SUMMARY REPORT 2014

Arctic

Modeling Oil Spills in the Beaufort Sea

Exploring the Risk: What would happen if oil spills in the Beaufort Sea?

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Introduction

The Beaufort Sea is a unique ocean environment that covers approximately 476,000 km^2 (184,000 sq. mi), spanning the Canadian-U.S. border and stretching across the northern coasts of Alaska, Yukon and the western Northwest Territories. This remote sea has always been dominated by sea ice. However, as the Arctic warms due to climate change, there is less summer ice than ever before in the Beaufort Sea, which could lead to increased shipping traffic. At the same time, there is renewed interest in offshore exploratory oil and gas drilling and development. These developments in the Beaufort Sea could increase the likelihood of a minor, major or catastrophic oil spill, to this sensitive Arctic ecosystem. What would an oil spill look like in the Beaufort Sea? How would the oil interact with the ice and the unique environmental conditions of the area?

To find out, World Wildlife Fund Canada (WWF-Canada), contracted RPS Applied Science Associates, Inc. (RPS ASA), a world leader in modeling the transport, fate, and biological effects of oil and chemical pollutants in marine and freshwater environments, to evaluate different types of oil spills originating in the Beaufort Sea (Gearon et al., 2014). RPS ASA used the Spill Impact Modeling Application (SIMAP) (French McCay, 2004), a computer modeling software application that estimates physical fates of releases of oil, to investigate possible oil spills associated with increased ship traffic and offshore petroleum exploration and development in the Beaufort Sea (Figure 2). The results are intended to be used to help inform local risk perception, ocean management and planning; and, to support oil spill response planning should these developments proceed.

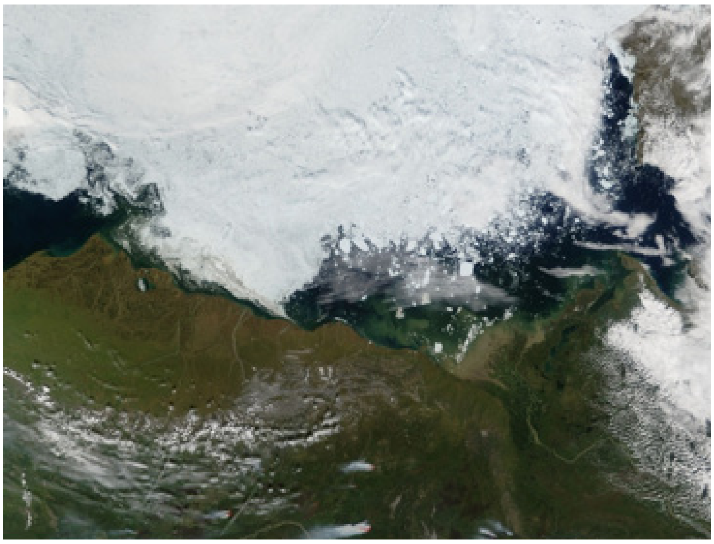


Figure 1. A satellite image of the Beaufort Sea in early Summer, 2005. (Source: NASA)

Figure 2. Map of the region of interest for this modeling study, the Canadian Beaufort Sea and coastline. (Source: Gearon et al., 2014)

This summary report was written by WWF-Canada and was adapted from the information presented in "SIMAP Modeling of Hypothetical Oil Spills in the Beaufort Sea for World Wildlife Fund (WWF)" (Gearon et al., 2014). It summarizes how RPS ASA evaluated different hypothetical oil spills, how the parameters of the oil spill scenarios were determined, and presents key results from RPS ASA's report.

Four types of oil spills were analyzed in the study:

- a shipping spill in the eastern region of the Beaufort Sea in the Amundsen Gulf;
- various trans-boundary spill types on the coastal Beaufort Shelf near the U.S./Canadian border resulting from shipping crude oil to Alaska by pipeline or tanker;
- a shallow water blowout from an oil well close to shore on the Beaufort shelf, an area potentially subject to exploratory drilling; and,
- a deep water blowout from an oil well on the Beaufort shelf break, an area potentially subject to exploratory drilling.

Various scenarios were analyzed for each of the four types of oil spill resulting in a total of 22 models of unique oil spills (See Appendix A for a detailed list of the 22 scenarios). For each scenario the following specifications were considered:

1. The source of the oil spill: e.g., a spill from a shipping accident, a sub-sea pipeline leak or an oil well blowout.
2. The flow rate of the oil and the total volume of oil spilled. Considering the flow rates and volumes of historical incidents, existing/proposed shipping activity and proposed oil and gas projects, the study identified the Maximum Most Probable Discharge (MMPD) or Worst Case Discharge (WCD) in terms of volume for each scenario. NOTE: the WCDs are not the most likely events.
3. The location, time of year, and duration of the spill were also considered: e.g., spills in oil and gas lease areas; along shipping or pipeline routes; during active shipping months or during the oil and gas operating season; time required to cap a well. Seasonal conditions also determined the presence, location, and type of ice conditions.
4. Spill response mechanisms, if any: The standard responses to oil spills are burning, mechanical collection, and/or application of chemical dispersants. If there was a response, impact of the response on the trajectory and concentration of oil at both the surface and subsurface.
5. Type of fuel spilled: e.g. crude oil, heavy shipping fuel or a lighter fuel such as diesel.

RPS ASA and its subcontractor, Environmental Research Consulting (ERC), worked with WWF to develop the oil spill scenarios that were investigated in the modeling study. ERC reviewed worldwide literature and data on plausible discharge volumes and incident probability for each spill analysis. For blowouts and pipeline leaks, discharge volumes selected for modeling were based on a review of historical blowout and leakage events. For shipping related accidents, discharge volumes were based on a review of vessel types and associated fuel carrying capacities that either currently operate in Canadian and U.S. Arctic waters or are purposed for future operation in the area. For more detailed information on how these scenarios were developed see "Modeling Oil Spill Trajectories in the Beaufort Sea: Spill Scenario Development and Probability Analysis" a paper by Dagmar Schmidt Etkin, PhD. The paper was prepared for RPS ASA and is presented as Appendix C in RPS ASA's report "SIMAP Modeling of Hypothetical Oil Spills in the Beaufort Sea for World Wildlife Fund (WWF)." (Gearon et al., 2014)

Several environmental factors affect the fate and trajectory of oil. In order to create the most accurate predictions of how each oil spill would act given the real-life conditions in the Beaufort Sea, RPS ASA gathered the best available data on the environmental and geographical conditions in the Beaufort Sea from many publicly available sources, the details of which are in the following section.

SIMAP used site specific wind and current data, and state-of-the-art transport and oil weathering algorithms to quantify areas swept by floating surface oil of varying thicknesses, fates and concentrations of subsurface oil components (dissolved and particulate), areas of shoreline affected to varying degrees, and areas/volumes where biological effects would occur for habitats and wildlife (Figure 3). The SIMAP modeling system is unique in that it not only models particulate oil content at the surface and in the water column, but it also accounts for the dissolved component: this includes soluble polynuclear aromatic hydrocarbons (PAHs) and monoaromatic hydrocarbons (MAHs), which may dissolve into the water column potentially causing toxicity. Also known as "dissolved aromatics", these are the most toxic portion of the oil. Out of all the components of the oil; dissolved aromatics impact water column organisms the most.

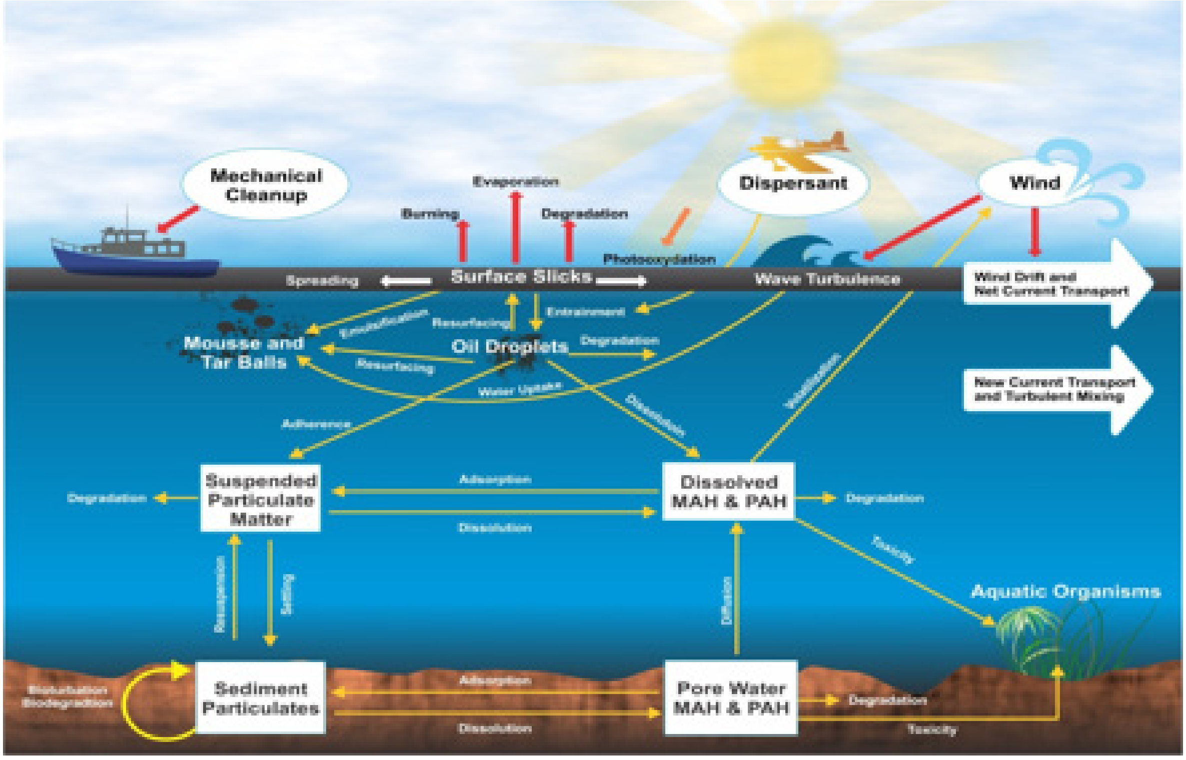


Figure 3. Open water oil fates and behaviour processes simulated in the SIMAP modeling system. (Source: Gearon et al., 2014)

Data Input

The data inputs into SIMAP included environmental and oceanographic conditions such as the velocity and direction of winds in the Beaufort Sea, ocean currents, mobile sea ice and anchored land-fast ice, and the structure of the water column including the ocean temperature and salinity. Geographical data was also input into the modeling system including shoreline and habitat types and the bathymetry (depths and shapes of underwater terrain).

The different chemicals in oil react in different ways to environmental conditions e.g., some parts of the oil easily evaporate when exposed to the atmosphere. The chemical changes that occur in oil when it is exposed to the physical environment are known as "oil weathering".

WIND

The greatest surface oil movement results from persistent winds from the same general direction. In order to reproduce the natural variability of wind direction and speed for the purposes of this study, historical observed multiple-year (2008-2013) wind records were used in the modeling process. Data on wind was obtained from the ERA-40 (ECMWF RE-ANALYSIS) wind model, which was developed and is operated by the European Center for Medium-range Weather Forecast (ECMWF). This model has global domain coverage with 0.75° resolution and the dataset contains 3-hourly (8 times a day) wind speed and direction readings at all grid nodes included in the region of interest.

WATER AND ICE CIRCULATION

Currents transport spilled oil at all water depths and influence the behaviour and weathering processes of oil, especially for subsurface releases such as blowouts. Water and ice circulation data generated from the Towards an Operational Prediction system for the North Atlantic European coastal Zones (TOPAZ4) hydrodynamic model were used in this modeling study. TOPAZ4 is an ocean/sea ice data assimilation system for the North Atlantic and the Arctic. The dataset was developed by the Nansen Environmental and Remote Sensing Center (NERSC). Daily mean 3-dimensional current speed and direction, surface sea ice drift speed and direction, ice thickness, and ice coverage fraction were acquired for the time period April 2008 – March 2013 and used as input to the SIMAP model. It is important to note that TOPAZ4 does have limitations that need to be considered while interpreting the results of this study. The primary objective of TOPAZ4 project was to resolve large-scale Arctic Ocean circulation; however, the Beaufort shelf, as compared to other continental shelves, is relatively narrow and the area exhibits complex coastal features and dynamics (e.g., counter currents and eddies). Some of the complex features that were unresolved in the TOPAZ4 data include:

- The influence of the Mackenzie River discharge and the eastward flowing shelf counter current;
- The coastal counter current does occur in the modelled data but was variable in speed and direction and its presence was highly erratic throughout the years;
- Inspection of local surface currents in TOPAZ4 compared well with local wind stress in various coastal areas along the North Slope, but fluctuated often in direction. Schulze (2012) found that the eastward flowing current, under enhanced easterly winds, is subject to reversals to the west with current speeds up to 1 m/s.

Reversal of the shelf break current in the TOPAZ4 data may not be completely unjustified, but this pattern was still assumed by the authors of RPS ASA's report (Gearon et al., 2014) to be somewhat suspect.

BATHYMETRY (depths and shapes of underwater terrain)

Bathymetry data for the study area was obtained from the General Bathymetric Chart of the Oceans (GEBCO) Digital Atlas (IOC, IHO and BODC, 2003)

SHORELINE AND HABITAT TYPES

Mapped shoreline classification data from the "Environmental Atlas for Beaufort Sea Oil Spill Response" (AXYS, 2004) and the National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration (OR&R) Environmental Sensitivity Index (ESI) were used to define habitat types. The SIMAP model includes an oil-shoreline interaction algorithm which is used to estimate the amount of oil retained onshore based on shoreline type. For example, flat sandy beaches typically retain much more oil than steep rocky coast, and furthermore, oil that cannot be retained on the shore is susceptible to further transport, thereby potentially affecting other regions. A habitat grid containing both shore and subtidal habitat types was constructed for the study area and used as an input to the SIMAP modeling system.

WATER COLUMN AND SALINITY

A definition of the physical properties of the water column in the area of interest is an important input for oil spill modeling, especially for subsurface releases. Water temperature dictates many physical attributes and weathering processes, including the viscosity and evaporation rate of the spilled oil. Temperature and salinity also dictate the density of the surrounding water body, which influences the speed at which entrained oil (oil that has been drawn into the water column and transported by subsurface currents) can re-surface. Similarly, these physical attributes play an important role in the physics of a subsurface blowout. For this study, data defining the vertical structure of the water column, temperature and salinity, were obtained from the publicly available World Ocean Atlas 2001 (WOA01) (Boyer, 2005).

Sea ice coverage in the Canadian Beaufort was typically lowest in August and September. The descent of increasing ice coverage from the North Pole begins in October, with close to full ice coverage up to the coast occurring in mid-November. From December to May, almost 100% sea ice coverage was observed in the entire Beaufort Sea. The ice starts to break up and retreat north in June and July.

OIL AND ICE

Oil interactions with mobile sea ice or immobile landfast ice involve several processes that affect transport and fate of the oil. If oil is released at or above the water surface, it may spill into water and/or onto the surface of the ice. Oil deposited on ice may absorb into surface snow, run off and become trapped between cracks or in open water fields between floes, and/or become encapsulated in the ice. Oil released into and under water may become trapped under the ice in ridges and keels, or build up along, and become trapped in, sea or landfast ice edges (Drozdowski et al., 2011).

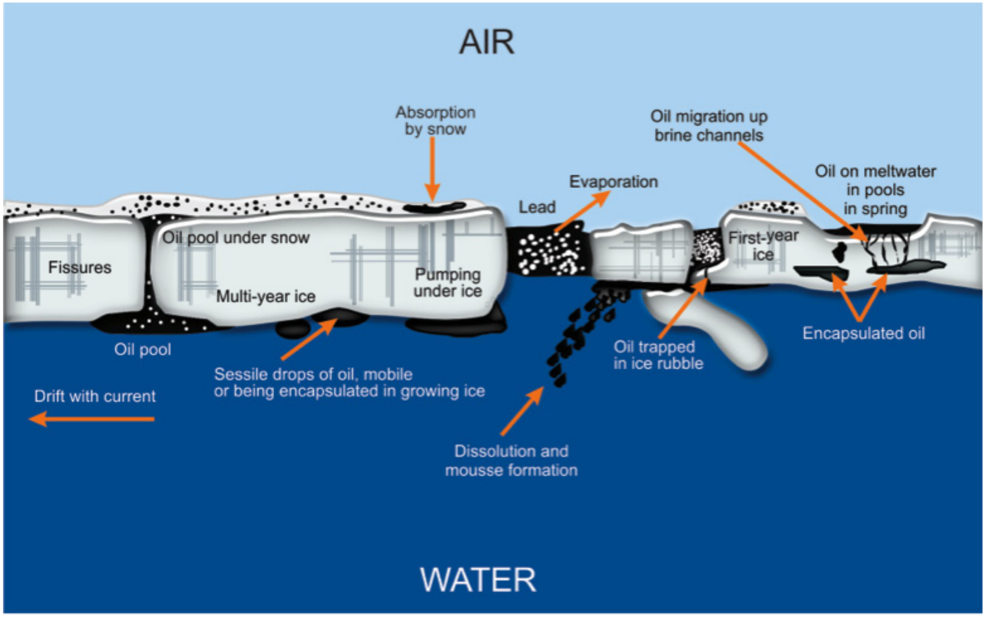


Figure 4. General schematic showing dynamics and characteristics of sea ice and oil interaction at the sea surface. (Source: Original figure by Alan A. Allen).

To simulate oil transport in this study, the SIMAP model used the ice coverage variable, and both the regular water currents and the ice currents or ice velocities available in the hydrodynamics and ice model TOPAZ4.

The landfast ice that accumulates along the coastline of the Beaufort Sea creates a temporary barrier where surface oil can become trapped until the ice thaws. Two datasets, one from the US Bureau of Ocean Energy Management (BOEM) and the other from the National Snow and Ice Data Centre (NSIDC), were merged to create continuous landfast ice coverage. The map below (Figure 5) shows both landfast ice and the monthly average for sea ice coverage for September - December.

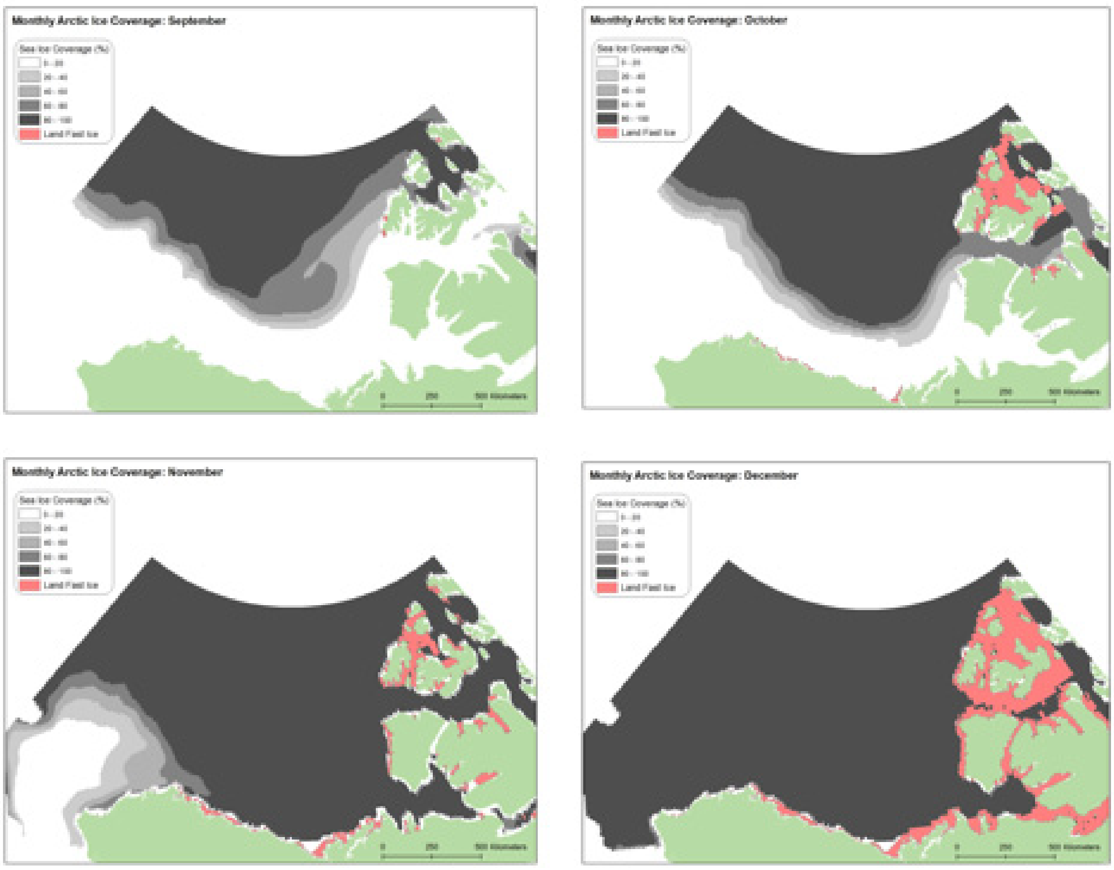


Figure 5. Grey shows the 2011 monthly average sea ice coverage generated from TOPAZ4 for September - December and pink shows landfast ice coverage generated from data provided by BOEM and NSIDC for September - December. (Source: Gearon et al., 2014)

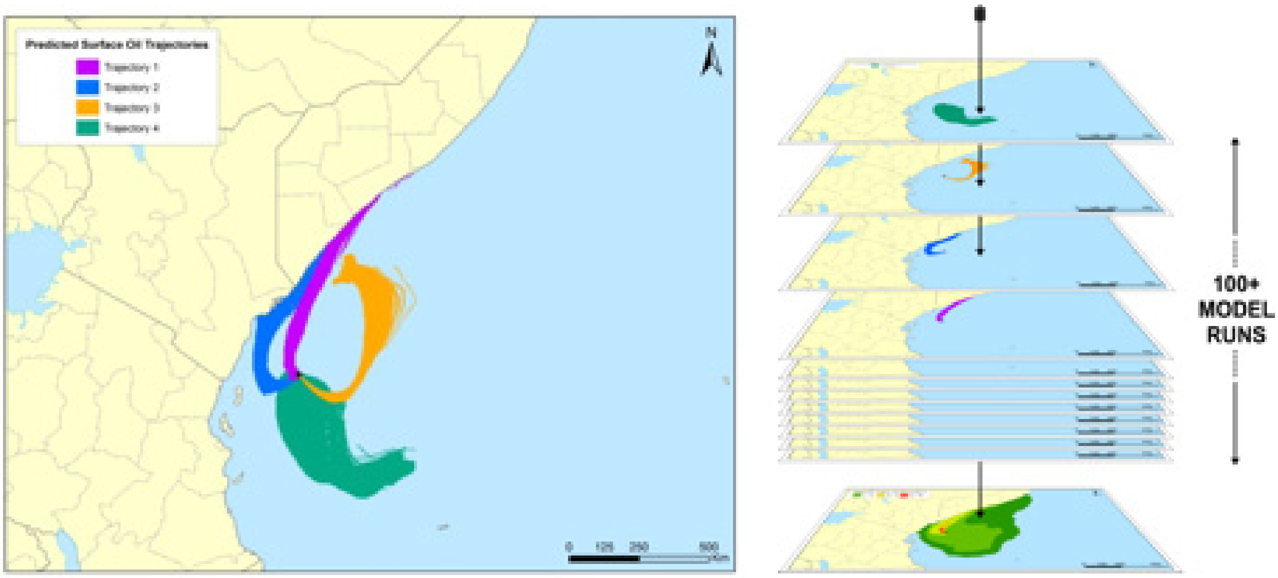


Figure 6. Examples of four individual spill trajectories predicted by SIMAP for a generic spill scenario. All 100+ individual trajectories are overlain (shown as the stacked runs on the right), and the frequency of contact with given locations is used to calculate the probability of how oil can affect an area during a spill. (Source: Gearon et al., 2014)

Output

Once all of the detailed data on the complexities of the environment of the Beaufort Sea were collected and input into SIMAP, the modeling program produced graphs, maps, and animations for each of the 22 oil spill scenarios that illustrate events such as: oil encountering sea ice; how far and in which direction a surface oil slick could travel; how much of the oil could entrain into the water column; how many kilometres of shoreline would be affected; and how long it would take for the oil to spread and reach the shoreline.

Two types of results were attained from SIMAP:

1. Stochastic model outputs: These maps represent a composite of 100 individual trajectories of the same oil spill scenario (see figure 6) that determine the probability of a certain concentration of surface oiling, of shoreline oiling, and the minimum travel times for oil to spread on the ocean surface and reach the shore. Because these trajectories started on different dates/times, they were exposed to varying environmental conditions, and thus traveled in different directions. RSP ASA used historical observed multiple-year wind records and performed the simulations within the coinciding time period, as this allowed reproduction of the natural variability of the wind direction and speed. It is important to note that the stochastic map is not a map of an individual spill but rather, it provides a statistical representation of probability of oiling extent and travel time given a wide range of environmental conditions.

2. Individual trajectory modeling outputs include:

    - Mass balance charts that provide an estimate of the oil's weathering and fate for a specific run for the entire model duration. Components of the oil tracked over time include the amount of oil on the sea surface and on shore as well as the total hydrocarbons in the water column, oil in subsea sediments, oil evaporated into the atmosphere, oil burned, and oil decay;

    - Maps showing the footprint of floating surface oil concentration (g/m^2), or maximum water column concentration of aromatics in parts per billion (ppb), at various time steps during the individual spill simulation. As mentioned above, the stochastic scenarios are comprised of 100 individual trajectories of the same spill scenario, each run with a different start time. The individual trajectory results were selected from the stochastic ensemble of results. Out of the 100 different trajectories run, only the 95th percentile – those identified as having the highest degree of surface and shoreline oiled or highest degree of water column contamination are presented in the report and in this summary. NOTE: Unlike the stochastic water column contamination results (showing total or all components of oil), only the resulting dissolved aromatic concentrations are shown in the individual trajectory time series maps. Dissolved aromatics in the water column resulting from an oil spill may reach toxic concentrations. Subsurface oil droplets in particulate form can, for example, cause clogging of feeding appendages and gills of fish, and can impede movement. Organisms at highest risk of water column effects include invertebrates and fish larvae.

Section 1 takes an in-depth look at one of the oil spill scenarios in order to highlight and explain the full suite of information produced by SIMAP for each of the 22 scenario's and how this information could be useful for future management and planning. Section 2 looks at 12 of the 22 oil spill models and highlights the pertinent results from each different type oil spill scenario.

SECTION 1: An in-depth exploration of the SIMAP analysis of a shallow water well blowout

One of the oil spill scenarios run through SIMAP was a shallow subsurface well blowout in the Amauligak Lease Area (see Figure 7) at a depth of 32 meters. The Amauligak lease area was selected because of its close proximity to the sensitive habitats of key species in the Beaufort, for its past exploratory drilling history, and future interest in drilling in this lease area. At shallow depths in a less turbulent or mixed water column, oil will typically rise to the surface quickly. At high exit velocities and high gas content in shallow water, oil can be shot up to the surface causing a "boiling over" or "bubbling up" effect. Under these turbulent release conditions a concentration of potentially toxic oil components within the water column.

The oil spill in this model lasted for 90 days and the oil type was Alaska North Slope (ANS) crude oil. This oil is characterized as a light to medium crude with high aromatic content and is assumed to have oil properties typical of the oil that will potentially be extracted from the Beaufort Sea. 2,700,000 barrels (bbl) of oil were spilled in total (30,000 bbl per day). A very large oil spill, this is an example of a potential worst case discharge (WCD). Note: a WCD is the maximum potential spillage from a source containing oil (the volume depends on the source) but is not the most likely event. This was a late operating season spill that started in August and ran through October when sea ice is rapidly forming. No response was undertaken -- WWF believes that it would not be possible to conduct response actions (e.g., mechanical collection or dispersant application) after October 31st due to harsh environmental conditions in the Beaufort Sea.

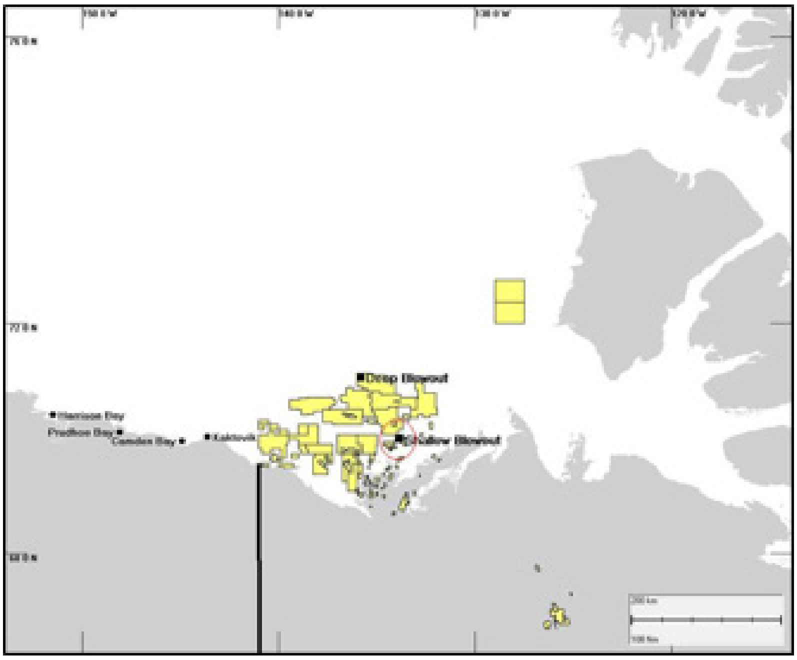


Figure 7. Location of the shallow blowout release site (circled in red), in the Amauligak lease area on the Beaufort shelf. Yellow polygons outline all lease areas in Canadian Beaufort. Thick black line represents U.S./ Canadian border. (Source: Gearon et al., 2014)

How to Read the Stochastic Maps

Figure 8 shows two stochastic maps. The first map shows water surface oiling probabilities. The coloured area in the stochastic maps indicates areas that may receive oil pollution in the event of that particular spill scenario. The reds indicate areas that are more likely to be affected while the greens indicate areas that are less likely to be affected. These figures do not imply that the entire contoured area would be covered with oil in the event of a spill. For these maps the oil slick exceeds the threshold of 0.01 g/m² meaning that this oil would, at least, present a visible sheen on the surface of the water and could potentially have an effect on socioeconomic resources such as fishing (French McCay et al. 2011). The second map shows minimum travel time for floating oil. Stochastic maps have been created that show probable surface oiling, shoreline oiling and subsurface contamination given a wide range of environmental conditions.

Stochastic Maps Showing Probability of Surface Oiling and Minimum Travel Times for Floating Oil

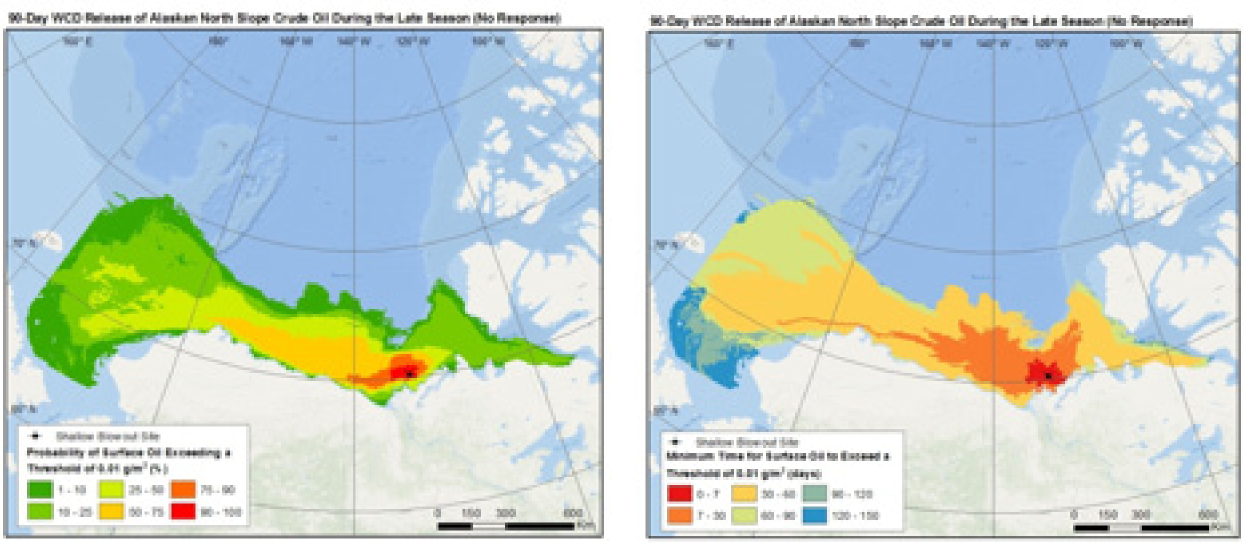


Figure 8. Water surface oiling probabilities and minimum travel times for floating oil ≥0.01 g/m². This map illustrates that there is 50-75% probability that this 90 day WCD shallow well blowout occurring late in the operating season (August-October) could cause oil slicks and result in thin sheens that travel far to the west, extending 1,200 km to just west of Point Barrow, Alaska. (Source: Gearon et al., 2014)

Figure 9 below shows another stochastic footprint (i.e. areas where oiling could occur) showing potential surface oiling however, this map used a higher threshold for floating surface oil thickness: (≥10 g/m^2). The oil footprint is much less expansive but represents the probable extent of thicker oil (whereas the maps using a lower threshold show thin oil including a surface sheen). Figure 9 therefore shows an area that could be covered at some time after a spill, with thick, dark brown oil after a shallow well blowout. A thicker oil slick would have a greater effect on wildlife in the area including, for example, coating and smothering of sea birds. A set of maps showing results using the higher thresholds are summarized, and stochastic results are presented in Appendix E of Gearon et al's 2014 report.

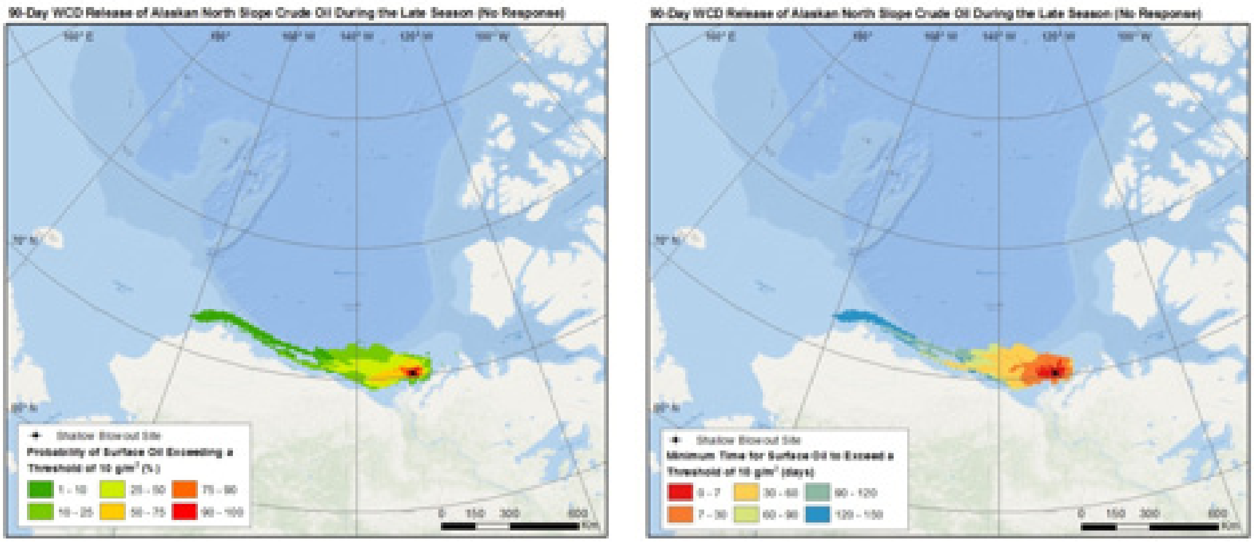


Figure 9. Water surface oiling probabilities and minimum travel times for floating oil ≥10 g/m^2. (Source: Gearon et al., 2014)

Stochastic Map Showing Probability of Shoreline Oiling and Minimum Travel Times for Shoreline Oil

Figure 10 below shows the probability of oil reaching various shorelines, given a spill. The extent of shoreline oiling probabilities >1% was from Point Barrow, Alaska east to shorelines of the Amundsen Gulf, and the southwest coast of Banks Island.

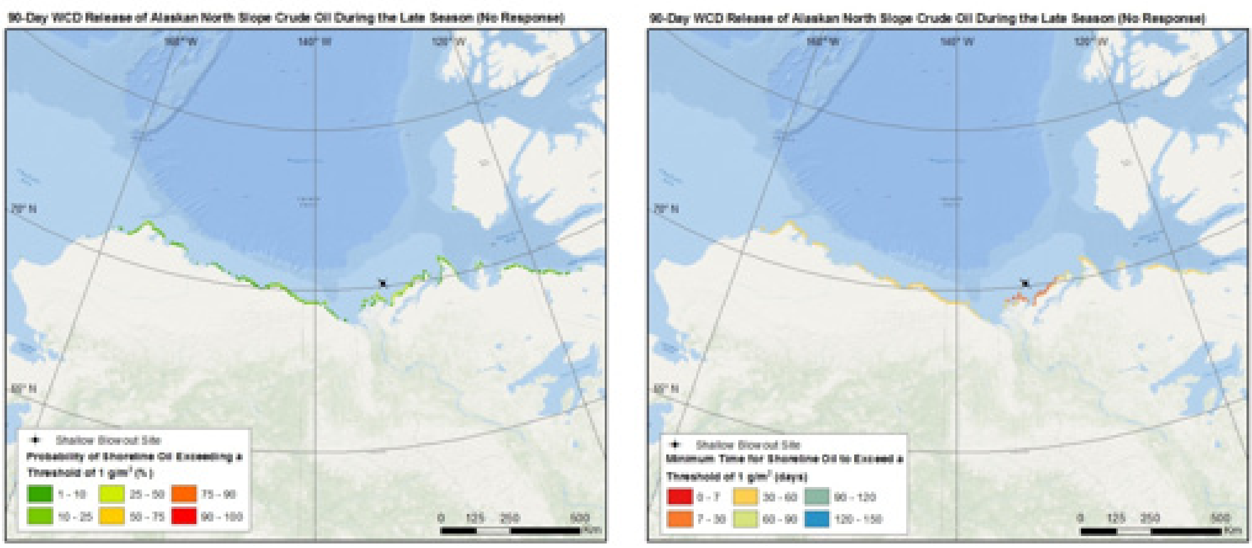


Figure 10. Shoreline oiling probabilities and minimum travel times for shoreline oil ≥1 g/m^2. This threshold represents an oil amount that would appear as a dull brown colour and could affect socioeconomic resources (i.e. need for shoreline cleanup) (French McCay et al. (2011). (Source: Gearon et al., 2014).

Figure 11 below shows shoreline oiling probabilities and minimum travel times with a higher threshold: ≥100 g/m². Due to the higher threshold used the map actually shows thicker oil that affects organisms in the water as well as shoreline fauna (e.g., this type of oil could coat and smother sea birds) more so than the thinner sheen represented in the lower threshold map in Figure 10.

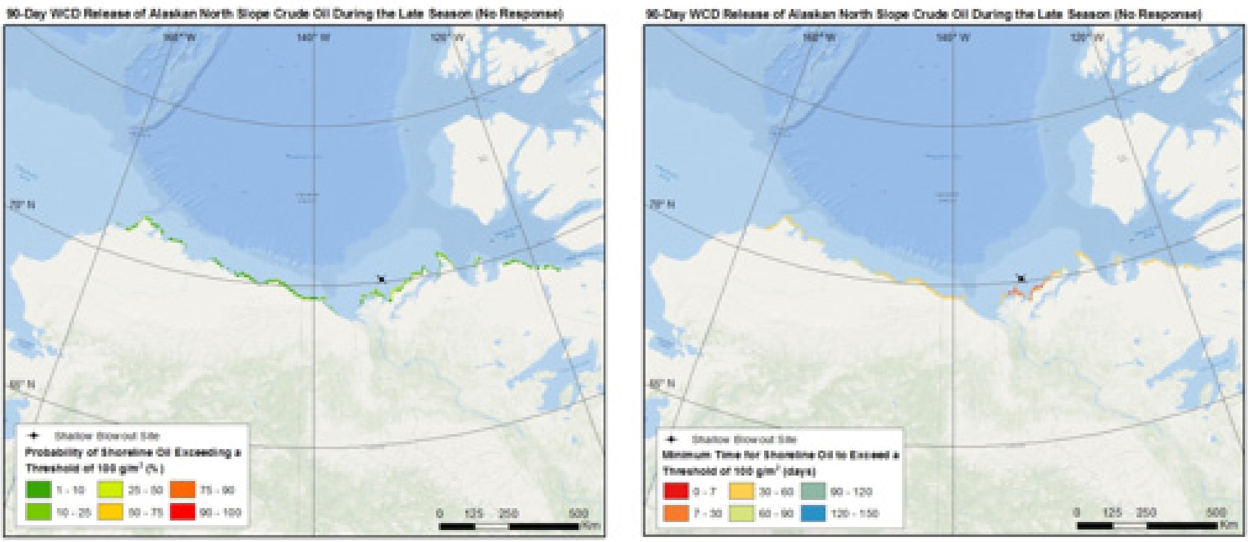


Figure 11. Shoreline oiling probabilities and minimum travel times for shoreline oil ≥100 g/m². (Source: Gearon et al., 2014).

Stochastic Map Showing Probability of Subsurface Contamination and Minimum Travel Times for Oil in the Water Column

Oil released at the subsurface shallow spill site surfaced very quickly. Subsurface contamination was primarily from surface oil entraining (entering the water column) from wind stress as it travelled with the surface currents. The subsurface stochastic map in Figure 12 below mirrors the surface oiling (Figure 8) pattern's movement primarily to the west but does not travel as far.

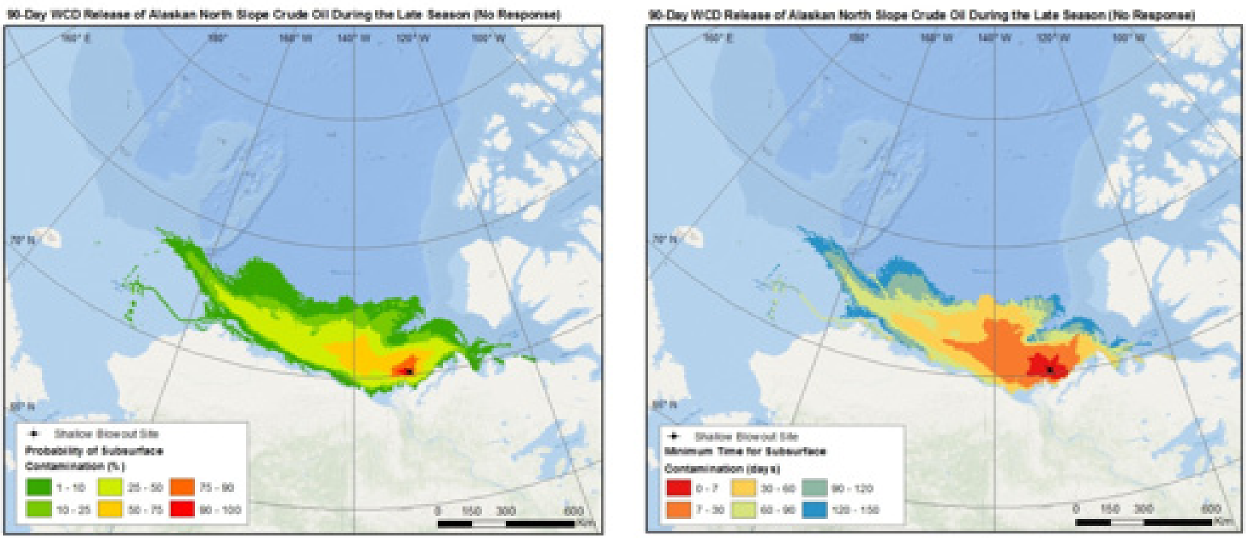


Figure 12. Subsurface contamination probabilities and minimum travel times for total oil in the water column. (Source: Gearon et al., 2014).

Representative Individual Trajectory Results

The results of the individual simulations provide a time history of oil weathering over the duration of the spill (mass balance), expressed as the percentage of spilled oil on the water surface, on the shoreline, evaporated, entrained in the water column, and decayed. In addition, times series snapshots of the individual trajectories showing concentration of floating surface oil, shoreline oil, and the concentration of total hydrocarbons in the water column are provided.

Individual trajectories that were identified as producing the highest degree of surface area and shoreline oiled, or water column contamination were selected from the stochastic ensemble of results (the 95th percentile). An individual trajectory simulation was performed for each 95th percentile trajectory for degree of surface and shoreline oiling, and water column contamination. Again, it is important to note that the individual trajectory simulations provided estimates of the oil's fate and transport for a specific set of environmental conditions, which is why each individual trajectory result has a "start date" in the caption. Historical data on the Beaufort Sea conditions such as wind, current and ice were taken from a 5 year period (2008-2013). The start date, selected at random from a relatively long term window, is the day (from within the 5 year period) on which each individual trajectory started when the oil spill simulation was run through SIMAP.

Individual Trajectory Mass Balance Chart Showing 95th Percentile Surface Oiling

Figure 13 is a mass balance chart that shows a high volume of oil from this shallow well blowout scenario could decay and enter the atmosphere as time goes on. NOTE: For all oils and scenarios modelled, assumed decay rates were based on those applied to the Alaska province of the CERCLA Type A Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME) (French et al., 1996). Degradation may occur as the result of photolysis, which is a chemical process energized by ultraviolet light from the sun, and by biological breakdown, termed "biodegradation". Generally speaking, little reliable data exists on the true decay rate of oil hydrocarbons in the ocean. Several factors can affect decay including temperature and chemical composition. Overall, by the end of the simulations, decay represented a relatively high percentage of the oil, and in some cases accounted for up to 67% of the oil in the mass balance. However, the rates used are relatively low compared to some literature estimates, available for lower molecular weight compounds.

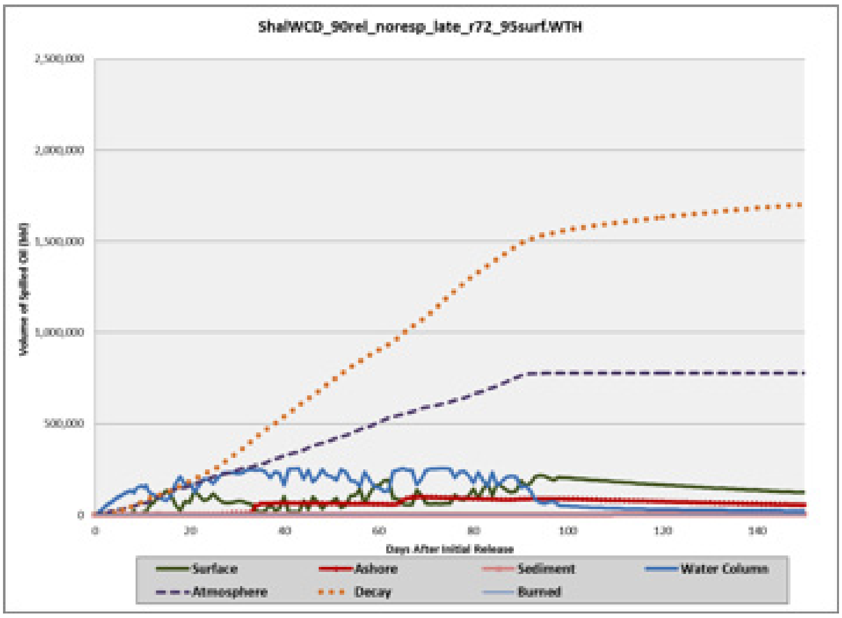


Figure 13. Distribution and weathering of oil over time as illustrated using a mass balance chart. Start date: 8/6/2012. (Source: Gearon et al., 2014).

Individual Trajectory Time Series Maps Showing 95th Percentile Surface Oiling

Figure 14 below consists of times series maps that show the footprint of floating surface oil concentration (g/m²), at various times during the oil spill. The maps are valuable in that they not only show the footprint of the oil spill over time, they also show the ice conditions as they develop. Figure 14 below shows that by day 150 both sea ice and landfast ice have formed and the oil has become trapped in the ice.

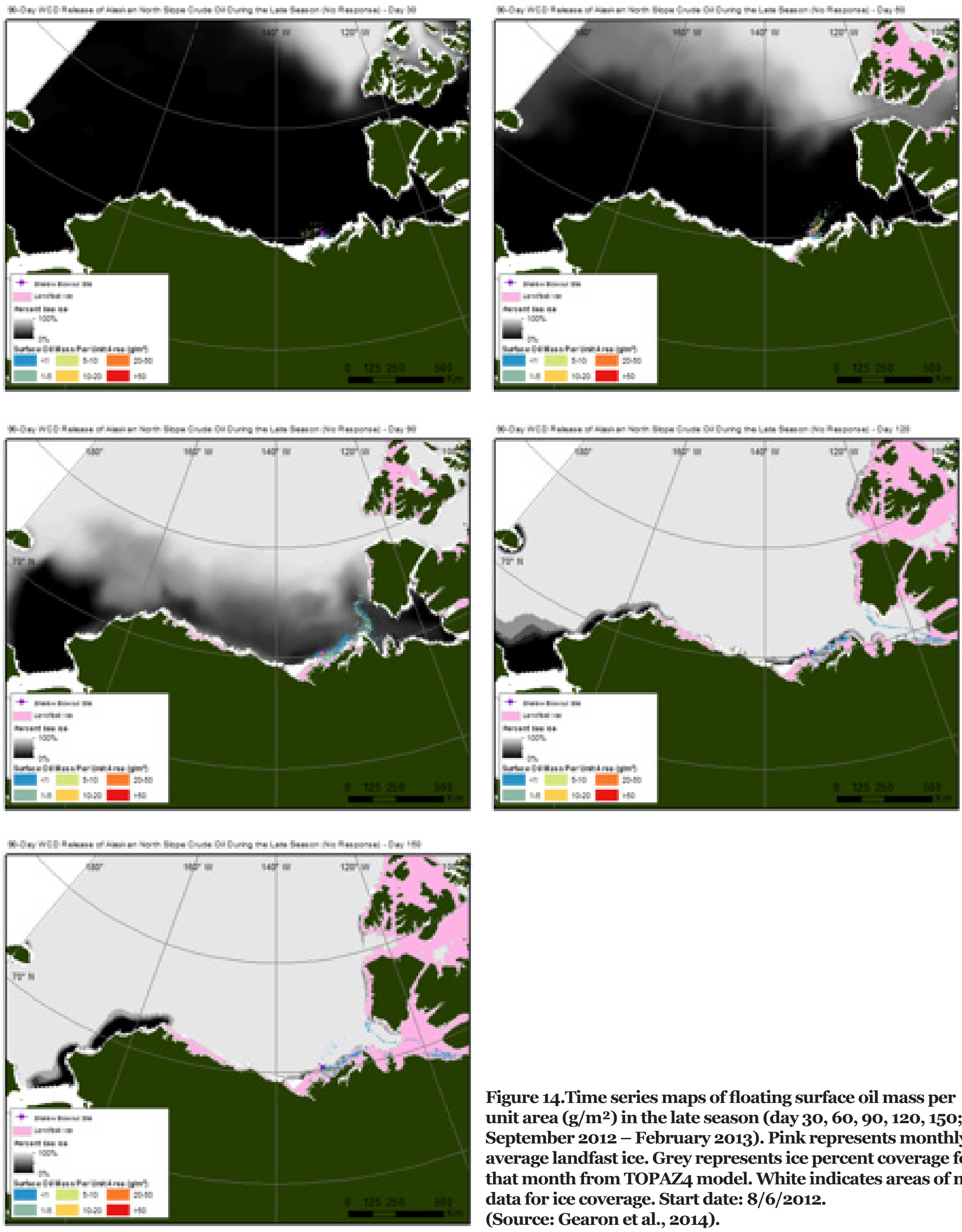


Figure 14.Time series maps of floating surface oil mass per unit area (g/m²) in the late season (day 30, 60, 90, 120, 150; September 2012 – February 2013). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start date: 8/6/2012. (Source: Gearon et al., 2014).

Individual Trajectory Mass Balance Chart Showing 95th Percentile Shoreline Oiling

Figure 14 below consists of times series maps that show the footprint of floating surface oil concentration (g/m²), at various times during the oil spill. The maps are valuable in that they not only show the footprint of the oil spill over time, they also show the ice conditions as they develop. Figure 14 below shows that by day 150 both sea ice and landfast ice have formed and the oil has become trapped in the ice.

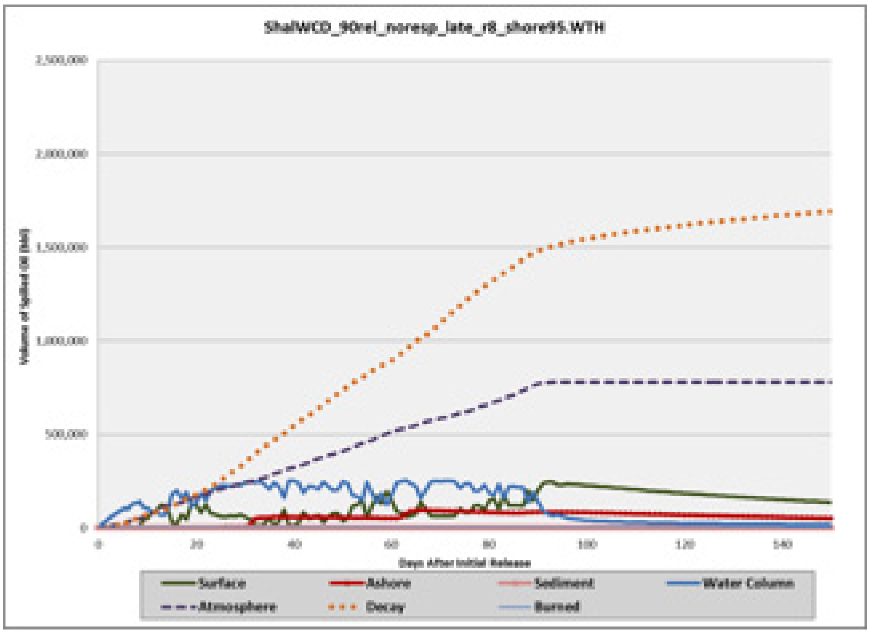


Figure 15. Distribution and weathering of oil over time as illustrated using a mass balance chart . Start date: 8/8/2012. (Source: Gearon et al., 2014).

Individual Trajectory Showing 95th Percentile Shoreline Oiling

This Shoreline Effects Table explains how many kilometres of shoreline could become covered in oil after the WCD shallow well blowout scenario was run and what type of habitat was affected.

Shore Type	Shore Length Oiled (km)
	> 1 micrometer
Seaward Gravel Beach	534.3
Seaward Sand Beach	105.9
Seaward Fringing Mud Flat	201.6
Seaward Fringing Wetland	15.1
Total Shoreline	**856.9**

Figure 16 below is a time series map showing oil that has reached the shore by day 150 of the oil spill and has encountered landfast ice that has formed on the shoreline (represented in pink). The landfast ice on the shore has trapped oil and kept it localized around the spill site.

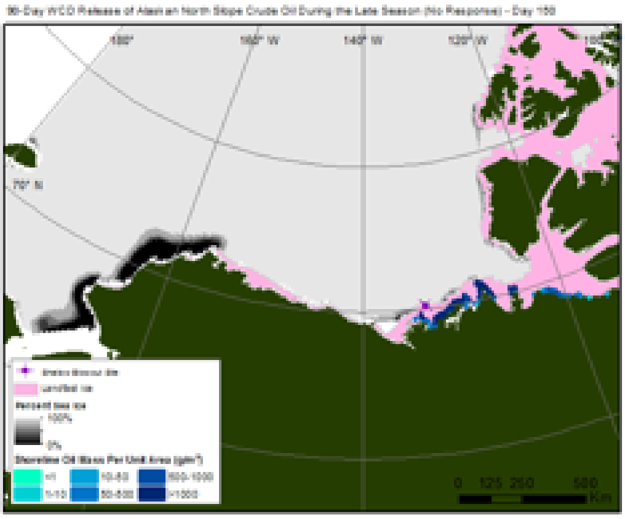


Figure 16. Map of overall effects to shorelines as mass of oil deposited on shore per unit of area (g/m²) in the late season (day 150 – December 2012). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start date: 8/8/2012. (Source: Gearon et al., 2014).

Similar to sea ice, landfast ice begins to build from the coast in October, mainly in areas of Mackenzie Bay and along the North Slope up to Point Barrow. Landfast ice growth increased throughout the fall and winter months, peaking in extent from the coastline in March, and begins to recede in May. The modeling shows that late season oil spills resulted in lower shoreline oiling due to landfast ice build-up into the winter months. Oil coming in contact with the landfast ice edge became trapped in the ice. As the ice built over the months and extended out from shore, new oil encountering the newly established ice edge became trapped. Oil from previous months still appeared trapped at the previous ice edge.

Individual Trajectory Mass Balance Chart Showing 95th Percentile Water Column Contamination

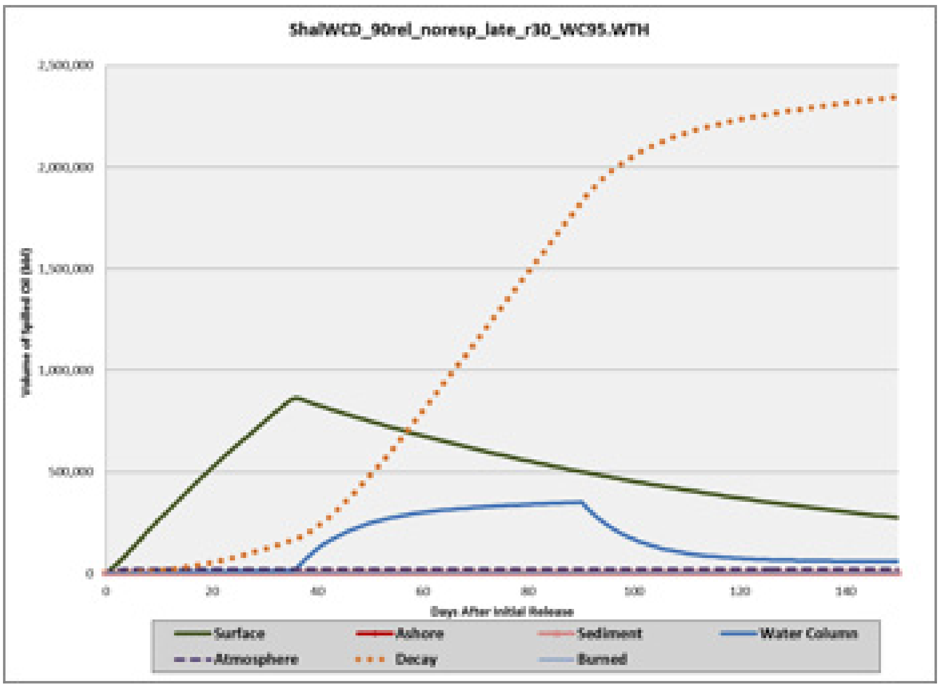
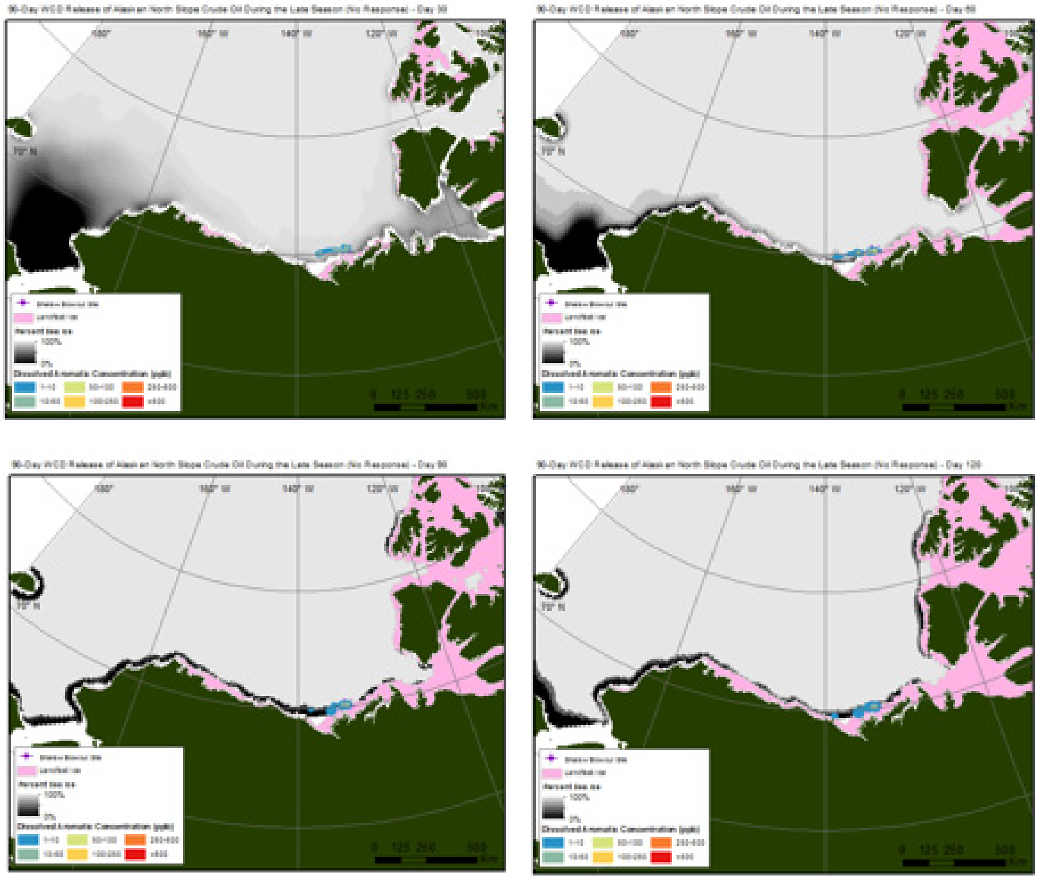


Figure 17. Distribution and weathering of oil over time as illustrated using a mass balance chart. Start date: 10/26/2008. (Source: Gearon et al., 2014).

Water Column Contamination Time Series Maps: The maps in figure 18 show the maximum water column concentration of aromatics (the most toxic portion of the oil that can dissolve into the water column and have the greatest effect on flora and fauna) in parts per billion (ppb)--parts per billion represent the mass of a chemical or contaminate per volume of water -- at various times during the individual spill simulation. Unlike the stochastic water column contamination results (showing total or all components of oil), only the resulting dissolved aromatic concentrations are shown in these maps. Persistent water contamination by dissolved aromatics may result from long subsurface blowout releases (such as this 90 day subsurface release), but this contamination would be relatively localized around the spill site area as oil was trapped in and under landfast ice and not transported with subsurface currents.

Individual Trajectory Time Series Maps for 95th Percentile Water Column Contamination



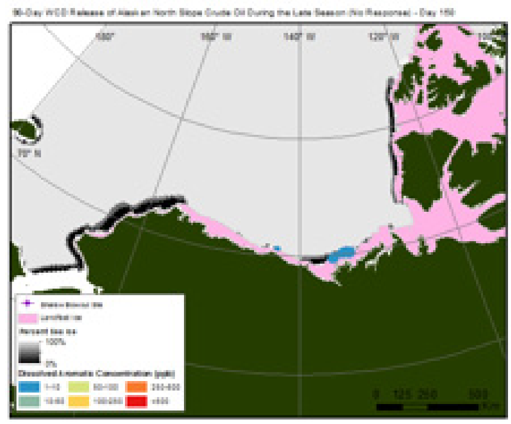


Figure 18. Time series maps of spill dissolved aromatics ≥1 ppb in the late season (day 30, 60, 90, 120, 150; November 2008 - March 2009). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start date: 10/26/2008. (Source: Gearon et al., 2014).

SECTION 2: 12 Oil Spill Scenarios

Section 2 looks at 12 of the 22 oil spill models and highlights the pertinent results from each different type oil spill scenario. Both stochastic maps and individual trajectory maps and graphs representing the 95th percentile highest oiling probability are presented to help the reader visualize potential oil spill scenarios.

Eastern Shipping Analysis

The eastern shipping release site was located in the Amundsen Gulf, approximately 45 km north of Baillie Island, along a known shipping route (Figure 19). The location for the Eastern Shipping Release scenario was selected because it is predicted that this area will see increased ship traffic in the future with several bulk carrier ships transporting heavy fuel. There are also many other vessels in the area e.g., support and supply ships and other passing vessels containing diesel fuel.

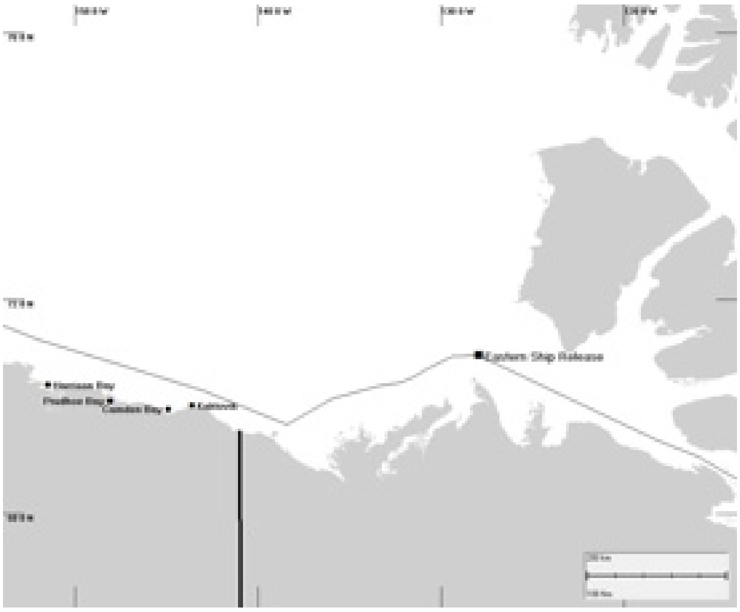


Figure 19. Location of the eastern shipping release site in the Amundsen Gulf, along the shipping route (thin black line). Thick black line represents U.S./ Canadian border. (Source: Gearon et al., 2014).

Two oil spill scenarios were simulated in the eastern shipping release site:

- An instantaneous surface release of intermediate fuel oil (IFO), the bunker fuel commonly used in large ships from a bulk ore carrier, from a shipping accident. The release time frame analyzed was the active shipping months (July-October), when the route is relatively ice free. The total volume was 21,000 bbl and the spill lasted for 0.25 days.
- An instantaneous surface release of diesel fuel from a resupply tanker barge. The release time frame analyzed was the active shipping months (July-October), when the route is relatively ice free. The total volume was 5,400 bbl and the spill lasted for 0.25 days.

The maps and graphs on the next page compare the probability for surface oiling, shoreline oiling and for oil entering the water column for these two simulated spills.

Stochastic Maps Showing Probability of Surface Oiling

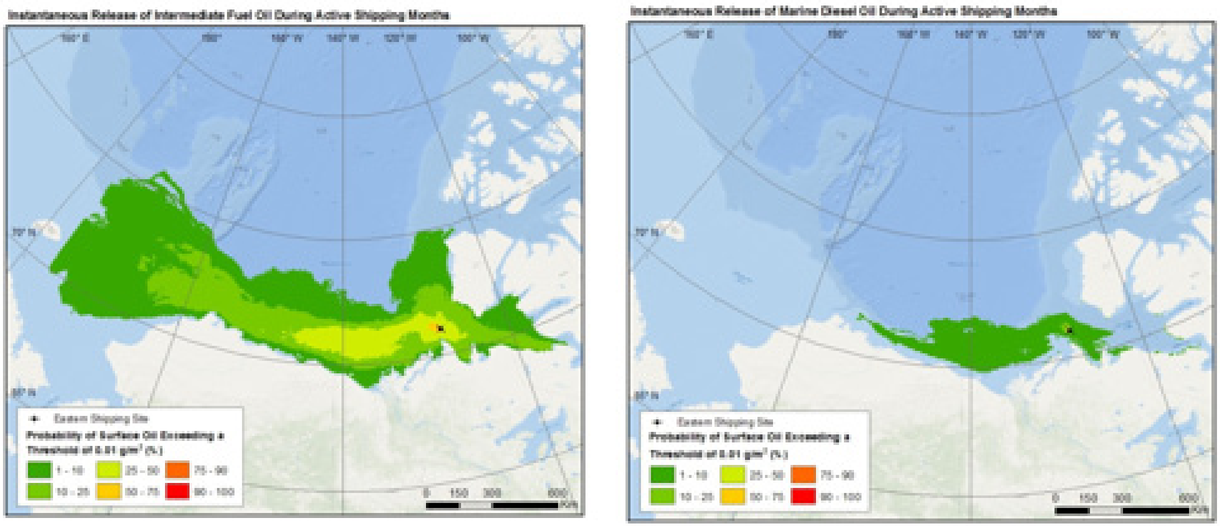


Figure 20. Two stochastic maps side-by-side showing water surface oiling probabilities. The left hand map shows the footprint of the IFO 380 spill and the map on the right shows the surface footprint of the smaller diesel spill. (Source: Gearon et al., 2014).

The IFO spill stochastic probability footprint is much larger, and extends further to the west, as compared to the diesel in this analysis. IFO is a very heavy viscous product that typically does not readily entrain into the water column, doing so only under highly turbulent conditions. In open water IFO surface slicks may travel long distances. Surface and shoreline oiling of the diesel cases was less extensive due to the overall lower volume released, the high evaporation associated with light fuel oils, and the tendency of diesel fuel to enter the water column. Both stochastic cases exhibited some less common eastward trajectories resulting in surface and shoreline oiling in the channels of the Canadian Archipelago.

Individual Trajectory Time Series Maps Showing 95th Percentile Surface Oiling

When IFO trajectories encounter ice, such as those occurring in the later months of the active shipping season, its travel time could get extended. As the map below illustrates, this spill scenario started when the water was relatively ice free but by day 90, the oil has encountered ice.

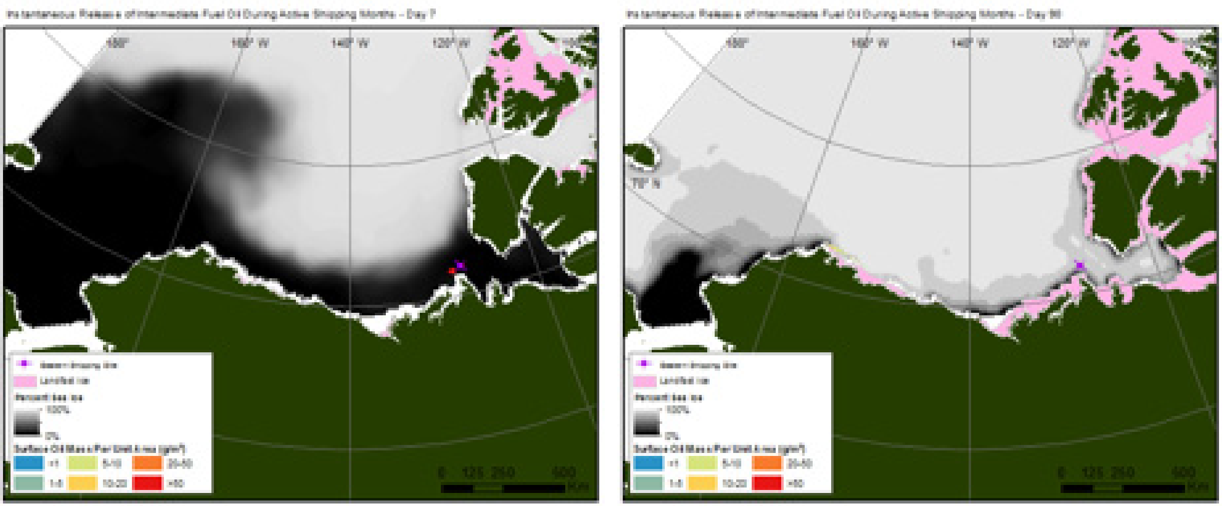


Figure 21. Time series maps of spill floating surface oil mass per unit area (g/m²) (day 7, 90; September – December 2009). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start Date: 9/28/2009. (Source: Gearon et al., 2014).

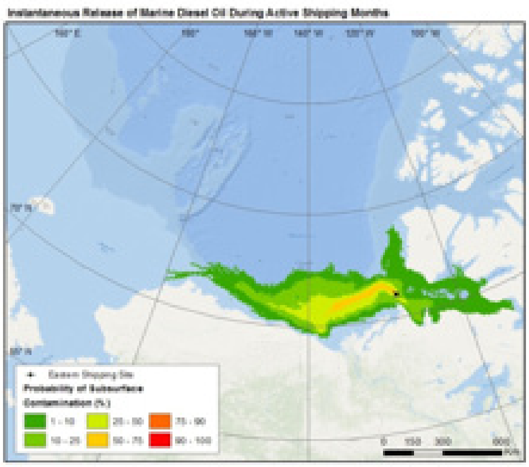
Individual Trajectory Shoreline Effect Table Showing 95th Percentile Shoreline Oiling

Shore Type	Shore Length Oiled (km)
	> 1 micrometer
Seaward Gravel Beach	418.4
Total Shoreline	**418.4**

Table 2. Shoreline length oiled (km) by habitat type, for the threshold >1 g/m². Start Date: 8/26/2012. (Source: Gearon et al., 2014).

Subsurface Contamination

Diesel will entrain into the water column much easier than a heavier oil product such as IFO. IFO only enters the water column under highly turbulent conditions, therefore water column contamination results are only presented for the diesel scenario.



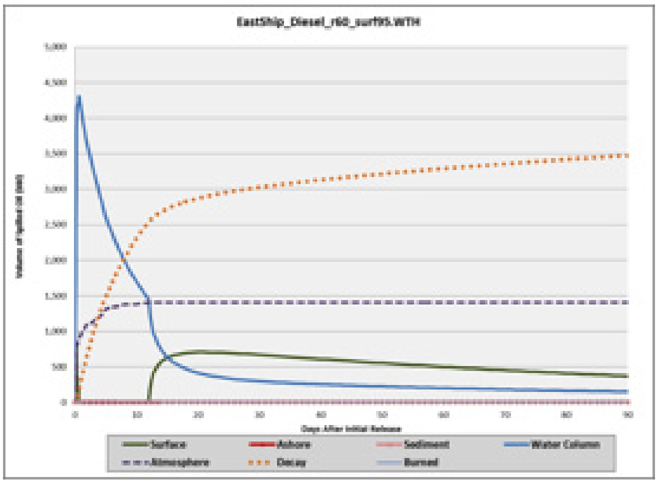


Figure 22. The map on the left is a stochastic map showing the subsurface contamination probabilities for total oil in the water column. The individual trajectory model mass balance chart for 95th percentile water column contamination illustrates that diesel fuel enters the water column almost immediately, which can have negative effects on organisms in the water. Start date: 10/17/2011. (Source: Gearon et al., 2014).

Trans-boundary Analysis

The trans-boundary analysis spill locations were on the Beaufort shelf near the U.S./Canadian border (Figure 23). The release sites ranged in depth from approximately 30m - 70 m. These sites were selected based on known shipping routes, and a proposed subsea oil pipeline route following the 60 m bathymetric contour. Two release regions were investigated and were situated on either side of the border: Canadian Beaufort coast from Herschel Island westward to the U.S./Canadian border, and U.S. Beaufort Coast from Kaktovik to Prudhoe Bay eastward to the U.S./Canadian border.

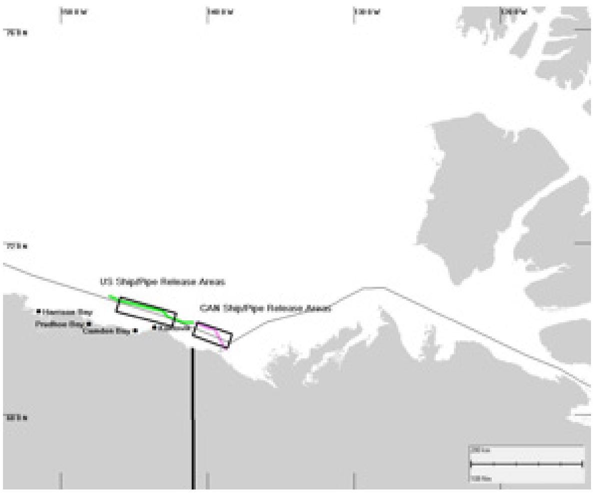


Figure 23. Location of the trans-boundary release sites near the U.S./Canadian border (thick black line). Shipping route is indicated by thin black line. Spill release sites associated with shipping incidents were randomly distributed inside each of the black rectangles. Rectangle to the east of the border represented the release region along the Canadian Beaufort coast, and the rectangle to the west of the border represented the release region along the U.S. Beaufort coast. Release sites for spills originating from the pipeline occurred along the coloured lines; pink for the Canadian Beaufort coast, and green for the U.S. Beaufort coast. (Source: Gearon et al., 2014).

Two oil spill scenarios are presented for the trans-boundary analysis in this section: an instantaneous surface release originating from a shipping accident of an oil tanker on the Canadian side and a subsea pipeline leak originating on the Canadian side.

The first spill scenario discussed here is a surface crude oil spill from a tanker located along a shipping route in the Canadian Beaufort coast (Herschel Island to US/Canada border). The spill in this scenario lasts half of a day and releases at total volume of 533,000 bbl. This is a WCD, a significant tanker crude spill volume, which is about two times the size of the Exxon Valdez oil spill, albeit with a different oil type. It should be noted that typical tankers do not hold that much oil and that there will also be smaller tankers moving crude oil up the coast in the area. However, the specifications for the large ice class vessel used for the study were based on those proposed by Imperial Oil for future use at the Pokak lease site (IORVL, 2013). The release time frame is January – December, as Ice class tankers can operate year-round).

Stochastic Map Showing Probability of Surface Oiling

The total volume of oil released in this oil spill scenario is large and is released quickly, therefore the probable oil footprint in the stochastic map is considerable. The trans-boundary analysis confirmed that most oil from spills originating from around the US/Canadian border would travel westward and impact the Alaskan coastline. Figure 24 shows a high surface oiling concentration and large surface slick that travels far away from the spill site.

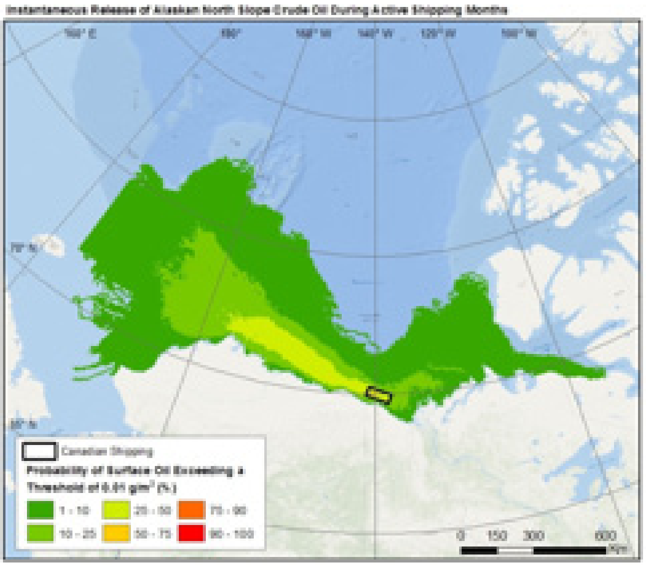


Figure 24. Water surface oiling probabilities for floating oil ≥ 0.01 g/m². Note: Oil between 0.01 and 1 g/m² covering much of the affected area, would appear as thin sheen. Oil slicks would be scattered in pockets under ice (for releases occurring during the winter the months), or if weathered enough in the warmer months as scattered tarballs -- when oil is exposed to wind, ocean currents and other environmental conditions some of it dissolves and some of it forms into small, sticky droplets called "tarballs". (Source: Gearon et al., 2014).

Stochastic Map Showing Probability of Surface Oiling

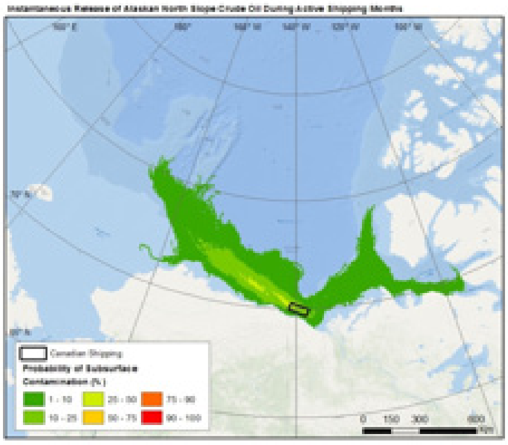
The model results for the crude oil spill scenario from the Canadian release site could result in oil coming ashore at areas just west of the border all the way east to the Mackenzie River delta. The 95th percentile shoreline oiling probability results for crude spills from the Canadian release region had a consistent coverage along coastlines.

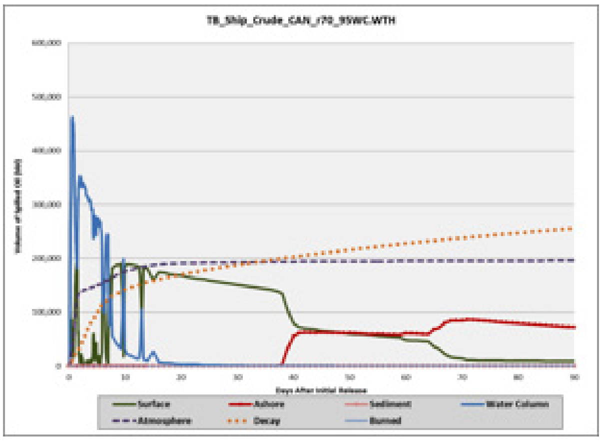
Shore Type	Shore Length Oiled (km)
	> 1 micrometer
Seaward Gravel Beach	267.2
Seaward Sand Beach	146.2
Seaward Fringing Mud Flat	95.8
Seaward Intertidal Macroalgal Bed	5.0
Total Shoreline	**514.2**

Table 3. Shoreline length oiled (km) by habitat type for the threshold >1 g/m². Start date: 5/17/2012.

Water Column Contamination

Subsurface stochastic output mirrored surface oiling patterns (movement primarily to the west), although extent was drastically reduced. Subsurface contamination of crude oil components due to surface entrainment was expected given the large volume of crude oil released in these spills (533,000 bbl).





Pipeline Leak

The second type of trans-boundary oil spill highlighted here is a spill from an offshore pipeline leak from a pipeline route along the Canadian Beaufort Coast, starting from Herschel Island moving toward the US/Canada border. This was a shallow, subsurface (60 m depth) release of crude oil with a spill rate of 4,800 bbl per day lasting 6 days (this is based on how long it typically takes to cut off the section of pipe leaking). The total volume of oil spilled was 28,800 (this is a MMPD) and the release timeframe was May-November. The oil type released was ANS crude oil.

Figure 25. A stochastic map on the left that shows subsurface contamination probabilities for total oil in the water column. A mass balance chart (start date: 7/5/2012) on the right for the 95th percentile trajectory for water column contamination shows that a high amount of oil is entrained in the water column very quickly. Wind events entrain the floating oil, which can subsequently resurface in calm periods. (Source: Gearon et al., 2014).

Stochastic Map Showing the Probability of Surface Oiling

The surface stochastic map for the offshore pipeline oil spill is similar to tanker trans-boundary release (although much smaller total volume) as it also shows a large area where surface oil could occur, depending on winds and currents to the west. This result is due to the fact that the scenario had a 6 day release period and because this was a subsurface release.

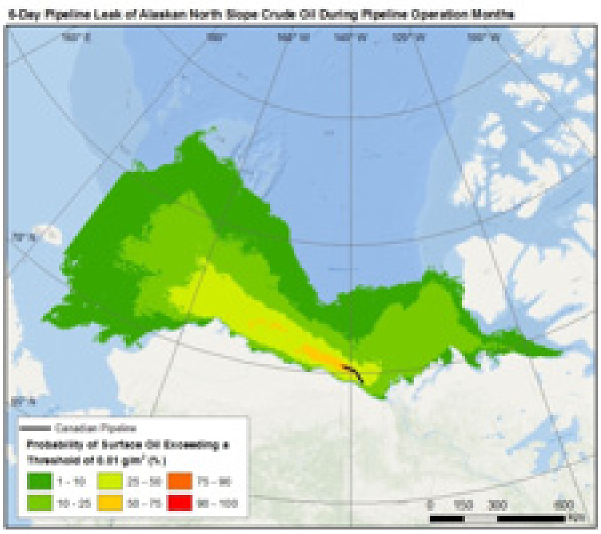


Figure 26. Water surface oiling probabilities floating oil ≥ 0.01 g/m². (Source: Gearon et al., 2014).

Individual Trajectory Showing 95th percentile Shoreline Oiling

Over 500 kilometres of shoreline could potentially be oiled, however with the time frame of this spill (May-November) ice build up could affect how much oil reaches shore because some of the oil could become trapped in the ice.

Table 4: Shoreline length oiled (km) by habitat type for the threshold >1 g/m^2 . Start date: 7/27/2008. (Source: Gearon et al., 2014).

Shore Type	Shore Length Oiled (km)
	> 1 micrometer
Seaward Rocky Shore	5.0
Seaward Gravel Beach	236.9
Seaward Sand Beach	161.3
Seaward Fringing Mud Flat	156.3
Seaward Fringing Wetland	5.0
Seaward Intertidal Macroalgal Bed	35.3
Shoreline Total	**599.8**

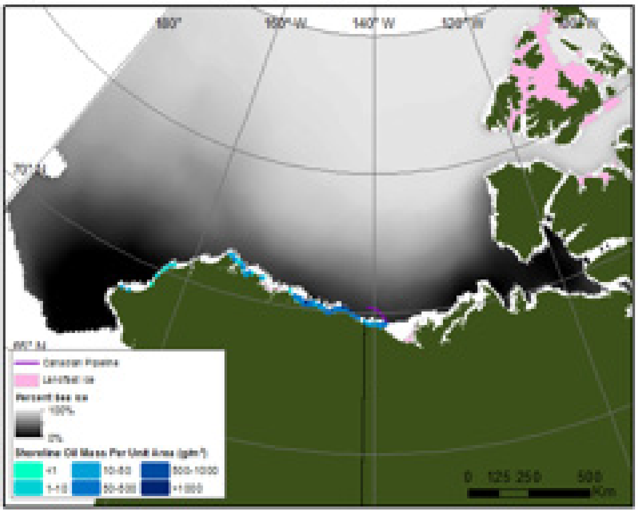


Figure 27. Map of overall impact to shorelines as mass of oil deposited on shore per unit of area (g/m^2) (day 90 – October 2008). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. The table shows the shoreline length oiled (km) by habitat type for the threshold >1 g/m^2. Start Date: 7/27/2008. (Source: Gearon et al., 2014).

Individual Trajectory Mass Balance Chart Showing 95th Percentile Water Column Contamination

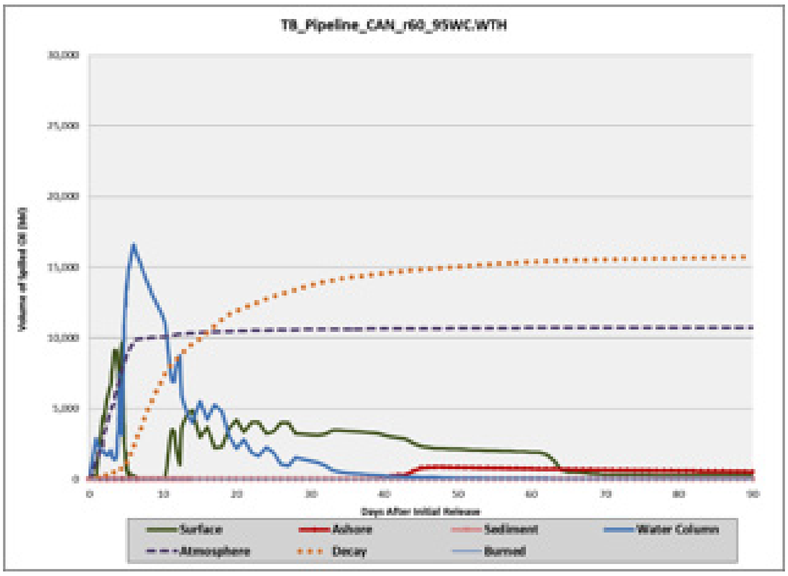


Figure 28. Distribution and weathering of oil over time as illustrated using a mass balance chart. This chart shows that the oil spill scenario in open water is affected by strong wind events, which entrain the floating oil in the water column. Start Date: 8/29/2010. (Source: Gearon et al., 2014).

Shallow Blowout Analysis

The shallow blowout release site was located in the Amauligak lease area on the Beaufort shelf (Figure 29).

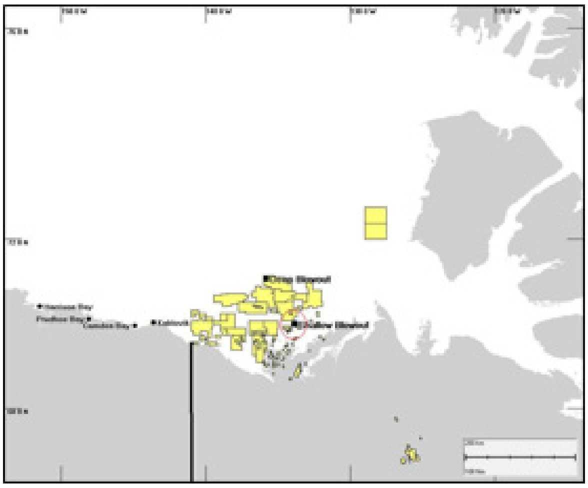


Figure 29. Location of the shallow blowout release site (circled in red), in the Amauligak lease area on the Beaufort shelf. Yellow polygons outline all lease areas in Canadian Beaufort. Thick black line represents U.S./Canadian border. (Source: Gearon et al., 2014).

The release type simulated was a shallow subsurface well blowout. The release time frames analyzed were "Early Operating Season (June-July)" and "Late Operating Season (August-October)". This section looks at four of the oil spill scenarios:

The first two include:

- A late season (August-October) shallow subsurface WCD crude oil blowout that lasts 90 days and spills a total volume of 2,700,000bbl of oil. No response is taken in this scenario (this scenario is explained in-depth in section 1).
- The same scenario as above (late season, WCD, 2,700,000 bbl of oil, 90 day duration) but in this instance a surface response is applied.

Individual Trajectory Time Series Maps for 95th PercentileSurface Oiling (No Response)

The surface oil footprint of the late season WCD spill scenario had higher probabilities of surface oiling further from the spill site with a probable surface slick extending up to approximately 1000 km to the west. Landfast ice extent intersected with the shallow blowout spill site in December and into the winter months. Some late season spills that started in October would have been releasing when landfast ice coverage above the spill site was growing. This trapped oil and kept it localized around the spill site.

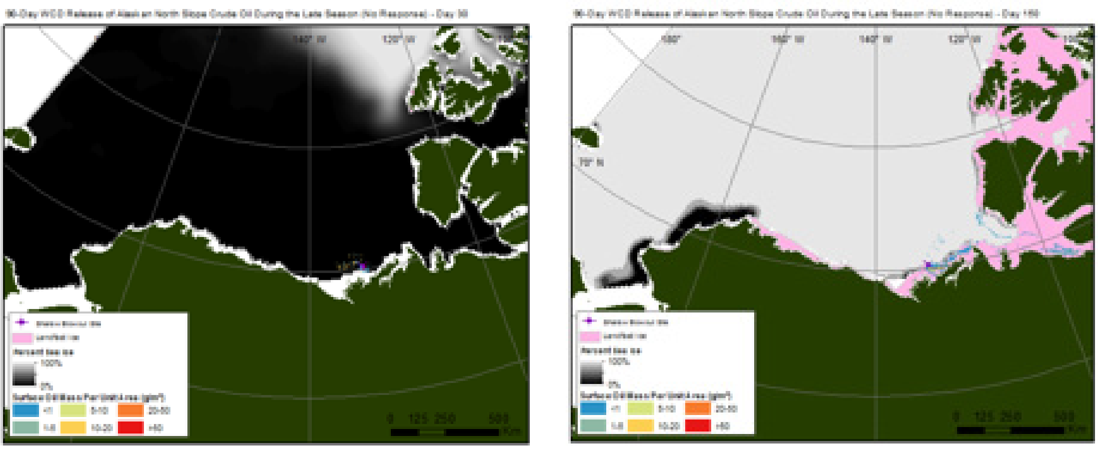


Figure 30. Time series maps of spill floating surface oil mass per unit area (g/m²) in the late season (day 30, and day 150; September 2012 – February 2013). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. (Source: Gearon et al., 2014).

Individual Trajectory Time Series Maps for 95th Percentile Surface Oiling (Response)

Two different responses were considered: dispersant application and in situ burning. Surface response measures were only simulated for the 95th percentile individual trajectories for degree of surface and shoreline oiling from the base case or parent stochastic scenario. It should be noted that for the purposes of this study, it was assumed that the surface responses were 100% effective, which represents the "best case" scenario for this response application. The amount of oil removed by burning from the late season scenarios was low (16% of the mass released was removed) because there are fewer hours of daylight and less time to respond. A response becomes much more complicated in the late season when oil encounters sea ice or landfast ice.

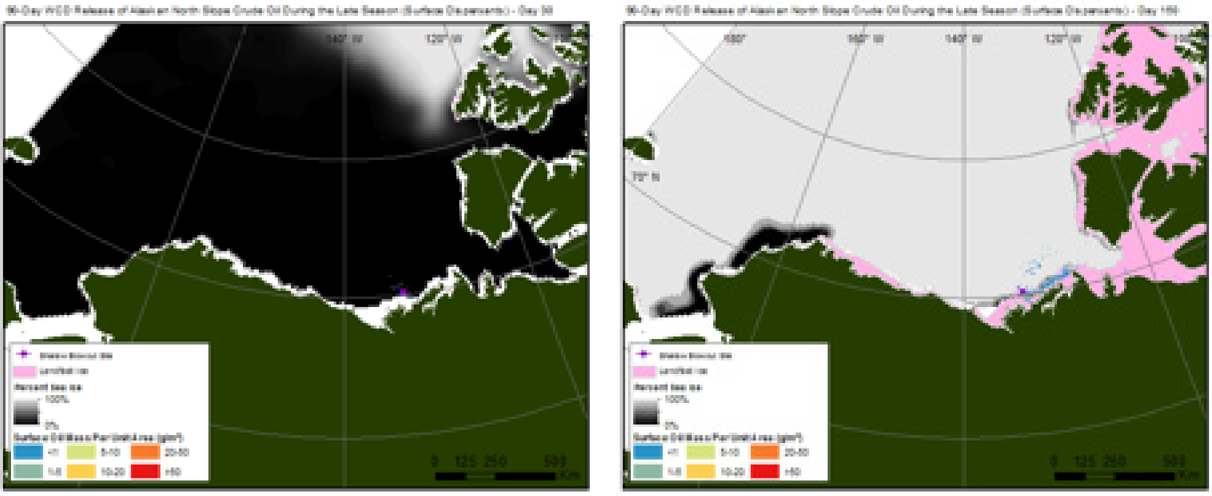


Figure 31. Time series maps of spill floating surface oil mass per unit area (g/m²) in the late season (day 30, and day 150; September 2012 – February 2013). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. (Source: Gearon et al., 2014).

Individual Trajectory Shoreline Effect Table for 95th Percentile Shoreline Oiling

Shoreline effects in the late season for the no response case was 857 km (>1 g/m²), whereas it was reduced to 272 km (>1 g/m²) for the response case.

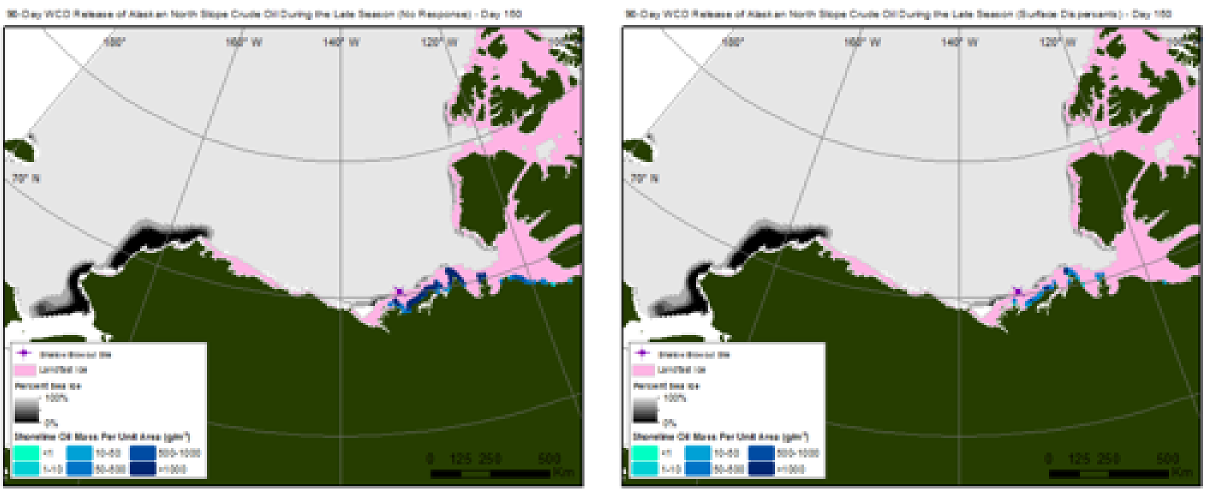


Figure 32. Map of overall impact to shorelines as mass of oil deposited on shore per unit of area (g/m²) in the late season (day 150 – December 2012). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start date: 8/8/2012 for both maps. (Source: Gearon et al., 2014).

Oil released at the subsurface shallow spill site surfaced very quickly. Subsurface contamination was primarily from surface oil entraining from wind stress as it travelled along with the surface currents, as oil originating from the subsurface release point quickly surfaced and formed a large oil slick. Subsurface stochastic output mirrored surface oiling patterns (movement primarily to the west), although extent was drastically reduced.

Individual trajectory 95th Percentile Water Column Contamination (No Response)

95th percentile dissolved aromatic concentrations for a late season WCD shallow well blowout primarily ranged between 1 and 100 ppb. The contamination was localized around the spill site because oil was becoming trapped in and under landfast ice as it formed.

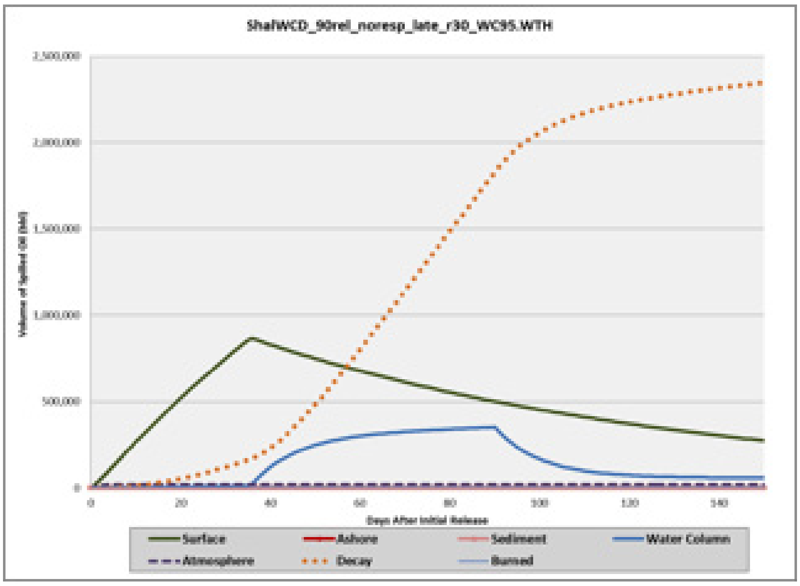


Figure 33. Distribution and weathering of oil over time as illustrated using a mass balance chart. Start date: 10/26/2008. Note that dark blue line represents water column in chart, while light blue line represents removal from burning. This scenario included no burning so the light blue line is not visible. Dissolved aromatic concentrations, as modelled in the individual 95th percentile runs for water column contamination, were observed in relatively close proximity to the spill site (within 250 km) with highest concentration nearest to spill site. General movement of the contamination was to the west, and it was present throughout each scenario's release duration as fresh oil was entering into the system. (Source: Gearon et al., 2014).

Shallow well subsurface blowout models for a 30-day early season spill and a 60-day late season spill

The early season (June-July) shallow subsurface blowout model analyses a spill of crude oil lasting 30 days. The total volume of oil spilled is 90,000 bbl. (this is a MMPD spill – it is assumed that the volume and duration of the release would be reduced because it would likely take less time to effectively cap the well in the early season) with 3,000 bbl spilled per day.

The late season spill model has the same spill rate (3,000 bbl./day) but lasts 60 days, as it is assumed that time it would take to shut off the well would be extended in the late season as ice builds and weather conditions worsen, therefore resulting in a total volume of 180,000 bbl. released. While much smaller than the WCD scenarios, these are still sizable blowout scenarios and comparable to those experienced worldwide as they are the more probable event types.

Stochastic Maps Showing Surface Oiling Probabilities

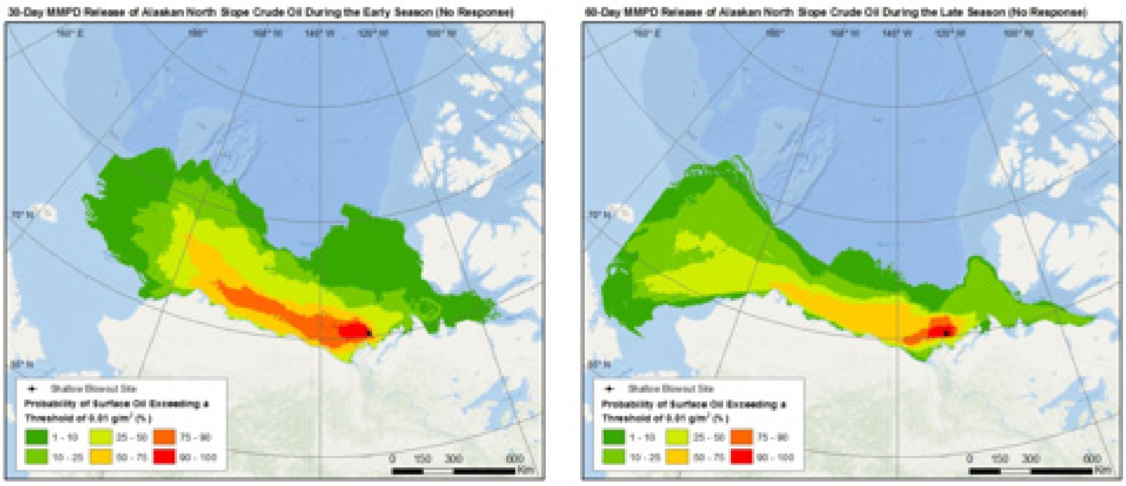


Figure 34 shows two stochastic maps. The map to the left shows water surface oiling probabilities for the early season 30 shallow subsurface blowout and the map to the right show water surface oiling probabilities for the 60 day late season shallow subsurface blowout (water surface oiling probabilities for floating oil ≥ 0.01 g/m².) (Source: Gearon et al., 2014).

Modeling results suggested that MMPD blowouts originating from the shallow spill site located in the Amauligak lease area, early in the operating season would result in extensive surface oiling to the west, as far as Point Barrow, Alaska. Late season stochastic surface oil footprints from the shallow blowout were narrower, or did not extend northward as much as the early season blowout scenarios. This reduction in overall footprint was due to limited spreading in the late season runs as oil encountered higher ice coverage.

Individual Trajectory Time Series Maps Showing 95th Percentile Surface Oiling

This oil spill scenario started in the early season when the water is relatively ice free.

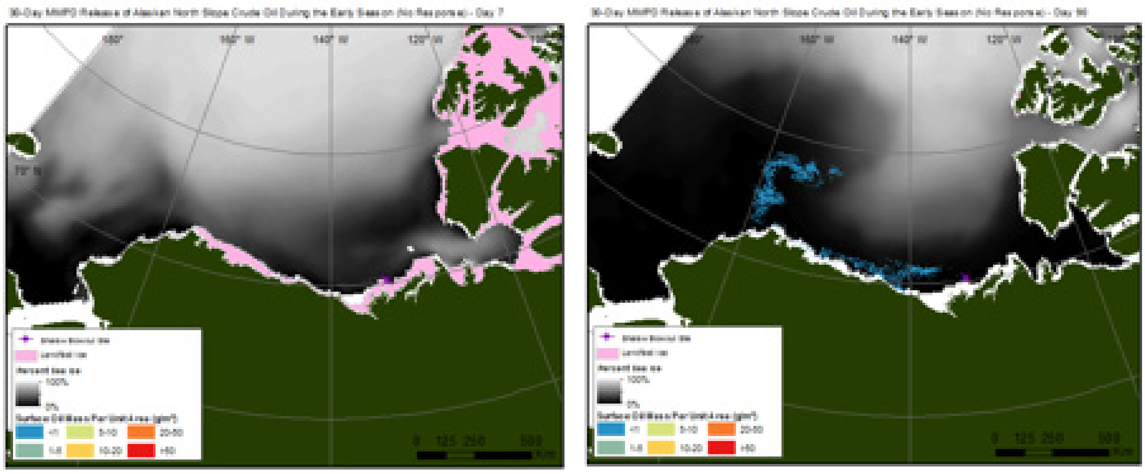


Figure 35. Time series maps of spill floating surface oil mass per unit area (g/m²) in the early season (day 7 and 90; June – September 2009). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start date: 6/23/2009. (Source: Gearon et al., 2014).

As compared to the maps of the early season 30 day release above, Figure 36 below shows the late season 60 day release. Oil in the late season release is trapped in the sea ice and landfast ice by 120 days after the oil spill.

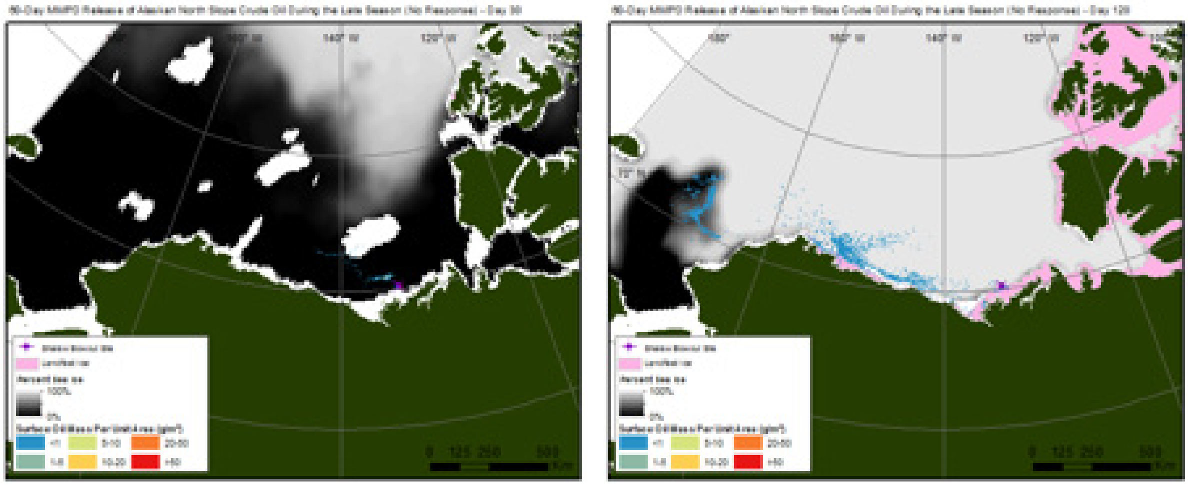


Figure 36. Time series maps of spill floating surface oil mass per unit area (g/m²) in the late season (day 30, 120; September – December 2010). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start date: 8/14/2010. (Source: Gearon et al., 2014).

Individual trajectory Shoreline Effect Tables Showing 95th Percentile Shoreline Oiling

Early season MMPD scenarios had higher probability of shoreline oiling as compared to the late season. This was attributed to landfast ice growth in the fall and winter months prohibiting landfall of oil. Early season shoreline probabilities were often in the 50-75% range south of the spill site reaching the Mackenzie River delta and to the west along the Canadian Beaufort coastline. The extent of shoreline oiling probabilities >1% was from Point Barrow, Alaska east to shorelines of the Amundsen Gulf, and also the southwest coast of Banks Island.

30 day early season

Shore Type	Shore Length Oiled (km)
	> 1 micrometer
Seaward Rocky Shore	60.5
Seaward Gravel Beach	499.1
Seaward Sand Beach	363.0
Seaward Fringing Mud Flat	322.6
Seaward Fringing Wetland	10.1
Seaward Intertidal Macroalgal Bed	105.9
Total Shoreline	**1,361.2**

60 day late season

Shore Type	Shore Length Oiled (km)
	> 1 micrometer
Seaward Gravel Beach	499.1
Seaward Sand Beach	352.9
Seaward Fringing Mud Flat	236.9
Seaward Fringing Wetland	15.1
Seaward Intertidal Macroalgal Bed	65.5
Total Shoreline	**1,169.5**

Table 5. Shoreline length oiled (km) by habitat type for the threshold ≥ 1 g/m². 30 day early season spill is to the left. Start date: 7/17/2008. 60 day late season spill is the right. Start date: 8/19/2008. (Source: Gearon et al., 2014).

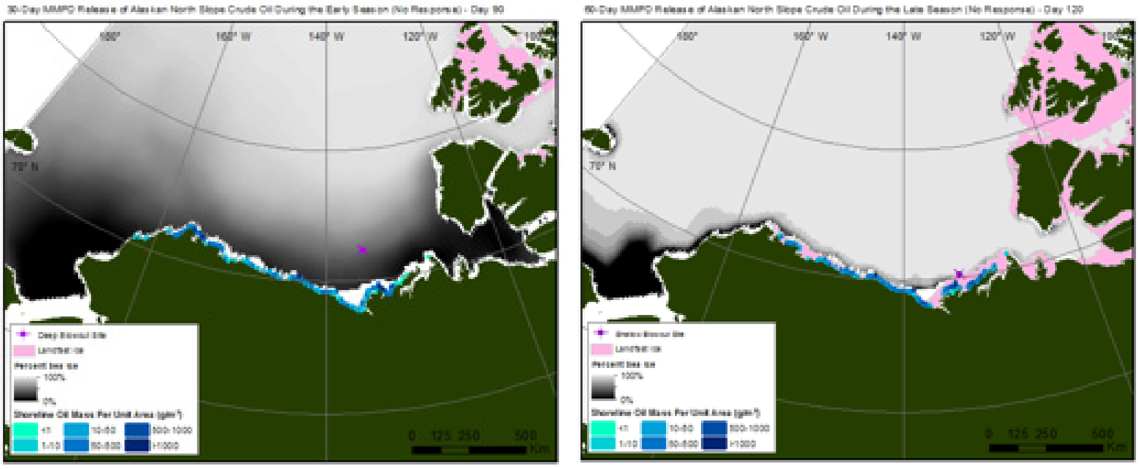


Figure 37. The map on the left side shows the impact to shoreline as mass of oil deposited on shore per unit of area (g/m²) (day 90 – October 2008) for the 30 day early season oil release. Start date: 7/17/2008. The map on the right shows the impact to the shoreline from the 60 day late season blowout (day 120 – December 2008). Start date: 8/19/2008. Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. (Source: Gearon et al., 2014).

Figure 37 above is a good visual representation of how oil can act in terms of shoreline oiling in an early season versus a late season oil spill. The 30 day release shows higher shoreline oiling while the 60 day release shows lower shoreline oiling because the oil is trapped in the landfast ice, which kept it from reaching the shore

Subsurface stochastic output mirrored surface oiling patterns (movement primarily to the west), although extent was much less.

Deep Blowout Analysis

As offshore oil development proceeds into deeper water, the possibility of an oil well blowout becomes more of a concern. The principal issues with a deep water blowout are that cleanup and containment for such a spill are extremely difficult (this is compounded by the fact that the Beaufort Sea is covered in ice for most of the year) and that subsurface oil may travel many kilometres in the water column.

The deep blowout release site was located in the deepest portion of what is referred to as the Pokak lease area on the Beaufort slope (Figure 38). The site was approximately 1,008 m deep. RPS ASA used its OILMAPDeep model to define the associated blowout plume and oil droplet size distribution for scenarios included in the analysis of deep subsurface blowouts. For the assumed OILMAPDeep model parameters, please see Appendix C of the full report (Gearon et al., 2014). This site was selected because it is deep and the Pokak lease area has been proposed for an exploratory drilling project. Deeper releases are more difficult to respond to and have more complex subsurface plume dynamics.

In order to evaluate potential accidental releases of oil and gas from a deepwater well blowout, RPS ASA developed OILMAPDeep. The OILMAPDeep blowout model is capable of evaluating spill response activities such as subsurface dispersant application. OILMAPDeep contains two sub-models:

- A plume model, which predicts the evolution of buoyant plume position, geometry, centreline rise velocity and oil and gas concentrations until either surfacing or reaching a terminal height at which point the plume is no longer buoyant and so is trapped. The plume dynamics transport released oil to the plume termination height, after which point the transport of the oil is dominated by the ambient environmental conditions.
- A droplet size model, which predicts the size and volume (mass) distribution of oil droplets resulting from the subsea plume.

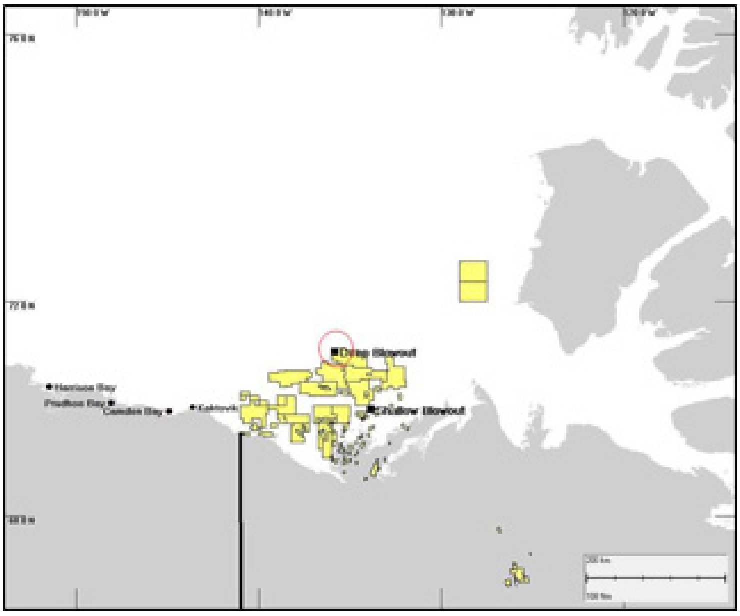


Figure 38. Location of the deep blowout release site (circled in red), in the deeper portion of the Pokak lease area on the Beaufort slope. Yellow polygons outline all lease areas in Canadian Beaufort. Thick black line represents U.S./Canadian border. (Source: Gearon et al., 2014).

The release time frames analyzed were the same as the shallow blowout analysis; early operating season (June-July), and late operating season (August-October). This section looks at four scenarios:

- A deep subsurface WCD blowout of ANS Crude oil. The spill duration is 120 days with a total volume of 7,200,000 bbl spilled. This spill occurred in the late operation season (August-October). There are three different response measures explored for this scenario: no response, a surface response (only individual trajectories are presented for the surface response), and a subsurface response.
- The final oil spill scenario discussed is a deep subsurface MMPD well blowout of ANS Crude oil. The spill lasts 60 days and releases a total volume of 360,000 bbl of oil. The spill occurred in the early operating season (June-July).

This section compares the results for the 120 day WCD crude blowout as it looks with no response, a surface response and a subsurface response. NOTES: A WCD late season spill is less likely to be stopped because sea ice could interfere with well control and capping operations.

Response Measure Assumptions: Both subsurface and surface response measures were modelled in the deep blowout analysis. Critical assumptions were made about response capabilities in the Beaufort region. Assumptions have not been tested or reviewed by response experts, considering Arctic conditions. Surface response assumptions were based around observed rates from previous incidents, hours of daylight in the Arctic region during the time periods of interest, and various thresholds from well-established response documents. Overall, favourable and beneficial "best case scenario" response outcomes were incorporated into the modeling. For example, the in situ burn rate observed during the Deepwater Horizon in the Gulf of Mexico was applied. This was a generous assumption considering conditions in the Arctic would be more inclement and the presence of ice would present difficulty. In addition, the number of daylight hours when response could take place was extended during the summer months in the Arctic. It was assumed that the subsurface dispersant application was 100% efficient- which again, represents the "best case scenario".

Individual Trajectory Time Series Map Showing the 95th Percentile Surface Oiling (No Response)

As seen in Figure 39 below, oil that is directly released into high sea ice coverage can become trapped in the ice. One hundred and eighty days after the spill, the ice appears as long thin continuous and highly concentrated streaks contained in ice floes.

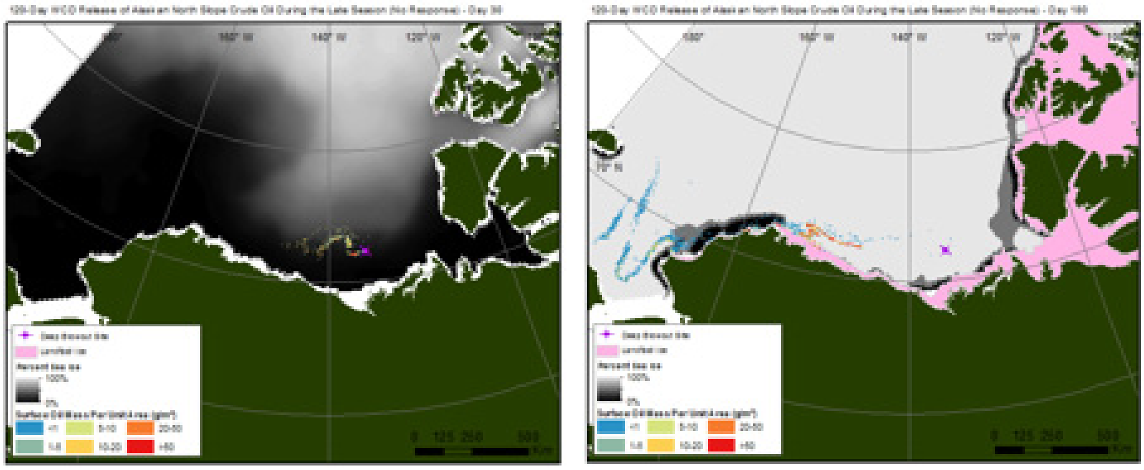


Figure 39. Time series maps of spill floating surface oil mass per unit area (g/m²) in the late season (day 30, and 180; September 2009 – February 2010). Pink polygons represent monthly average landfast ice. Grey scale contours represent ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start date: 8/16/2009. (Source: Gearon et al., 2014).

Individual Trajectory Time Series Map Showing the 95th Percentile Surface Oiling (Response)

As seen in Figure 39 below, oil that is directly released into high sea ice coverage can become trapped in the ice. One hundred and eighty days after the spill, the ice appears as long thin continuous and highly concentrated streaks contained in ice floes.

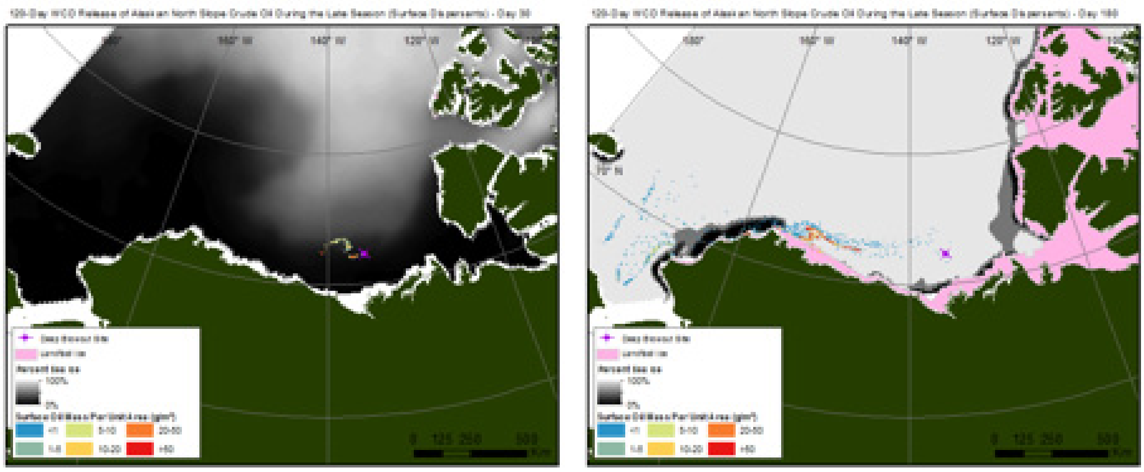


Figure 40. Time series maps of spill floating surface oil mass per unit area (g/m²) in the late season (day 30 and 180; September 2009 – February 2010). Surface response case including dispersant application and in situ burning. Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start date: 8/16/2009. (Source: Gearon et al., 2014).

As with the shallow well blowout, response measures included surface dispersant application and in situ burning and the amount of oil removed from burning and surface dispersants for the late season cases was lower due to fewer hours of daylight in the later summer and fall months.

Surface response scenarios in the early season (the blowout shown in this case was a late season blowout) showed differences in surface and shoreline effects as compared to the no response base cases. This was primarily due to the efficiency of in situ burning. Up to 13% of the total mass released was removed from burning in the early season. In June and July in the Arctic there is between 21-24 hours of daylight. This allowed for “around the clock” response during the first few months of the early season cases. More response effort was also possible in the early season before the October 31st response cut off (as noted earlier in this summary, WWF believes that it would not be possible to conduct response actions e.g., capping well, dispersant application after October 31st due to harsh environmental conditions in the Beaufort Sea).

Individual Trajectory Shoreline Effect Table Showing 95th Percentile Shoreline Oiling (No Response and Surface Response)

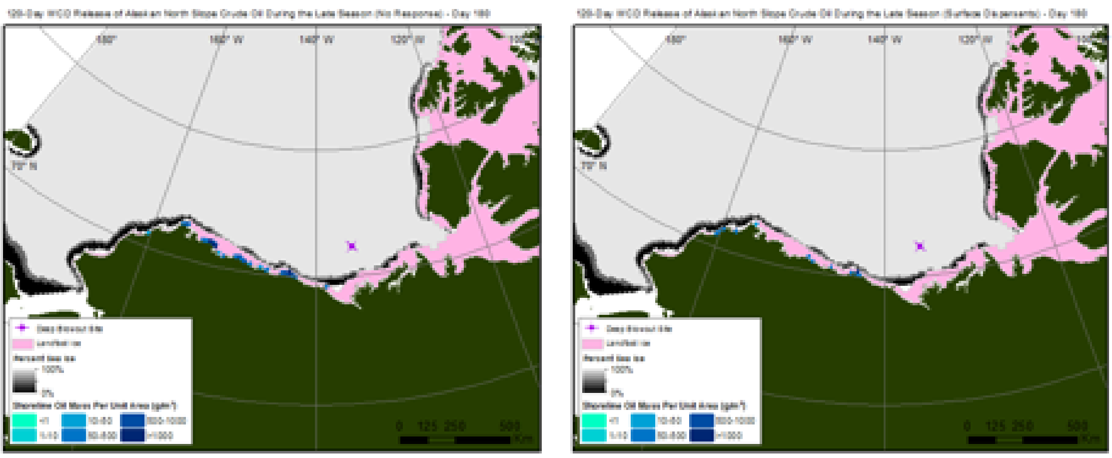


Figure 41. Map of overall impact to shorelines as mass of oil deposited on shore per unit of area (g/m²) in the late season (day 180 – February 2009). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. The start date is 8/12/2008 for both tables. The map to the left shows what would happen if there was no response and the map to the right shows what would happen if there was a surface response including dispersant application and in situ burning. (Source: Gearon et al., 2014).

Subsurface Contamination

Subsurface stochastic output primarily mirrored surface oiling patterns (movement to the west), although extent was drastically reduced. Subsurface oiling was observed in the channel north of Banks Island in late WCD scenarios. This did not correspond to surface oiling, suggesting that subsurface currents occasionally transported freshly released oil into the water column, which caused the oil to travel considerable distances. The results from the modeling predicted that long-term water contamination by dissolved aromatics (1-100 ppb) may result from long blowout releases, and could travel far distances from the spill site. If no dispersants are used, oil surfaces within a day and may become trapped in sea ice in the later operating season and winter. The modeling showed that use of subsea dispersants at the deep release site could cause subsurface oil to concentrate at depth along the Beaufort shelf.

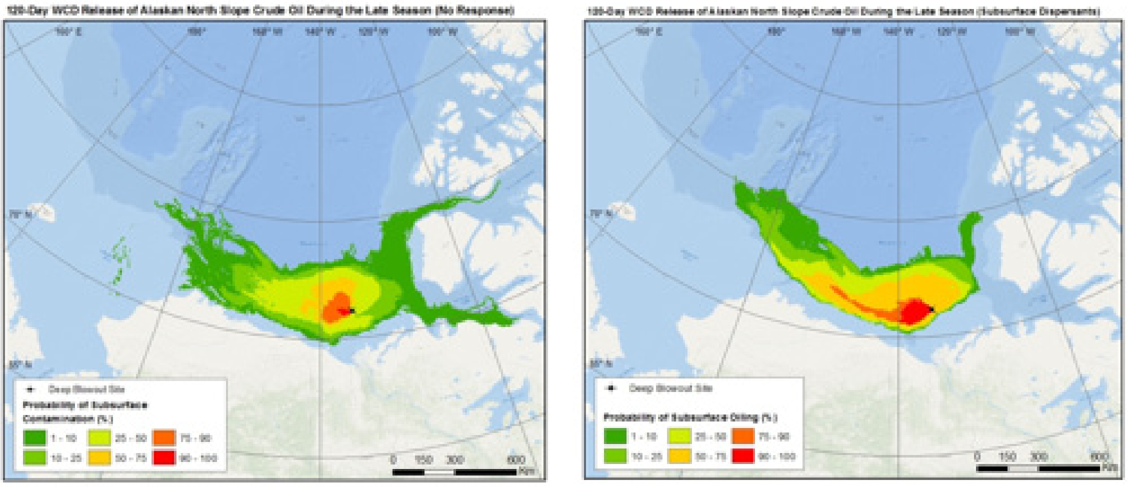


Figure 42. Subsurface contamination probabilities for total oil in the water. The map to the left shows the probable subsurface contamination for this late season deep well blowout if there was no response. The map to the right shows the probability of subsurface contamination for this late season deep well blowout if subsurface dispersants were applied to the oil. (Source: Gearon et al., 2014).

As with the shallow well blowout, response measures included surface dispersant application and in situ burning and the amount of oil removed from burning and surface dispersants for the late season cases was lower due to fewer hours of daylight in the later summer and fall months.

Individual Trajectory Time Series Maps Showing 95th Percentile Subsurface Contamination (No Response)

As seen in Figure 39 below, oil that is directly released into high sea ice coverage can become trapped in the ice. One hundred and eighty days after the spill, the ice appears as long thin continuous and highly concentrated streaks contained in ice floes.

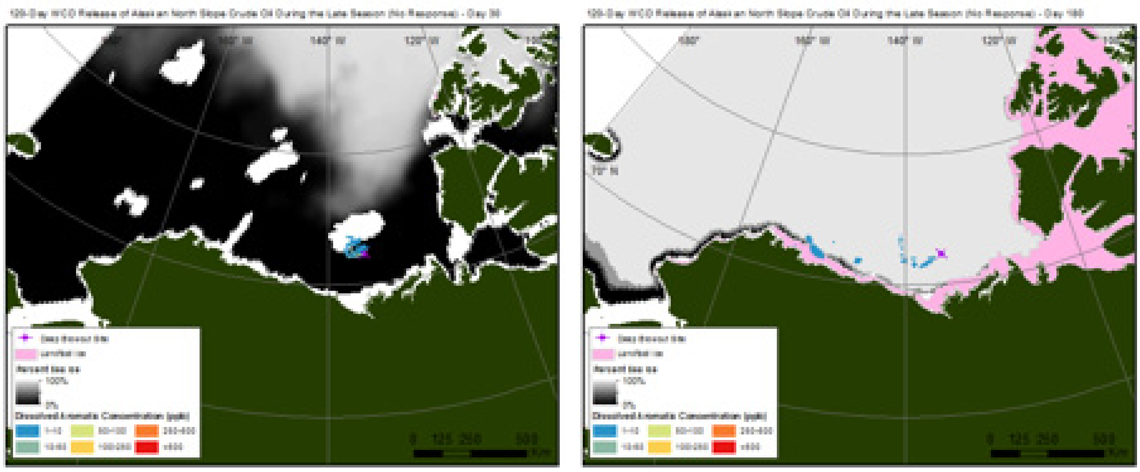
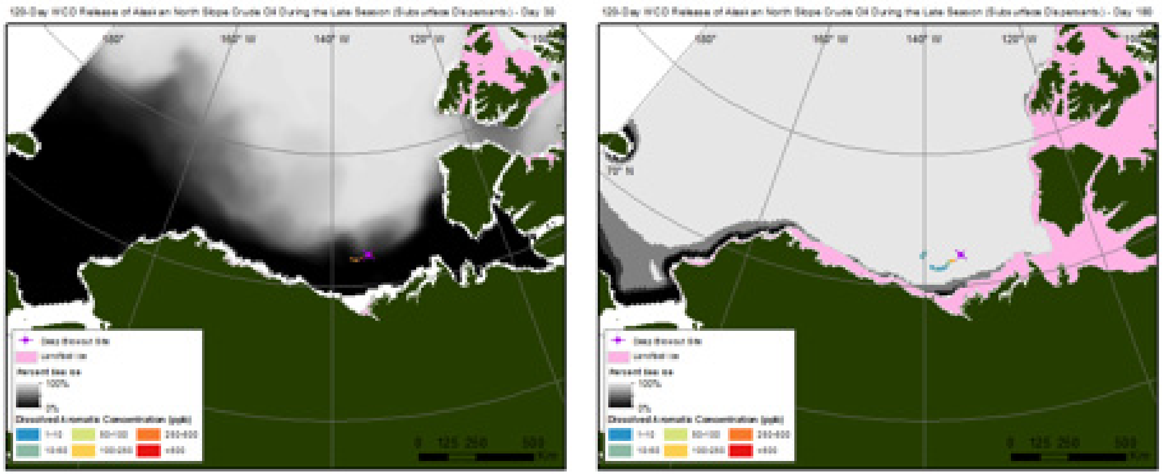


Figure 43. Time series maps of spill dissolved aromatics ≥ 1 ppb in the late season (day 30,180; September 2010 – February 2011). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start date: 8/7/2010. (Source: Gearon et al., 2014).

If no dispersants were used, oil surfaced within a day and became trapped in sea ice in the later operating season and winter. Concentrations of dissolved aromaticsw, as modelled in the individual 95th percentile runs for highest water column contamination for this spill were observed at further distances from the spill site (within 500 km), with this highest concentration occurring nearest to spill site.

Individual Trajectory Time Series Maps Showing 95th Percentile Subsurface Contamination (Response)



Subsurface response case including subsea dispersant application. Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start date: 9/2/2010.

Figure 44. Time series maps of spill dissolved aromatics ≥ 1 ppb in the late season (day 30, 180; October 2010 – March 2011). (Source: Gearon et al., 2014).

Subsurface dispersant response cases showed the highest overall water column contamination. It was assumed that all oil was 100% effectively treated by subsurface dispersant application; therefore, all oil remained subsurface broken up into tiny oil droplets. The area having the highest probability of subsurface oil contamination was to the southwest of the spill site along the shelf edge near the Mackenzie trough. The subsurface oil droplets tended to build up along the Beaufort shelf at depth (approximately 300-400 m). Often dissolved aromatic concentration was observed between 100-500 ppb, in areas near to the spill site (within 250 km).

Individual Trajectory Mass Balance Map Showing 95th Percentile Water Column Contamination

As seen in Figure 39 below, oil that is directly released into high sea ice coverage can become trapped in the ice. One hundred and eighty days after the spill, the ice appears as long thin continuous and highly concentrated streaks contained in ice floes.

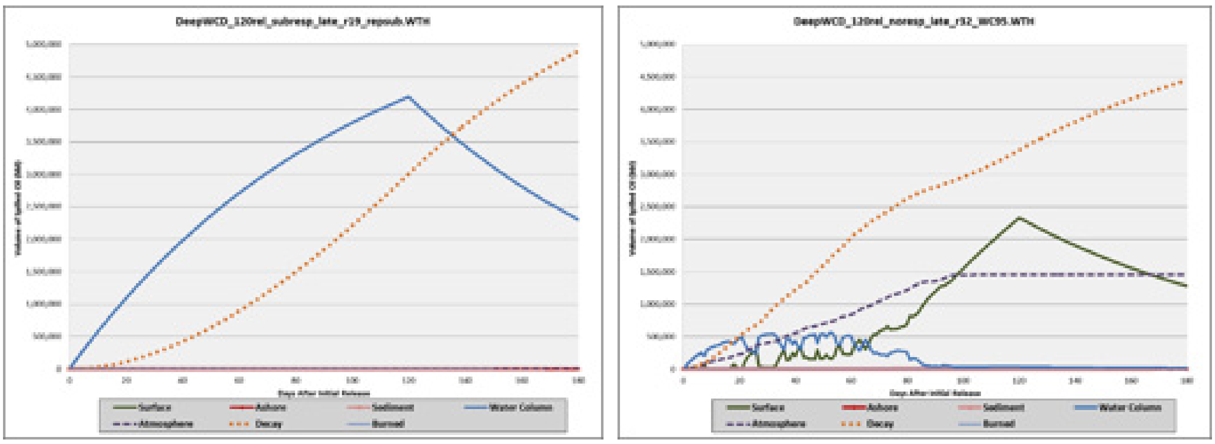


Figure 45. The mass balance chart on the left shows subsurface response case including subsea dispersant application (assumed 100% effective) Start date: 9/2/2010. The left-hand chart clearly illustrates the high occurrence of contamination in the water column when subsea dispersants are used (and absolute lack of oil on the surface). The mass balance chart on the right had NO dispersant application and shows a higher surface oiling but very little water column contamination. Start date: 8/7/2010. (Source: Gearon et al., 2014).

The final oil spill scenario discussed is a deep subsurface MMPD well blowout of ANS Crude oil. The spill lasts 60 days and releases a total volume of 360,000 bbl of oil. The spill occurs in the early operating season (June-July). Because this is a MMPD spill – it is assumed that the volume of release as well as the duration of the release would be reduced, because it would likely take less time to effectively cap the well with a lower release rate and earlier in the season.

Stochastic Map Showing Surface Oiling Probabilities

Surface oiling travels farther north in the early season due to lack of sea ice. Spills from the 60-day deep blowout site primarily travelled westward towards Alaska and into the Chukchi Sea. The overall surface oil footprint for the MMPD early season scenario was slightly smaller as compared to the WCD, although total westward extent was comparable. This was due to the shorter release period of the MMPD, as well as the lower spill volume. The higher probability of surface oiling contours (75-100%) extended great distances from the spill site and ran parallel and close to the coastline.

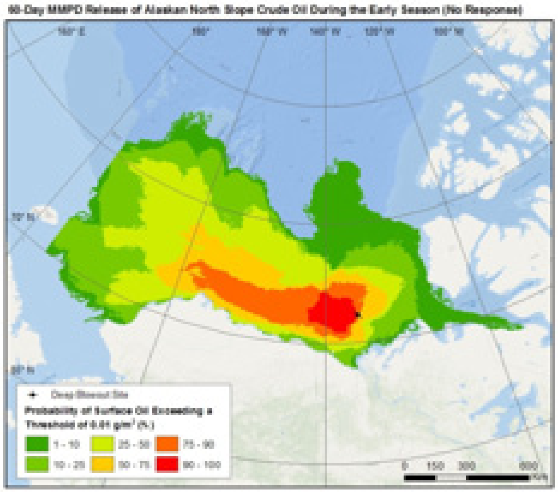


Figure 46. Water surface oiling probabilities for floating oil ≥ 0.01 g/m². (Source: Gearon et al., 2014).

Individual Trajectory Time Series Maps Showing 95th Percentile Surface Oiling

Early season scenarios had higher probability of shoreline oiling as compared to the late season. This was attributed to landfast ice growth in the fall and winter months prohibiting landfall of oil. Highest probabilities for shoreline oiling for the MMPD early scenario occurred around Point Barrow, Alaska.

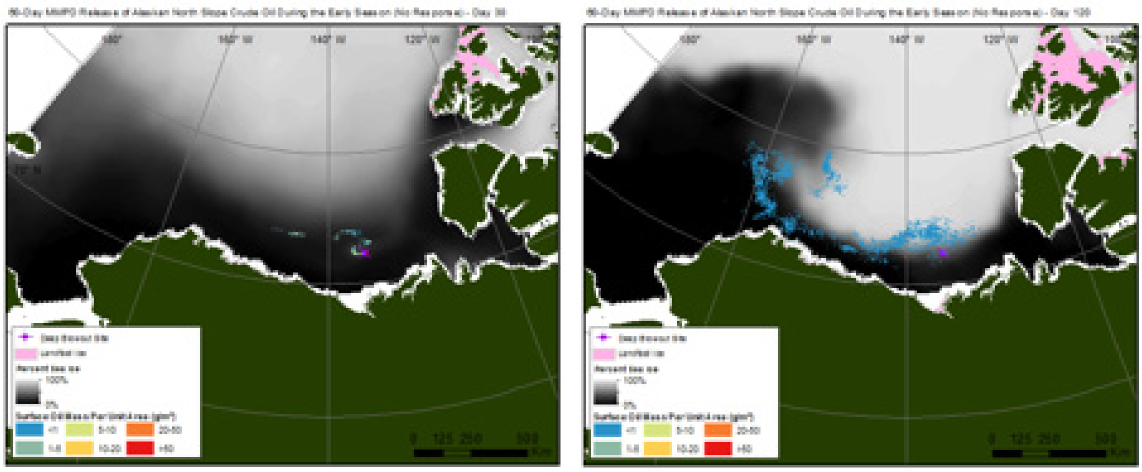


Figure 47. Time series maps of spill floating surface oil mass per unit area (g/m²) in the early season (day 30, 120; July – October 2009). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. Start date: 6/3/2009. (Source: Gearon et al., 2014).

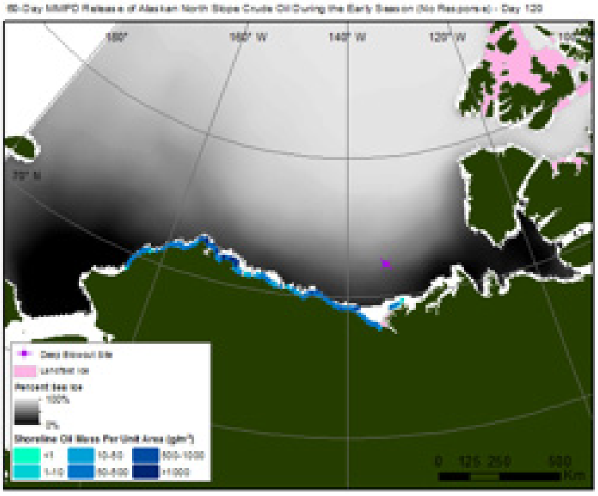


Figure 48. Map of overall impact to shorelines as mass of oil deposited on shore per unit of area (g/m²) in the early season 60-day MMPD deepwater blowout (day 120 – October 2008). Pink represents monthly average landfast ice. Grey represents ice percent coverage for that month from TOPAZ4 model. White indicates areas of no data for ice coverage. The table shows the shoreline length oiled (km) for the threshold ≥ 1 g/m² by habitat type. Start date: 6/22/2008. (Source: Gearon et al., 2014).

Shore Type	Shore Length Oiled (km)
	> 1 micrometer
Seaward Rocky Shore	50.4
Seaward Gravel Beach	463.8
Seaward Sand Beach	448.6
Seaward Fringing Mud Flat	292.4
Seaward Fringing Wetland	15.1
Seaward Intertidal Macroalgal Bed	126.0
Total Shoreline	**1,396.3**

Table 6. Shoreline length oiled (km) by habitat type for the threshold ≥ 1 g/m² in the early season 60-day MMPD deepwater blowout (day 120 – October 2008). Start date: 6/22/2008. (Source: Gearon et al., 2014).

Stochastic Map Showing Subsurface Contamination Probabilities

Oil released at the subsurface deep well spill site surfaced in less than a day. Subsurface contamination was from both fresh oil ascending to the surface, and from surface oil entraining from wind stress as it travelled with the surface currents. Subsurface stochastic output primarily mirrored surface oiling patterns (movement to the west), although extent was much less.

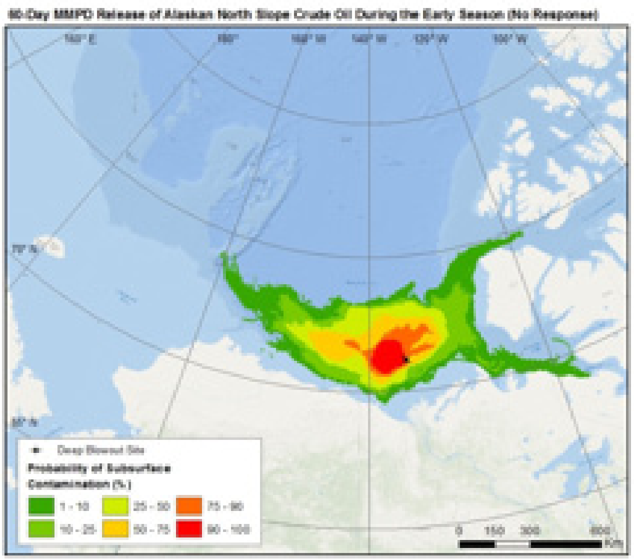


Figure 49. Subsurface contamination probabilities for total oil in the water column. (Source: Gearon et al., 2014).

Conclusions

After analyzing the results of the 12 oil spill scenarios discussed in this summary, several overarching themes became clear which will help future ocean management and planning for the risks and impacts inherent in oil and gas and shipping activities in the Beaufort Sea.

Oil and Ice

How ice affects oil is possibly the most critical factor to consider when thinking about an oil spill in the Beaufort Sea. The Beaufort Sea is covered by ice for much of the year and ice can have profound effects on the behaviour of spilled oil. Oil weathering processes, including spreading, evaporation, emulsification, entrainment, and volatilization may be slowed as higher ice coverage is encountered. This inherently may increase the residence time of oil on the sea surface, which undoubtedly contributes to increased distance traveled while trapped in and/or under moving sea ice, even for lower volume spills. When oil is trapped in ice, it becomes more difficult to clean up.

The spreading of oil on the water surface was limited as ice coverage increased. This was apparent in scenarios that had the oil spill starting in open water and continuing throughout the winter ice freeze up. Oil released in open water spread into larger and wider surface slicks than when surfacing in ice. When subsequently encountering high ice coverage, these wider slicks continued to be transported in the ice in a more spread out patchy pattern. Oil that was directly released into high sea ice coverage appeared as long thin continuous and highly concentrated streaks of oil contained in ice floes.

Shoreline oiling was highest in cases that started early in the summer when coastlines were the most free of landfast ice. For cases that continued into or started in the landfast freeze up period, oil became entrapped in the ice. As the ice formed over the months and extended out from shore, new oil encountering the newly established ice edge would become trapped. Oil from previous months still appeared trapped at the previous ice edge.

Oil trajectory pattern

The most common surface oil trajectory pattern observed across the 5-year (spring 2008-spring 2013) wind and current record at all spill sites evaluated in this region of the Beaufort, was transport very far to the west by the westward flowing Beaufort Gyre current along the shelf break. In many cases, oil was transported west of Point Barrow and past the Canadian border. This movement pattern coincides with the observed prevailing wind pattern (coming from the east, blowing towards the west).

Subsea dispersants

As a result of the Deepwater Horizon incident, subsea dispersant application is now considered as an effective response tool during a catastrophic blowout. However, subsurface dispersant response cases showed the highest overall water column contamination due to assumptions made by the authors of the full report (Gearon et al., 2014). It was assumed that all oil was 100% effectively treated by subsurface dispersant application; therefore, all oil remained subsurface broken up into tiny oil droplets. Subsurface oil droplets tended to build up along the Beaufort shelf at depth, possibly creating toxic concentrations within this ecologically significant area. However, this represents a tradeoff, saving surface oiling over an extensive area, if dispersants were not applied for this scenario.

Coastal Oiling

For every scenario run, results showed the possibility of hundreds of kilometres of shoreline oiling. There was a relatively high chance that spilled oil originating from Canadian waters could reach United States shorelines, meaning the oil spill and clean up operations could potentially become an international issue.

Appendix A

The results are summarized in Tables A1-A4. The development of the scenarios is described in greater detail in this report.

Table A1. Summary of scenarios simulated for the eastern shipping analysis (2 scenarios total).

Source Type	Release Location	Water Depth (m)	Release Type	Oil Type	Spill Duration (days)	Total Volume (bbl)	Release Time Frame
Bulk Ore Carrier	Amundsen Gulf, shipping route, approx. 45 km N Baillie Island, single point release	40 - 100	Surface MMPD	IFO 380	0.25	21,000	July – October
Resupply Tank Barge	Amundsen Gulf, shipping route, approx. 45 km N Baillie Island, single point release	40 - 100	Surface MMPD	Diese l	0.25	5,400	July – October

Table A2. Summary of scenarios simulated for the trans-boundary analysis (6 scenarios total).

Source Type	Release Location	Water Depth (m)	Release Type	Oil Type	Spill Rate (bbl/day)	Spill Duration (days)	Total Volume (bbl)	Release Time Frame
Bulk Ore Carrier	Shipping route, Canadian Beaufort coast Herschel Island to US/Can Border	40 - 100	Surface MMPD	IFO 380	NA	0.25	21,000	July - October
Bulk Ore Carrier	Shipping route, US Beaufort coast Kaktovik to Prudhoe Bay	40 - 100	Surface MMPD	IFO 380	NA	0.25	21,000	July - October
Tanker	Shipping route, Canadian Beaufort coast Herschel Island to US/Can Border	40 - 100	Surface WCD	Crude	NA	0.50	533,000	January-December
Tanker	Shipping route, US Beaufort coast Kaktovik to Prudhoe Bay	40 - 100	Surface WCD	Crude	NA	0.50	533,000	January-December
Offshore Pipeline	Pipeline route, Canadian Beaufort coast Herschel Island to US/Can Border	60	Shallow subsurface MMPD	Crude	4,800	6	28,800	May – November
Offshore Pipeline	Pipeline route, US Beaufort coastline from US/Canadian Border Prudhoe Bay	60	Shallow subsurface MMPD	Crude	4,800	6	28,800	May – November

Table 3. Summary of scenarios simulated for the shallow blowout analysis (6 scenarios total). *Note: Surface response measures were only simulated in iterations of the 95th percentile trajectory for surface and shoreline from the base case or parent stochastic scenario. Therefore, surface response was not simulated in a full stochastic analysis.

Source Type	Release Location	Water Depth (m)	Release Type	Oil Type	Spill Rate (bbl/day)	Spill Duration (days)	Total Volume (bbl)	Response Measures	Release Time Frame
Well	*Amauligak* Lease Area	32	Shallow Subsurface WCD	Crude	30,000	60	1,800,000	None	June – July
Well	*Amauligak* Lease Area	32	Shallow Subsurface WCD	Crude	30,000	60	1,800,000	Surface*	June – July
Well	*Amauligak* Lease Area	32	Shallow Subsurface WCD	Crude	30,000	90	2,700,000	None	August – October
Well	*Amauligak* Lease Area	32	Shallow Subsurface WCD	Crude	30,000	90	2,700,000	Surface*	August – October
Well	*Amauligak* Lease Area	32	Shallow Subsurface MMPD	Crude	3,000	30	90,000	None	June – July
Well	*Amauligak* Lease Area	32	Shallow Subsurface MMPD	Crude	3,000	60	180,000	None	August – October

Table A4. Summary of scenarios simulated for the deep blowout analysis (8 scenarios total). *Note: Surface response measures were only simulated in iterations of the 95th percentile trajectories for surface and shoreline from the base case or parent stochastic scenario. Therefore, surface response was not simulated in a full stochastic analysis.

Source Type	Release Location	Water Depth (m)	Release Type	Oil Type	Spill Rate (bbl/day)	Spill Duration (days)	Total Volume (bbl)	Response Measures	Release Time Frame
Well	*Pokak* Lease Area	1,008	Deep subsurface WCD	ANS Crude	60,000	90	5,400,000	None	June – July
Well	*Pokak* Lease Area	1,008	Deep subsurface WCD	ANS Crude	60,000	90	5,400,000	Surface*	June – July
Well	*Pokak* Lease Area	1,008	Deep subsurface WCD	ANS Crude	60,000	90	5,400,000	Subsurface	June – July
Well	*Pokak* Lease Area	1,008	Deep subsurface WCD	ANS Crude	60,000	120	7,200,000	None	August – October
Well	*Pokak* Lease Area	1,008	Deep subsurface WCD	ANS Crude	60,000	120	7,200,000	Surface*	August – October
Well	*Pokak* Lease Area	1,008	Deep subsurface WCD	ANS Crude	60,000	120	7,200,000	Subsurface	August – October
Well	*Pokak* Lease Area	1,008	Deep subsurface MMPD	ANS Crude	6,000	60	360,000	None	June – July
Well	*Pokak* Lease Area	1,008	Deep subsurface MMPD	ANS Crude	6,000	90	540,000	None	August – October

Each of the spill scenarios in Tables A1-A4 represents what is believed and expected to be a relatively rare or unlikely event with regard to likelihood of occurrence. In addition, the spill volumes represented are also relatively unlikely scenarios in the scope of actual spill events. The probabilities of these events and spill volumes are discussed in this report to provide a general perspective.

Glossary

95th Percentile: For this study, each stochastic scenario was comprised of 100 individual trajectories of the same spill scenario, each run with a different start time, to develop an expectation of risk. Individual trajectories that were identified as the 95th percentile for highest degree of surface area and shoreline oiled, or water column contamination were selected from the stochastic ensemble of results. The 95th percentile classification is a rank order from lowest to highest and 95th in list is the 95th percentile. The 95th is used as statistic without being unduly influenced by a potential outlier of the highest one.

Alaska North Slope (ANS) Crude Oil: This oil is characterized as a light to medium crude with high aromatic content and is assumed to have oil properties typical of oil potentially extracted from the region of interest. Other oil types also possible in the area, but have not yet been characterized.

Barrel (bbl.): A unit of liquid measure, which is the equivalent of 42 US gallons, 35 Imperial gallons, or 0.159 cubic meters.

Blowout: Loss of well control or uncontrolled flow of formation or other fluids, including flow to an exposed formation (an underground blowout) or at the surface (a surface blowout), flow through a diverter, or uncontrolled flow resulting from a failure of surface equipment or procedures.

Diesel Fuel: A typical marine diesel fuel was selected to represent the light fuel oil carried by re-supply vessels in the Beaufort Sea. This diesel fuel was non-biodiesel based.

Dispersants: Dispersants are composed of surfactants -- materials that can reduce surface tension of water. Dispersants themselves have very low toxicity to aquatic organisms, but when applied to oil, effects of organisms in the water column can increase. These chemicals can reduce the interfacial tension of oil, facilitating increased entrainment of oil into water as microscopic droplets. This leads to more oil in water column, increased dissolution rates of soluble hydrocarbons (mostly aromatics), and enhanced biodegradation rates due to more surface area than if a floating slick. Application of subsea dispersants reduces the effects of surface floating oil on birds and other wildlife, and on shorelines. However, dispersant use is a trade-off with increased risks to fish and invertebrates in the water column.

Dissolved aromatics: Dissolved aromatics enter the water column after an oil spill has occurred and the different chemical components of the oil begin to break down. Dissolved aromatics in the water column resulting from an oil spill may reach toxic concentrations. Subsurface oil droplets in particulate form can, for example cause clogging of feeding appendages and gills of fish, and can impede movement. Organisms at highest risk of water column effects include invertebrates and juvenile fish. Out of all the components of the oil, dissolved aromatics impact water column organisms the most.

Ecologically significant area: An area that contains unique or irreplaceable biological resources.

Entrain: Oil is "entrained" when it is drawn into the water column and transported by subsurface currents.

Emulsification: When oil mixes with water.

Hydrodynamic: Relating to the force of liquid in motion.

Intermediate Fuel Oil (IFO): Intermediate fuel oil, the bunker fuel commonly used in large ships.

In-situ burning: A controlled burning of spilled oil.

Landfast ice: Immobile ice that extends out from the coast in the fall and winter seasons and acts as a natural barrier where oil collects.

Maximum Most-Probable Discharge (MMPD): the volume that is 10% of the WCD (see WCD).

Oil weathering: The different chemicals in oil react in different ways to environmental conditions e.g., some parts of the oil easily evaporate when exposed to sunlight. The chemical changes that happen to oil when exposed to the physical environment is known as "oil weathering".

Part Per Billion (ppb): Parts per billion represent the amount of a chemical or contaminate per volume of water.

Probabilistic: A model where there are several different possible outcomes each with varying degrees of certainty.

Sea Ice: Sea ice is formed entirely in the ocean and forms and melts each year.

Stochastic: A stochastic model involves chance or probability. The stochastic model is capable of evaluating areas affected by oil and oil concentrations over a prescribed minimum threshold value.

Threshold: A value above which something is true or will take place and below which it is not or will not take place. Often thresholds are based on response requirements or environmental impact assumptions.

Volatilization: Volatilization of oil is when oil evaporates.

Worst-Case Discharge (WCD): the maximum potential spillage from a source containing oil; the volume depends on the source. For vessels, the WCD is the entire oil contents of the vessel (cargo and bunker fuel for tankers and only bunker fuel for non-tank vessels). For pipelines, it is the amount of oil that would be released until the pipeline flow is stopped. For offshore wells, the WCDs depend on the pressure in the well, the size and type of pipe or riser, the type of blowout prevention, the length of time before a discharge is detected, and the length of time to capping of the well or stemming of the flow of oil. Canadian federal regulations define WCD with respect to response planning as 10,000 tonnes (70,000 bbl), but do not define WCDs with regard to specific source types.

References

AXYS, (2004). Environmental Atlas for Beaufort Sea Oil Spill Response. Provided as PDF to RPS ASA from WWF Fall 2013.

Boyer, T., Levitus, S., Garcia, H., Locarnini, R. A., Stephens, C., and Antonov, J. (2005). Objective analyses of annual, seasonal, and monthly temperature and salinity for the World Ocean on a 0.25°grid. International Journal of Climatology (25) 931-945.

Drozdowski, A., Nudds, S., Hannah, C. G., Niu, H., Peterson, I., and Perrie, W. (2011). Review of Oil Spill Trajectory Modeling in the Presence of Ice. Can. Tech. Rep. Hydrogr. Ocean Sci. 274: vi + 84 pp.

French McCay, D.P., (2004). Oil spill impact modelling: development and validation. Environmental Toxicology and Chemistry. 23(10): 2441-2456.

French,, D., Reed, M., Jayko, K., Feng, S., Rines, H., Pavignano, S., Isaji, T., Puckett, S., Keller, A., French III, F. W., Gifford, D., McCue, J., Brown, G., MacDonald, E., Quirk, J., Natzke, S., Bishop, R., Welsh, M., Phillips, M., and Ingram, B.S. (1996). The CERCLA Type A Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME), Technical Documentation, Vol. I -VI, Final Report, submitted to the Office of Environmental Policy and Compliance, U.S. Dept. of the Interior, Washington, D.C., Contract No. 14-0001-91-C-11, April, 1996.

French McCay, D., Reich, D., Rowe, J., Schroeder, M., and Graham, E. (2011). Oil Spill Modeling Input to the Offshore Environmental Cost Model (OECM) for US-BOEMRE's Spill Risk and Cost Evaluations. In: Proceedings of the 34th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar, Emergencies Science Division, Environment Canada, Ottawa, ON, Canada.

Gearon, M.S., French McCay, D., Chaite, E., Zamorski, S., Reich, D., Rowe, J., and Schmidt-Etkin, D. (2014). SIMAP Modeling of Hypothetical Oil Spills in the Beaufort Sea for World Wildlife Fund (WWF). 311pp. Report for WWF-Canada by RPS ASA.

Imperial Oil Resources Ventures Limited (IORVL), (2013). Beaufort Sea Exploration Joint Venture Drilling Program, Environmental Impact Screening Committee.

IOC, IHO and BODC, 2003. Centenary Edition of the GEBCO Digital Atlas, published on CD-ROM on behalf of the Intergovernmental Oceanographic Commission and the International Hydrographic Organization as part of the General Bathymetric Chart of the Oceans, British Oceanographic Data Centre, Liverpool, U.K.

Schulze, L. M., Pickart, R. S. (2012), Seasonal variation of upwelling in the Alaskan Beaufort Sea, Journal of Geophysical Research (117).

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