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Verificarion and Validation of An in-Ice Oil Spill Trajectory Model Based on Satellite-Derived Ice Drift Data

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ABSTRACT

A future increase in hydrocarbon exploration and development activities driven by the probable existence of hydrocarbon reserves and an expected increase in shipping activities due to less severe ice conditions, pose a risk of potential oil spills in the offshore Arctic. Estimating oil spill trajectories is essential in quantifying risks and planning an effective spill response.

An in-ice spill trajectory modelling, analysis and visualization tool suitable for spills in highly ice-infested waters has been previously developed at NRC. The source data is historical satellite-derived ice drift. The model has been enhanced by including time dependent land-fast ice extent to better estimate coastal spill trajectories.

Two hypothetical in-ice spill scenarios in the Canadian Beaufort Sea were modelled based on 34 years of ice velocity data. In four months starting in November, a deep water spill in ice could travel over 700 km, while for a shallow water spill in ice, the travel distance could exceed 400 km. Depending on how fast an in-ice spill could be cleaned, both investigated deep water and shallow water spills could be an international issue, particularly the deep water spill scenario.

Present model results were compared with an observed in-ice spill trajectory in the Barents Sea. Because of an underestimation of ice speeds in the input satellite-derived ice drift dataset, the present model underestimates the extent of the trajectory. However, the model estimated the trajectory of an observed buoy well.

Present model results were also compared with an independent numerical study of oil spills in the Beaufort Sea. Coastward motions of an in-ice spill are found to be generally similar, however, along the coast, motions deviate after a certain time in the modelled period. Both models are based on data that are expected to be less accurate in the nearshore zone. We did not investigate what caused this deviation or whether the present model or the independent study is a better representation of reality.

KEY WORDS: Oil spill; Trajectory modelling; Ice; Validation; Verification; Satellite-derived ice drift

INTRODUCTION

A large proportion of the world's undiscovered hydrocarbon reserves are expected to be found in the offshore Arctic (Eurasia Group, 2014) where the average monthly ice extent has been declining since 1978 (National Snow and Ice Data Centre, 2016). This means a probable increase in the exploration and development of hydrocarbon resources and an increase in shipping if the decline of ice extent continues. More activities in the offshore Arctic pose a higher risk of large spills of chemicals, particularly crude oil with potentially significant negative socio-economic and environmental impacts. The trajectory estimation of such spills is crucial for timely, optimized and successful clean-up efforts, particularly in colder seasons when cleanup operations are more challenging because of shorter or no daylight periods and harsher ice conditions.

Trajectory of an oil spill in the presence of ice depends on several factors including the concentration of ice. In high ice concentrations, oil tends to move with the ice and not with the water current. Oil follows the trajectory of ice for several reasons: it can be trapped in leads between ice floes, absorbed in snow on ice (for an on-ice spill), encapsulated in ice brine channels (for an under-ice spill), trapped in under-ice depressions, and adhere to ice floe edges. An under-ice spill could also move relative to the ice when currents are high, however this is not generally expected except in river and fjords and where tides are strong (MAR Incorporated et al., 2008). The ice concentration required for oil to move with the ice is not fully known; values as low as 30% (Venkatesh et al., 1990) and as high as 70% (LOOKNorth, 2014) have been mentioned in literature.

Computer modelling of different aspects of in-ice oil spills including trajectory estimation is under active development. A review of some of the models can be found in LOOKNorth, 2014 and Drozdowski et al., 2011. To model the trajectory of a spill in highly ice covered waters, the motion and deformation of the ice field is required. To our knowledge, all numerical oil spill trajectory models rely on numerical estimations of ice motion and deformation computed by different numerical ice-ocean models with different length scale applicability, levels of sophistication and accuracy. Satellite-derived ice motion data may potentially be used to estimate the trajectory of in-ice spills as an alternative to numerically generated ice motion data or to validate it. Several publicly available satellite-derived ice drift datasets exist (see Tschudi et al., 2016; Muir et al., 2011; Kimura et al., 2013; Lavergne et al., 2010, and www.seaice.dk) which could be considered for trajectory estimation, however the literature on this subject is not fully developed.

We have previously developed a model based on a satellite-derived ice drift dataset for in-ice trajectory modelling, analysis and visualization and studied several hypothetical spill scenarios in the Beaufort Sea during fall and winter (Babaei et al. 2016) when usually the ice concentration is high and hence oil spills are expected to move mainly with ice. In that study, the trajectory algorithm of the model was successfully validated by comparing the model trajectory with an observed buoy trajectory for a 5-month-long period from November to March. The present paper reports about further developments, validation and verification of the model. To improve the reliability of the model in coastal regions of the Beaufort Sea, observed time-dependent landfast ice extents from ice charts were included in the model. We have verified results of the present model with results of an independent numerical oil spill study. We have also compared the present model results with an actual in-ice oil spill trajectory in the Barents Sea and with an observed buoy trajectory in the Arctic Ocean.

MODEL DESCRIPTION AND TWO HYPOTHETICAL IN-ICE SPILLS IN THE BEAUFORT SEA

Model Description

The core of the model simply calculates trajectory of particles in a gridded time dependent ice velocity field. An oil slick is numerically represented by a cluster of points that are moved separately. This movement of the points is calculated using a spatially and temporally gridded ice velocity field. The velocity of each point is interpolated using the three nearest nodes on the grid. To model a spill lasting for a given period, a point is introduced at the location of spill with a frequency equal to the temporal resolution of the ice velocity dataset. Each point is then moved and tracked based on the above algorithm to the end of the simulation. Weathering of oil is not modelled.

Generally, both numerical and satellite-based ocean ice drift data are less accurate for coastal regions than farther offshore. For numerical ice drift data, a reason could be the challenge involved to capture current features caused by typical high coastal bathymetric gradients and by rivers flows at their mouth. For satellite-derived ice drift data, there is the challenge to correctly distinguish land from sea ice depending on the spatial resolution of the satellite sensors.

In the present study, to model in-ice coastal spills based on satellite-derived ice drift data, time-dependant landfast ice extents from historical ice charts have been incorporated into the model; ice velocities within landfast ice are set to zero (if not already zero in the raw dataset) and when and if spill points are in landfast ice, spill points remain stationary until the landfast ice recedes and is replaced by drift ice. Coastlines are also included in the model to distinguish land from ocean. The present model is also capable of Monte-Carlo modelling of in-ice spills when uncertainties in the input satellite-derived ice drift dataset are known.

The third version of the Polar Pathfinder satellite-derived ice drift dataset (Tschudi et al., 2016) was selected for the present study because of the dataset's long term data availability spanning from 1978 to 2015 and the dataset's spatial coverage availability for our locations of interest. The spatial resolution of the dataset is 25 km and the selected temporal resolution is 1 day. The dataset is based on several different data sources including several satellite sensors and it is improved by observed buoy velocities collected under the International Arctic Buoy Program (IABP).

Model results include contamination probability (the probability that oil reaches a location), contamination intensity (how frequently a location is contaminated), contamination probability for water and land boundaries including territorial water boundary and coastlines, and residence time of spill in different locations.

Two Hypothetical In-ice Spills in the Beaufort Sea

Two hypothetical spill scenarios were selected to briefly show some of the model outputs, capabilities, and applications for spill analysis. Scenarios only differ in the spill location. We have modelled a deep (location: 71.036N, 136.507W; water depth: ~ 1170 m; offshore distance: ~ 180 km) and a shallow (location: 70.174N, 133.357W; water depth: ~30 m; offshore distance: ~ 70 km) water spill starting on November 1st lasting for 42 days. The location of the spills is the Canadian Beaufort Sea and the total model duration is 120 days.

For each scenario, spill was modelled for each year from 1978 to 2012 (thirty four years) and trajectories were combined and analyzed. Canadian Ice Service (CIS)'s Regional Western Arctic ice charts were used to extract the extent of landfast ice for the above period. The frequency of ice charts for the period of interest is different from year to year and month to month with an average of 2 weeks.

Figure 1 shows the contamination probability for the deep water spill scenario. The dominant direction of motion is towards the west. This dominant direction is consistent with the general ice drift direction in the Beaufort Sea known as the Beaufort Gyre. In 120 days, the spill could move west more than 700 km and there is a 40% to 50% chance that the spill moves west more than 200 km reaching to the US Beaufort Sea. The spill does not reach the coastline although it can reach the Alaskan territorial waters (dashed black line in the figure) close to Utqiagvik (Barrow) (<10% chance, shown by dark blue in Figure 1).

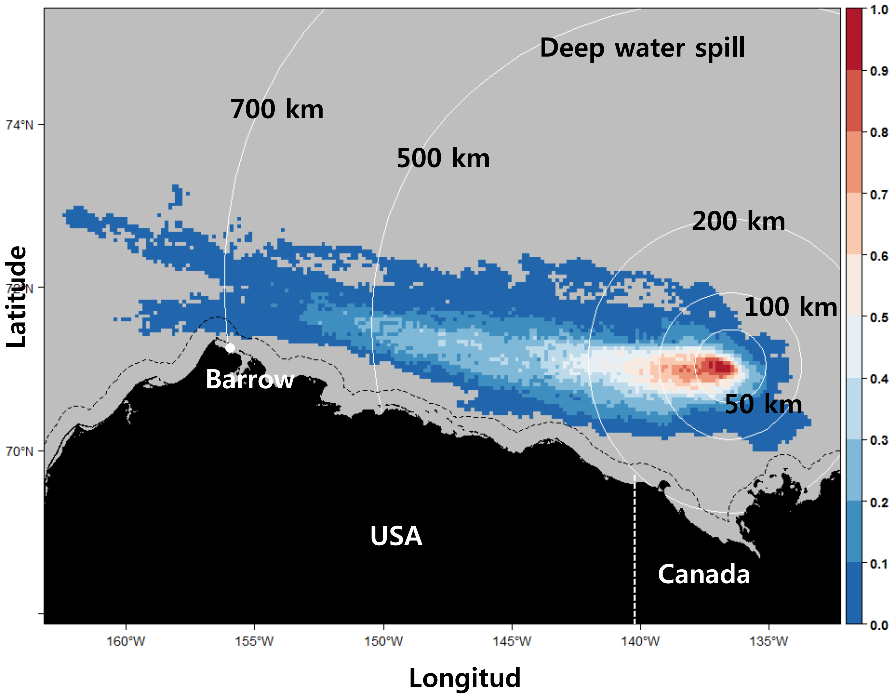

Figure 1. Probability of contamination (the chance that the spill reaches a location) for the deep water in-ice spill scenario. In 120 days, the spill could move west more than 700 km, but coastlines are not impacted. The dashed line shows the offshore distance of 25 km.

Figure 2 shows the contamination probability for the shallow water spill scenario. In 120 days, the spill could move west more than 400 km which is considerably less than the deep water spill scenario. As expected, the shallow water spill scenario impacts coastlines and territorial waters much more than the deep water spill scenario; the spill could reach the Alaskan coastline east of Kaktovic (<10% chance, shown by dark blue in Figure 2).

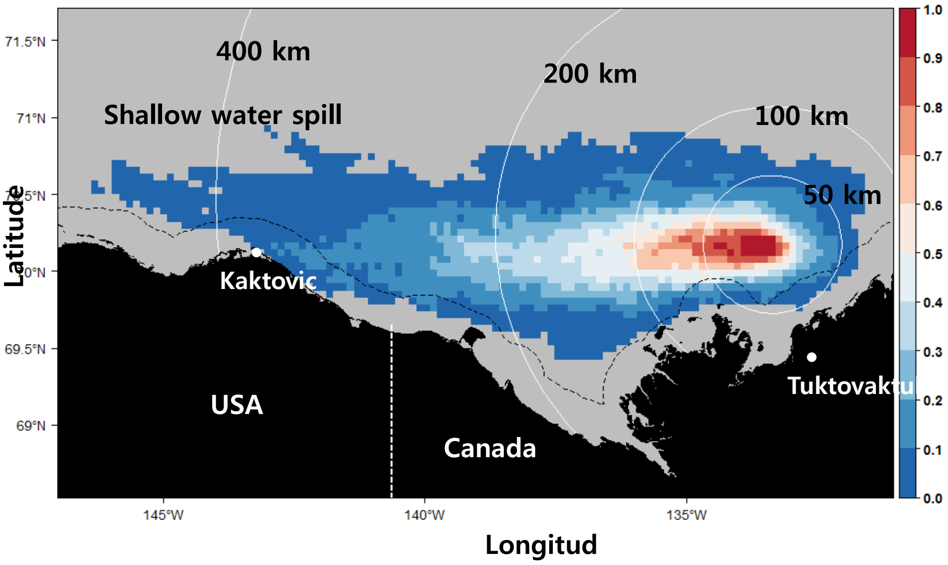

Figure 2. Probability of contamination (the chance that the spill reaches a location) for the shallow water in-ice spill scenario. In 120 days, the spill could move west more than 400 km and coastlines could be impacted. The dashed line shows the offshore distance of 25 km.

VALIDATION OF THE MODEL WITH AN OBSERVED IN-ICE OIL SPILL AND A BOUY TRAJECTORY

Validation of the Model with an Observed In-ice Oil Spill

As part of a SINTEF-led Joint Industry Partnership to study fate and behavior of spilled oil and the effectiveness and applicability of different cleanup technologies in ice-covered waters, oil was released between ice floes in the Barents Sea southeast of Svalbard in May 2009 (Sorstrom et al., 2010). The spill was tracked for 6 days (from May 15th to 20th) and reported to move with and remain between floes of ice, with concentrations ranging from 70% to 90% (Sorstrom et al., 2010). Figure 3a through 3d show the observed oil spill trajectory (reproduced from Sorstrom et al., 2010 and Ragnhild et al., 2011) on four available ice charts for the study period. The time-dependent location of the spilled oil is shown in Figure 3e.

Figure 4 shows the present NRC model results and the SINTEF observed trajectory. Although the present model predicts the general shape of the trajectory correctly, the extent of the trajectory is significantly underestimated. This underestimation is more pronounced along the east-west direction (~ 3 times) than along the north-south direction (~ 1.6 times). The final location of the modelled spill is approximately 23 km away from the start location of the spill while the observed value is approximately 37 km away. Table 1 lists the approximate observed and modelled movement of the oil for each day from May 15th to 20th 2009.

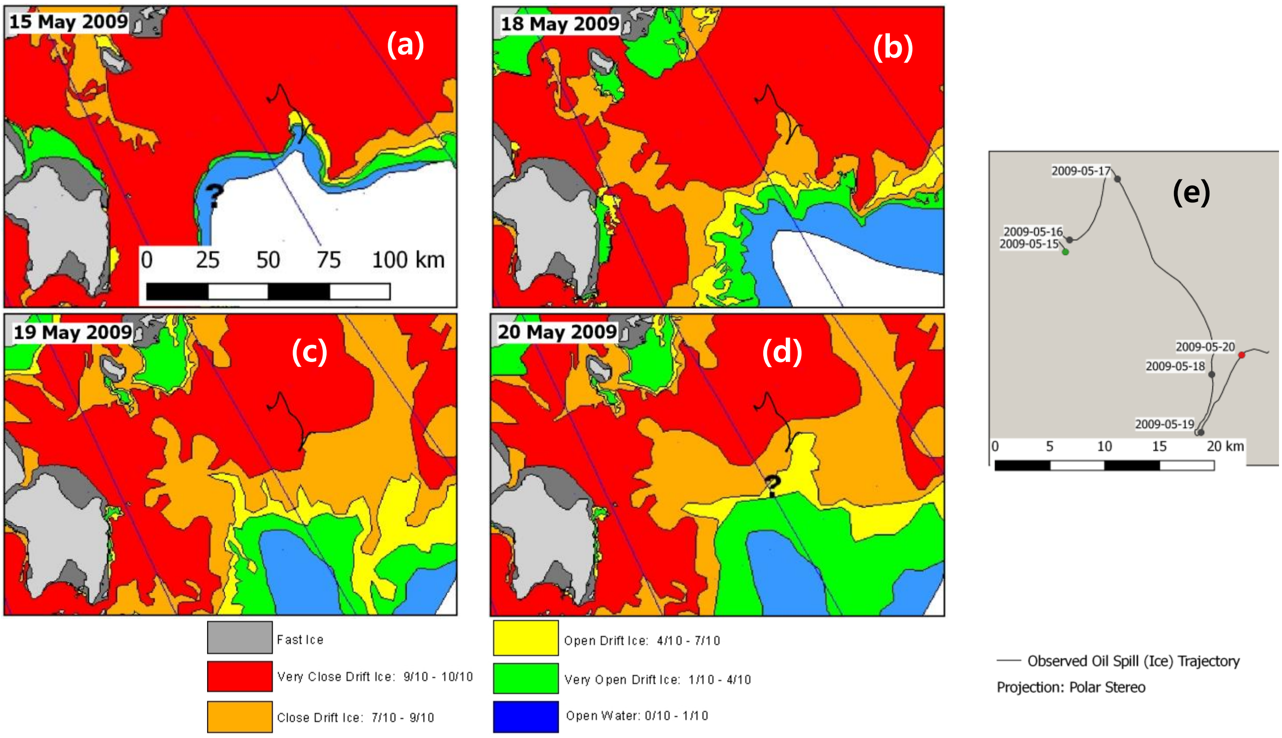

Figure 3. The relative location of the observed oil spill trajectory with respect to different ice categories for four days from the observation period in 2009. (a) 15 May, (b) 18 May, (c) 19 May, (d) 20 May. Ice charts are from the Norwegian Meteorological Institute. Observed oil is within 50 km from open water. (e) Observed trajectory (Sorstrom et al., 2010; Ragnhild et al., 2011) with dates.

Table 1. Approximate daily displacement of observed and modelled oil

Time period in 2009	**Approximate daily movement of oil, km**	
	Observed (Sorstrom et al., 2010 ; Ragnhild et al., 2011)	**Modelled**
May 15 to 16	3	3.5
May 16 to 17	13.5	2.5
May 17 to 18	42	16
May 18 to 19	10	8
May 19 to 20	17	5

The difference between the modelled trajectory and observation is attributed to the underestimation of ice speeds in the Polar Pathfinder dataset. It is known that the accuracy of the Polar Pathfinder data is higher when the concentration of ice and/or ice thickness is high (Sumata et al., 2014). Figure 3a through 3d show that the spill is within one to two Polar Pathfinder grid cell sizes from open water. We do not explore further whether this proximity to open water is the reason for the underestimation of ice drift by the Polar Pathfinder. We however briefly studied how the Polar Pathfinder data uncertainty impacts the modelled spill trajectory. The Polar Pathfinder dataset reports root-mean-square of error in the estimation of ice drift as a function of time and location. This error estimate with the mean value of error reported for the entire temporal and spatial coverage of the dataset (Miller et al. 2006) was the basis of a previous Monte-Carlo modelling whose details is given in (Babaei et al. 2016). Figure 4 shows the Monte-Carlo results as the probability of the oil reaching to any location. Although the results explain some of the differences between the modelled and observed trajectories, the modelled extent of the spill is still underestimated even if the uncertainties are included in the trajectory modelling.

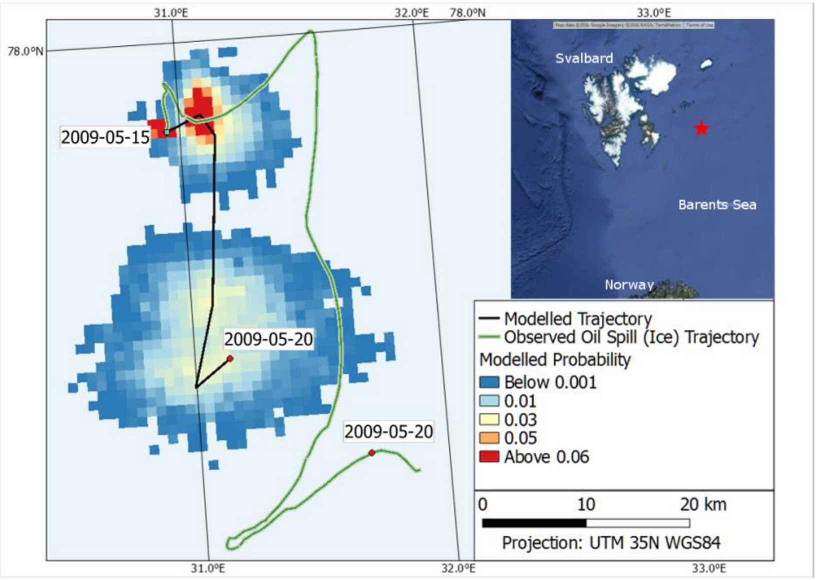

Figure 4. Observed oil moved more than the modelled oil. This difference is in part explained by considering the uncertainty in the Polar Pathfinder data input to the present model. The observed trajectory is reproduced from Sorstrom et al., 2010 and Ragnhild et al., 2011.

Validation of the Model with a Buoy Trajectory

Buoys of the International Arctic Buoy Program (IABP) are used to improve the accuracy of the Polar Pathfinder dataset (Fowler et al. 2013). It is then expected that the Polar Pathfinder data to be closely correlated to IABP data. We have previously validated the trajectory algorithm of the present model by comparing a modelled trajectory in the Beaufort Sea with an IABP buoy trajectory (Babaei et al. 2016). To further validate the present trajectory algorithm and to investigate how closely the Polar Pathfinder data is correlated to IABP data, we selected the trajectory of an IABP buoy in the Arctic Ocean north of Svalbard and compared it with the present model trajectory. Figure 5 shows the observed and modelled trajectories for the 20 Feb. 2009 to 8 Mar. 2009 period. The modelled trajectory closely follows the observed trajectory. The total observed travel distance is approximately 206 km while the modelled travel distance is approximately 188 km. The maximum difference between the location of the modelled and observed trajectory is approximately 15 km. The slight difference between the modelled and observed trajectories could be partially attributed to the large spatial (25 km) and temporal (1 day) resolution of the Polar Pathfinder dataset which are not enough to fully resolve sub-resolution events.

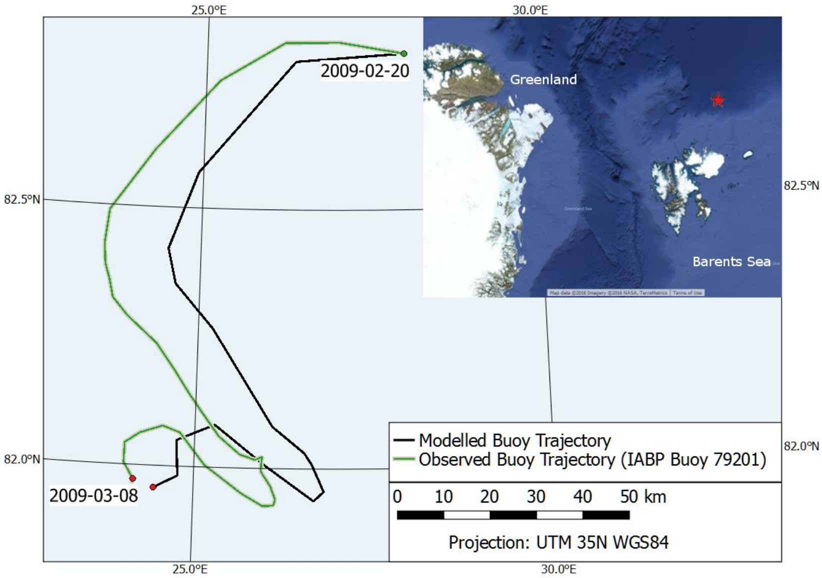

Figure 5. The present model closely predicts the trajectory of a buoy in the Arctic Ocean. The observed buoy moves approximately 206 km and the maximum difference between the model and observed trajectory is approximately 15 km.

VERIFICATION OF THE MODEL WITH AN INDEPENDENT NUMERICAL MODEL RESULTS FOR THE BEAUFORT SEA

The World Wildlife Fund (WWF) Canada sponsored a numerical study (Gearon et al., 2014) to model the fate, effects and trajectory of different hypothetical oil spill scenarios in the Beaufort Sea and their impact on wildlife. Spill scenarios included shallow and deep water blowouts and transportation and pipeline-based spills with different occurrence probabilities, locations, and onsets. Ice velocities for the modelling were based on a numerical ice-ocean data assimilation system named TOPAZ4 as a driver of a commercial oil spill modelling suite. When ice concentrations were more than 30%, the surface oil plume was modelled to move with ice. Modelled weekly locations of the surface oil plume are publicly available online through an interactive map at http://arcticspills.wwf.ca/. In our case, we selected an in-ice period of one of the modelled scenarios named Eastern Shipping-Bulker from the WWF study, to compare with the present model results. We modelled the trajectory of the in-ice plume from 27 Oct. to 15 Dec. 2009 and compared it with the WWF plumes reproduced from the online interactive map.

The Polar Pathfinder dataset, which is the input to the present model, does not have ice drift data for a region associated with a portion of the WWF plume on 27 Oct. 2009. This portion overlaps an open water region identified on the CIS ice chart for 26 Oct. 2009 (no ice chart was available for 27 Oct. 2009) shown in Figure 6a. The existence of the open water region explains the unavailability of ice drift data in the Polar Pathfinder dataset. We then chose to model only the trajectory of the in-ice portion of the WWF plume on 27 Oct. 2009.

Figure 6a through 6c compares the present modelled plume locations with those of the WWF study. WWF plumes reach closer to the coastline than the present modeled plumes by 40 km or less. Along parallels to the coastline, the difference between the location of the west edge of the plumes is less than 15 km until 17 Nov. 2009 after which the present NRC model plume moves faster than the WWF plume. This difference in the parallel to the coastline component of the plume (ice) velocity leads to an approximately 130 km difference in the locations of the west edges of the plumes on 15 Dec. 2009. Landfast ice is treated similarly in the present model and in the WWF study. However, the landfast ice extents used for the present model and in the WWF study were different; for the Alaskan Beaufort, the WWF study used a monthly average landfast ice extent based on observations between 1996 and 2008, and the present model uses time varying landfast ice extents extracted from the CIS's Regional Western Arctic ice charts. Figure 6c shows the average landfast ice extent used in the WWF study for the month of Dec. and one of the weekly CIS landfast ice extents for the month of Dec. 2009. We investigated whether this difference in the landfast ice extents caused the difference in the location of the plume; neither the present model plume nor the WWF plume is impacted by the existence of landfast ice because both plumes are away from the landfast ice edge. Note that we have not shown landfast ice extents in Figures 6a and 6b because plumes are far from the land for the dates associated with these two figures.

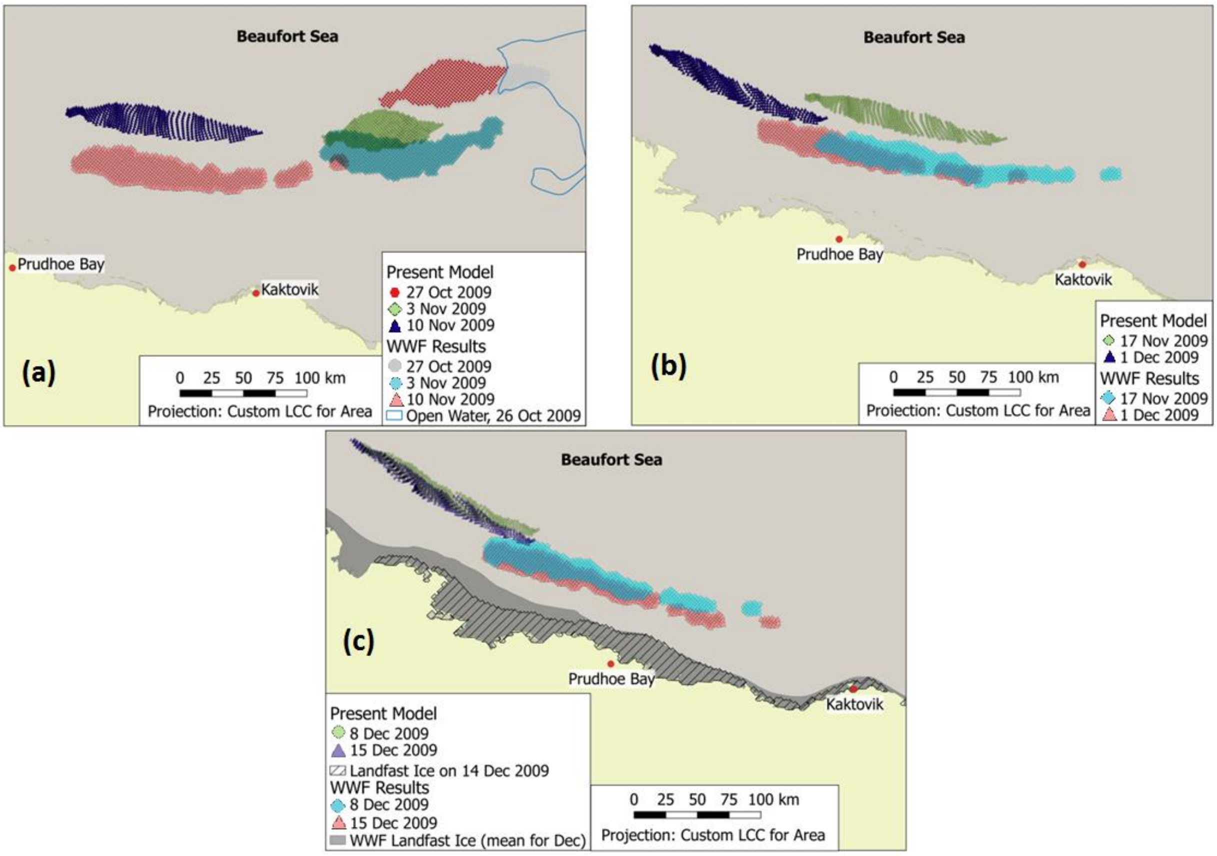

Figure 6. Comparison of the present model results with the WWF results reproduced from http://arcticspills.wwf.ca/. The difference in the coastward motion of the modelled and WWF plumes is within 40 km. The difference between the along the coast motion is within 15 km until Nov. 17 2009 after which the present model predicts faster motions.

It is challenging to find out whether the WWF or the present model results is a closer estimate of where the plume would go in reality. This is particularly true for the modelled nearshore plumes because both models are based on data known to have higher uncertainty levels closer to coastlines. For example, the Polar Pathfinder dataset, used in the present model, is expected to be less accurate close to coastlines and possibly in areas and times that no IABP buoys exists. To the best of the authors' knowledge, no IABP buoy exists in the space-time window of interest for the modelled scenario. The TOPAZ4 dataset, used for the WWF study, is expected to be less accurate nearshore (Gearon et al., 2014; Xie et al., 2016; Sakov et al., 2012) or even unavailable in some coastal regions of interest (Gearon et al., 2014).

CONCLUSIONS

Satellite-derived ice drifts were the basis of an in-ice oil spill trajectory model developed based on the assumption that oil moves with ice. To enhance the model, time dependent, spatially varying landfast ice extents were included in the model to reduce the uncertainty of satellite-derived ice drifts in coastal regions. Two hypothetical in-ice spill scenarios in deep and shallow waters of the Beaufort Sea were modelled and analyzed. The present model was used to estimate an observed spill trajectory that moved with ice in the Barents Sea; the model underestimated the extent of the trajectory because of the underestimation of ice drift in the input satellite-derived ice drift dataset. The trajectory of a buoy in the same general area was, however, closely estimated. The present model results were also compared with an independent numerical model results for in-ice oil spills in the Beaufort Sea. Coastward motions were generally similar but deviate after some time. Both the present model and the independent study results could be more uncertain nearshore and it is then challenging to know whether the present model or the independent study is a better representation of reality.

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REFERENCES

Babaei, H., Burcher, R., Watson, D., and Tivy, A., 2016. "In-ice Oil Spill Trajectory Modelling based on a Satellite-derived Ice Drift Dataset for the Beaufort Sea", *Proceedings of the thirty-ninth AMOP Technical Seminar*, Environment and Climate Change Canada, Ottawa, ON, pp.1-21.

Drozdowski, A., Nudds, S., Hannah, C.G., Niu, H., Peterson, I.K., and Perrie, W.A., 2011. *Review of Oil Spill Trajectory Modelling in the Presence of Ice*, Canadian Technical Report of Hydrography and Ocean Sciences 274, Fisheries and Oceans Canada, 92 p.

Eurasia Group, 2014. *Opportunities and Challenges for Arctic Oil and Gas Development*, The Wilson Center, Washington, D.C., 29 p.

Gearon, M. S., McCay, D. F., Chaite, E., Zamorski, S., Reich, D., Rowe, J., and Schmidt-Etkin, D., 2014. *SIMAP Modelling of Hypothetical Oil Spills in the Beaufort Sea for World Wildlife Fund (WWF)*, Project Number, ASA 13-235, 311 p.

Kimura, N. Nishimura, A., Tanaka, Y., and Yamaguchi, H., 2013. Influence of Winter Sea Ice Motion on Summer Ice Cover in the Arctic, *Polar Research*, 32, 20193.

Lavergne, T., Eastwood, S., Teffah, Z., Schyberg, H. and Breivik, L.-A., 2010. Sea Ice Motion from Low Resolution Satellite Sensors: An Alternative Method and its Validation in the Arctic, *Journal of Geophysical Research, Oceans*, 115, C10032.

LOOKNorth, 2014. *Oil Spill Detection and Modeling in the Hudson and Davis Straits*, Prepared for Nunavut Planning Commission, Report R-13-087-1096, 274 p.

MAR Incorporated, SL Ross Environmental Research Ltd., DF Dickins Associates Ltd., and Emergencies Science and Technology Division, 2008. *Empirical Weathering Properties of Oil in Ice and Snow*, Project Number 1435-01-04-RP-34501, Prepared for U.S. Department of the Interior Minerals Management Service Alaska Outer Continental Shelf Region, 170 p.

Miller, P.A., Laxon, S.W., Feltham, D.L., and Cresswell, D.J., 2006. Optimization of a Sea Ice Model Using Basinwide Observations of Arctic Sea Ice Thickness, Extent, and Velocity, *Journal of Climate*, 19, pp.1089–1108.

Muir, A., Baker, S., Laxon, S.W., Ridley, J., and Kwok, R., 2011. Arctic Sea Ice Dynamics for Climate Models: GlobICE Project Results and Products, *American Geophysical Union*, abstract #C52B-04.

National Snow and Ice Data Centre, 2016. *Arctic Sea Ice News & Analysis* [Online] Available at: http://nsidc.org/arcticseaicenews [Accessed 21 Nov. 2016].

Ragnhild, L. D., Faksness, L.G., Durgut, I., Brandvik, P. J., Leirvik F., 2011. *Modelling of Oil in Ice with OSCAR*, SINTEF A19804.

Sakov, P., Counillon, F., Bertino, L., Lisæter, K. A., Oke, P.R., Korablev, A., 2012. TOPAZ4: An Ocean-sea Ice Data Assimilation System for the North Atlantic and Arctic, *Ocean Science*, 8, pp. 633–656, doi:10.5194/os-8-633-2012.

Sorstrom, S., K., Brandvik, P., J., Buist, I., Daling, Per., Dickins, D., Faksness, L. G., Potter. S., Rasmussen, J.,F., Singsaas, I., 2010. *Joint Industry Program on Oil Spill Contingency for Arctic and Ice-covered Waters*, Summary Report: SINTEF A14181. Open.

Sumata, H., Lavergne, T., Girard-Ardhuin, F., Kimura, N., Tschudi, M.A., Kauker, F., Karcher, M., and Gerdes, R., 2014. An Intercomparison of Arctic Ice Drift Products to Deduce Uncertainty Estimates, *Journal of Geophysical Research, Oceans*, 119, 8, pp.4887-4921.

Tschudi, M., C. Fowler, J. Maslanik, J. S. Stewart, and W. Meier. 2016. *Polar Pathfinder Daily 25 km EASE-Grid Sea Ice Motion Vectors. Version 3. Boulder, Colorado USA: National Snow and Ice Data Center* [Online] Available at: http://dx.doi.org/10.5067/O57VAIT2AYYY [Accessed September 2016].

Venkatesh, S., El-Taha, H., Comfort, G. and Abdelnour, R., 1990. Modeling the Behaviour of Oil Spills in Ice-infested Waters. *Atmosphere-Ocean*, 28, pp. 303-329.

Xie, J., Bertino, L., Counillon, F., Lisæter, K. A., Sakov, P., 2016. Quality Assessment of the TOPAZ4 Reanalysis in the Arctic over the Period 1991-2013, *Ocean Science Discussions*, doi:10.5194/os-2016-38, 53 p.