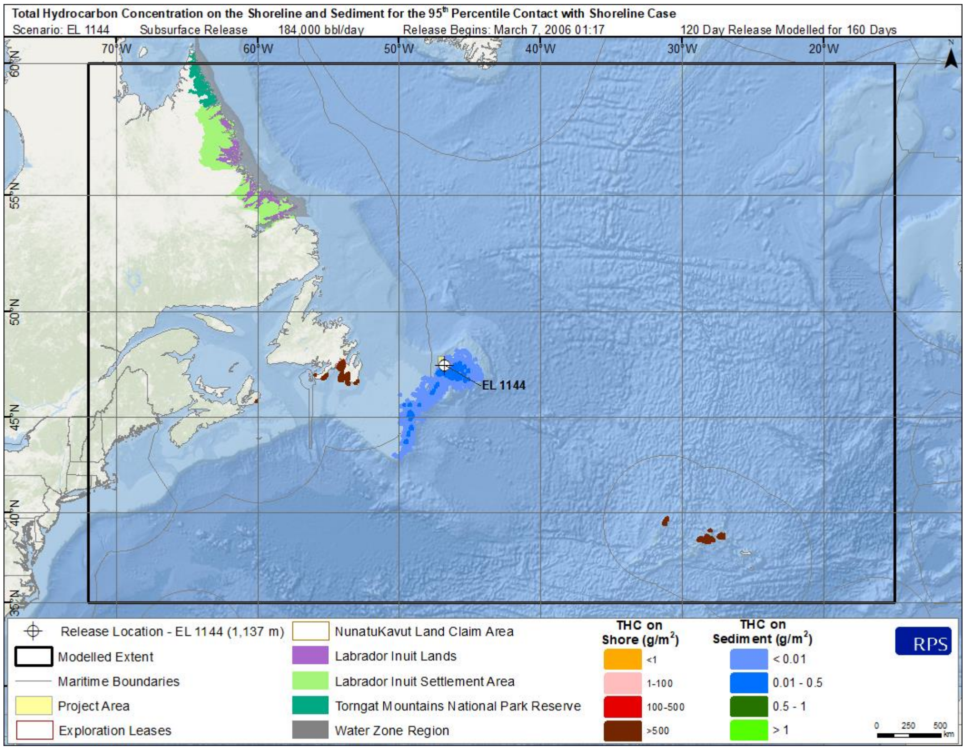


Figure 4-34. Maximum total hydrocarbon concentration (THC) at any depth in the water column for the 95th percentile contact with shoreline case resulting from a 120-day subsurface blowout at the EL 1144 (top) and EL 1150 (bottom) example well sites.



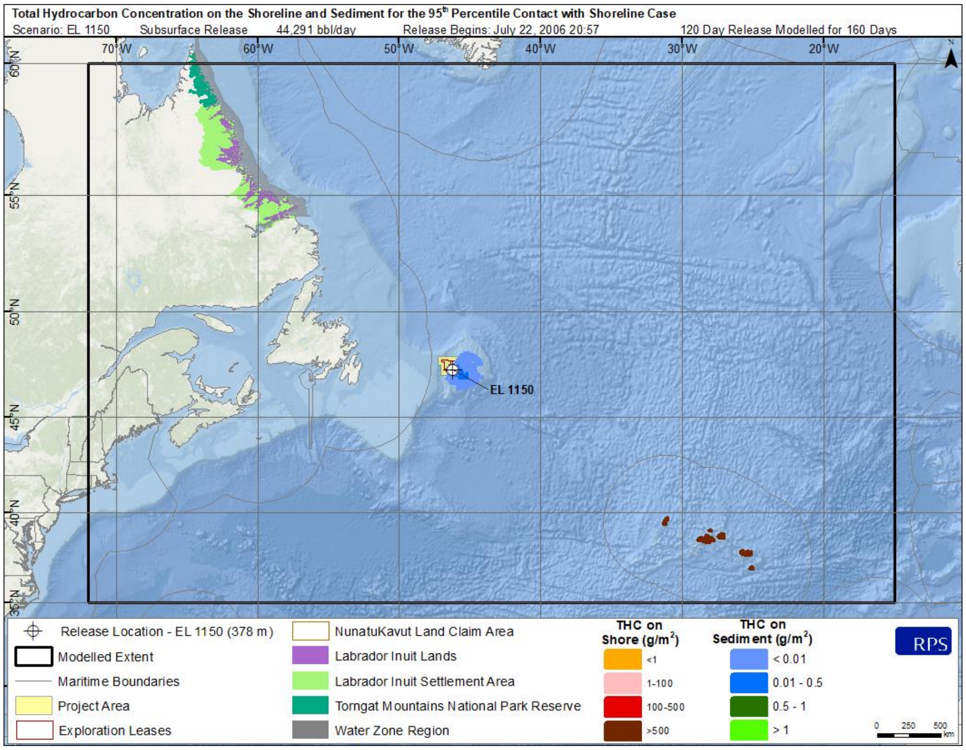


Figure 4-35. Total hydrocarbon concentration (THC) on the shore and sediment for the 95th percentile contact with shoreline case resulting from a 120-day subsurface blowout at the EL 1144 (top) and EL 1150 (bottom) example well sites.

4.2.4 Summary of Deterministic Results

The 95th percentile cases represent realistic "worst case" scenarios that may occur following the unmitigated subsurface blowouts that were modelled. From the stochastic analysis of 171 individual model runs, the site-specific environmental conditions (through space and time) resulted in a suite of model results. Scenarios were identified to maximize the potential exposure to either surface oil, in water contamination, or shoreline oil. Note that all scenarios were assumed to be completely unmitigated, which is an unlikely situation, as response efforts would be implemented immediately following a release, provided it was safe to do so.

For surface oil, both the 95th percentile release cases at the EL 1144 and EL 1150 example well sites occurred during the winter season (defined as periods of time where ice-cover within portions of the model domain may be possible for more than half the days of the model run) where winds resulted in more extensive surface slicks. For the 95th percentile water column contamination cases, scenarios began in early-summer, where winds were sufficient to result in a surface breaking waves and transport, which resulted in a large portion of the oil being re-entrained into the water column. The 95th percentile shoreline oiling cases were identified in the summer, where weather patterns were sufficient to transport oil to the west for EL 1144 oiling portions of Newfoundland (mainly the Avalon Peninsula) in 81 days and east to the Azores in 111 days. For EL 1150, oil was predicted to be transported to the east, oiling the shores of the Azores in 80 days following the modelled release. Only a small fraction of the total volume of oil released (<1%) was predicted to contact shorelines.

The depth of modelled releases and the total release volumes impacted results for the two modelled subsurface blowouts. The EL 1150 example well was the shallower of the two modelled water depths (378 m versus 1,137 m), which contributed to faster surfacing of subsurface oil. However, even though the release at the EL 1144 example well site occurred at a much deeper water depth (1,137 m), the larger release volume (over 4 times that of the EL 1150 example well site) was predicted to result in more extensive surface slicks (i.e. larger areas) that had the potential to be thicker. For modelled releases from the EL 1144 example well site, there were some limited areas with the potential for black oil (0.1 – 1 mm) in patchy and discontinuous slicks for distances up to approximately 100 km from the release. However, the thickest predicted oil over the largest areas was predominantly dark brown sheens (0.01 – 0.1 mm) for both release locations, with a higher potential for dull brown sheens (0.001 – 0.01 mm) and rainbow sheens (0.0001 – 0.001 mm) for releases at EL 1150. Note that the footprints provided are cumulative maximum values and the predicted surface oil at a snapshot in time would likely be of a lower thickness threshold and both patchy and discontinuous (Figure 4-19; Figure 4-20).

For all representative deterministic scenarios, the majority of the surface oil (78-93%) was predicted to either entrain, evaporate, or degrade by the end of the simulation. The high volatility and solubility of the BdN facilitated the large amount of predicted evaporation to the atmosphere (43-51%) and dissolution into and degradation within the water column (34-40%). A small amount of oil (7-12%) was predicted to remain on the surface after 160 days (Table 4-3). An even smaller percentage of the total released oil was predicted to remain in the water column, with entrainment ranging between 3% and 7% for the blowouts of BdN after 160 days, respectively. In total <0.1% of each modelled release was predicted to make contact with shorelines. In each case, oil on the sediments was predicted to be extremely limited, with less than 0.01% of the release making its way to the bottom. In many simulations, some portion of the released oil mass was predicted to travel outside of the model domain, in some cases up to 2%. This value is much lower than the mass predicted to leave the smaller model extent used in the previous modelling study.

The maximum subsurface water volume exposed to THC concentrations above 1 µg/L for the two 95th percentile water column cases were comparable to one another, with 220,850 km^3 predicted for EL 1144 and 196,700 km^3 predicted for the EL 1150 example well site (Table 4-4). As would be expected, this volume aligned with the predicted areal footprints of contamination for surface oil and reinforces the prediction that in water contamination was predominantly limited to the surface mixed layer depths (tens of meters). For the 95th percentile water column contamination cases at the EL 1144 example well site, the region that may experience concentrations >200 µg/L of dissolved hydrocarbons at any point (i.e. instantaneous point in space and time, which may be deemed overly-conservative) over the 160-day simulation was predicted primarily within 500 km to the southwest and east of the release site. At the EL 1150 example well site, dissolved hydrocarbon concentrations >200 µg/L were found to the southeast of the release within approximately 100 km. Entrained oil concentrations (i.e. THC) in surface waters were predicted to vary considerably from day to day, as would be expected due to the dependence on variable wind induced surface breaking wave formation, but were predominantly to the east of both release locations.

The predicted shoreline oiling from the release at the EL 1144 example well site was predicted to occur on Newfoundland and the Azores (Figure 4-35). The length of shoreline where oil was predicted to exceed the 1 g/m^2 totaled 767 km for EL 1144. However, shoreline oil was predicted to comprise an extremely small portion of the total mass of released oil (<0.03% or <662,400 bbl) in this case (Table 4-3). At the EL 1150 example well site, shoreline oiling was predicted only to the east of the release site, contacting 634 km of shoreline along the Azores.

Table 4-3. 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 160 day modelled simulations.

Summary of Mass Balance Information at the End of the Simulation (Percentage of Released Oil)										
Scenario Information			Surface (%)	Evaporated (%)	Water Column (%)	Sediment (%)	Ashore (%)	Degraded (%)	Outside Grid (%)
Example Well Site	Scenario	Product							
EL 1144	95th percentile surface oil exposure case	BdN	12.19	43.34	4.16	0.01	0.01	40.21	0.08
	95th percentile water column case		9.80	48.11	5.27	0.01	0.02	36.66	0.13
	95th percentile shoreline contact case		12.13	47.12	3.13	0.01	0.03	37.41	0.18
EL 1150	95th percentile surface oil exposure case		10.82	47.40	3.52	0.01	<0.01	36.49	1.75
	95th percentile water column case		7.95	50.56	6.47	0.01	0.01	34.20	0.80
	95th percentile shoreline contact case		7.16	50.22	6.59	0.01	0.09	34.36	1.57

Table 4-4. Representative deterministic cases and associated areas/lengths exceeding specified thresholds for 95th percentile surface, water column, and shoreline contamination trajectories at the EL 1144 and EL 1150 example well sites.

Scenario Name	Example Well Site	Released Volume	Approximate Surface Area exceeding thickness thresholds (km^2)		Approximate Shore Length exceeding mass per unit area thresholds (km)		Approximate Subsurface Volume exceeding THC threshold (km^3)^
			Socioeconomic (0.04 µm)	Ecologic (10 µm)	Socioeconomic (1 g/m^2)	Ecologic (100 g/m^2)	Socioeconomic (1 µg/L)
95th percentile surface oil exposure case	EL 1144	184,000 bpd	5,844,000	872,300	455	441	214,850
95th percentile water column case			4,093,000	1,046,000	437	432	220,850
95th percentile shoreline contact case			4,974,000	1,086,000	767	758	158,650
95th percentile surface oil exposure case	EL 1150	44,291 bpd	2,153,000	20,120	55	51	57,300
95th percentile water column case			4,142,000	225,700	124	106	196,700
95th percentile shoreline contact case			4,442,000	169,800	634	625	203,700

^ There is only 1 category threshold (socioeconomic) for THC – calculated by multiplying the area times the depth of the grid cell.

5 Discussion and Conclusions

This study is a follow on to the original modelling report “Trajectory Modelling in Support of the Nexen Energy ULC Flemish Pass Exploration Drilling Project (2018-2028)” authored on January 26, 2018, which investigated shorter release durations (30-day subsurface blowouts) contained through the use of a “Capping Stack” technology. These unmitigated scenarios represent the range of water depths, release rates, and a conservatively long spill duration that is representative of the time that is expected to be required to mobilize a MODU and drill a relief well to stop a subsurface release. In addition, this modelling study included a larger model domain than the previous assessment.

For each of the modelled releases, oil on the surface was most likely to move to the east due to the prevailing westerly winds and surface currents within the region. Winds and currents in the Project Area are similar throughout the year, with most notable differences in wind intensity. The increased winds that typically occurred during wintertime conditions enhanced surface transport and formation of surface breaking waves that resulted in more complete entrainment of oil, which lowered the amount of oil that would remain on the surface for extended periods of time. In general, after 160 days, the majority of the oil was predicted to evaporate, entrain, and degrade, with a small percentage of the total release volume remaining on the surface after 160 days. In addition, small portions of each modelled release were predicted to make contact with shorelines (<0.1%) or oil sediments (<0.01%). Shoreline contact with oil was predicted to occur along portions of Newfoundland, specifically the Avalon Peninsula, and the Azores. The highest potential for shoreline oiling from the stochastic analysis was 77 and 70% for EL 1144 and EL 1150, respectively.

The larger potential for oil making contact with shorelines (70-77% in this modelling study versus 3% in the previous study) is based upon the much longer release duration (120 day release modelled for 160 days used in this modelling study vs. the previous study, which investigated 30 day releases for 60 days) and the much larger model domain used in this study, which included the Azores to the east (which accounted for as much as 44% of the increase in potential shoreline oiling). However, this larger domain was predicted to result in only a slight decrease in the maximum total mass of oil leaving the model domain (<1.75% in this study vs. <1.82% previously). While the larger model domain suitably captured the larger area over which oil would be expected to be transported, the simulation duration was nearly three times longer and the release duration (and resulting release volume) was four times larger than was used in the previous modeling. Therefore, the longer (and subsequently larger) simulated release and longer simulation duration (60 vs. 160 days) negated a portion of the benefits of this spatially and temporally broader analysis.

The releases modelled in this study may be considered representative of other potential releases in the Project Area. The water depth of release of the EL 1144 and EL 1150 example well sites (1,137 and 378 m below sea level, respectively) are within the range of depths found throughout the Project Area.

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

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