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Modelling the long-term evolution of worst-case Arctic oil spills

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ABSTRACT

We present worst-case assessments of contamination in sea ice and surface waters resulting from hypothetical well blowout oil spills at ten sites in the Arctic Ocean basin. Spill extents are estimated by considering Eulerian passive tracers in the surface ocean of the MITgcm (a hydrostatic, coupled ice-ocean model). Oil in sea ice, and contamination resulting from melting of oiled ice, is tracked using an offline Lagrangian scheme. Spills are initialized on November 1st 1980–2010 and tracked for one year. An average spill was transported 1100 km and potentially affected 1.1 million km^2. The direction and magnitude of simulated oil trajectories are consistent with known large-scale current and sea ice circulation patterns, and trajectories frequently cross international boundaries. The simulated trajectories of oil in sea ice match observed ice drift trajectories well. During the winter oil transport by drifting sea ice is more significant than transport with surface currents.

1. Introduction

In 2008, the U.S. Geological Survey released a study which estimated that 16% of the worlds remaining recoverable hydrocarbon resources are located in the Arctic offshore. The highest potential for discoveries is identified to be on the continental shelves (Gautier et al., 2008). The retreat of the summer sea ice cover and the resulting extended open ocean season have resulted in a significant increase in oil and gas exploration in the Arctic Ocean (AANDC (Aboriginal Affairs and Northern Development Canada), 2013). Drifting sea ice in the Arctic Ocean, with an average thickness of 2 m and maximum observed keel drafts exceeding 15 m, poses unique challenges for oil and gas activities (Perovich et al., 2014; Melling and Riedel, 1996; Wadhams, 2012). To date, oil and gas drilling in ice-affected areas has largely been conducted in the shallow waters of the continental shelves. During previous oil and gas exploration in the Canadian Arctic in the 1970s and 80s, drilling was confined to water depths less than 68 m (Callow, 2012). However, with the increased accessibility of Arctic offshore oil and gas, and the pressure to meet the world's growing energy demand, drilling is now being considered in water depths of 400 to 700 m (Imperial, 2012). This expansion of drilling and exploration activities gives rise to an increased risk of oil spills.

In ice-covered waters, the effectiveness of traditional open-water response measures for oil spills at the ocean surface is lessened, and the procedures and estimated response time frames for a subsurface well blowout are under debate (Sørstrom et al., 2010; SL Ross, 2010; NEB, 2014). There is agreement, however, on the fact that major oil spills in this region are unlikely to be fully remediated in a short time frame, and could persist through the winter. Therefore worst-case risk assessments require long-term trajectory modelling of these spills, for periods of one year or longer.

In state-of-the-art oil spill trajectory models, the interactions between oil and sea ice are parameterized. This is because the processes by which sea ice influences spreading and transport of oil generally occur at a length scale of meters, which is far smaller than the available spatial resolution of regional-scale coupled ice-ocean models, which is usually on the order of kilometers (Reed et al., 1999; Drozdowski et al., 2011). In the presence of sea ice, spreading of oil at the ocean surface is inhibited since the buoyant oil will collect in leads between ice floes and cavities in the undulating under-ice surface, rather than form a thin slick as on open water. Oil that is trapped under the ice during periods of ice growth will generally be encapsulated within three days and remain in the ice until it is released by melting or upward migration through brine channels in the following spring (NORCOR, 1975; Dickins et al., 1981). Oil that has collected between ice floes and in under-ice cavities will be transported with the ice field unless the oil is mobilized by very strong under-ice currents. Venkatesh et al. (1990) report that in ice concentrations greater than 30%, the oil will generally follow the trajectory

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of the ice, rather than the ocean surface currents. This is based on observations by Deslauriers (1979), Industry Task Group (1983), and Ross and Dickins (1987). This criterion is still widely used in oil spill trajectory models, although the exact formulation of the transition between ocean-surface and ice-transported oil varies between models (Khelifa, 2010).

The OILMAP software suite, developed by Applied Science Associates, is the most widely used model for predicting oil spill trajectories in the presence of ice. This is a Lagrangian particle-tracking model in which each particle is given an additional degree of freedom to simulate gravitational spreading of oil into a thin slick. The model calculates particle trajectories using inputs of ocean currents, winds, and ice conditions from observations or circulation models. It also takes into account changes in oil density and viscosity due to weathering by evaporation and emulsification. Oil-ice interaction is parameterized by assuming that the oil moves with the ice at concentrations $>30\%$ and with ocean surface currents at concentrations $<30\%$. Where sea ice coverage is less than 30%, the density of oil may increase due to evaporation and emulsification and heavier fractions of the oil may be entrained in the water column by wind and wave action. In the model, these processes are considered to be a function of wind speed. As sea ice coverage increases from 30% to 80% the applied wind speed is decreased linearly, resulting in reduced evaporation, emulsification, and entrainment. These processes are considered not to occur in ice coverages exceeding 80%. In ice coverages between 30% and 80%, horizontal spreading of oil due to gravitational and viscous forces is modified by increasing the terminal oil slick thickness proportionally to the sea ice coverage to represent uninhibited spreading for concentrations $<30\%$ and no spreading at concentrations $>80\%$ (Khelifa, 2010; Drozdowski et al., 2011; Gearon et al., 2014).

Reed and Aamo (1994) evaluated the forecasting ability of this model during field trials in the marginal ice zone of the Barents Sea, with ice coverage ranging from 60% to 90%. Inputting observed and forecast winds, known tidal currents, and observed ice coverage, they found that trajectories were predicted well while winds were moderate (3–7 m/s) and directed towards the open ocean. A drift factor of 2.5% of the wind speed at a clockwise turning angle of 35° was used to parameterize the wind effect on oil drift. Observed oil trajectories began to deviate from forecasts when the wind direction shifted to blowing towards the ice, and strengthened to $\sim$10 m/s. An adjustment of the drift factor and turning angle to 1.5% and 60° was required to correct for this deviation. The authors attributed this to an increase in ice thickness due to ice floes overriding one another, caused by the strong on-ice winds.

Gearon et al. (2014) used the SIMAP model, which contains the same trajectory calculation algorithms as OILMAP, to assess risks associated with oil spills in the Canadian Beaufort Sea. They considered scenarios corresponding to well blowouts on the continental shelf and the continental slope and presented results as probabilities of contamination from spills in either June or August between 2008 and 2012. For the shelf blowout scenario, oil was released for 30 to 90 days and tracked for 30 days after the flow stopped. For the slope blowout, oil was released for 60 to 120 days and tracked for two months after the flow was stopped. The trajectory calculation of oil at the ocean surface was driven by wind forcing from the ERA-40 (European Centre for Medium-Range Weather Forecast Re-Analysis) data set and daily mean 3-D ocean currents, sea ice concentration, and sea ice velocity fields generated by the TOPAZ4 (Towards an Operational Prediction system for the North Atlantic European Coastal Zones) data assimilation system (Sakov et al., 2012). Landfast ice is included in the oil spill trajectory model based on monthly averaged data from Mahoney et al. (2012) (Alaskan coast, 1996–2008) and Koenig-Beatty (2012) (East of Mackenzie Delta, 1991–1998). The treatment of oil-landfast ice interaction is described in detail in Gearon et al. (2014). The results for both scenarios revealed potential for contamination travelling westward into the Chukchi Sea. The spread of oil from spills occurring later in the operating season was found to be limited by increased ice presence. Contamination from a blowout on the continental shelf was also predicted east of the site, in the Canadian archipelago.

Khelifa (2010) and Drozdowski et al. (2011) suggest that the accuracy of oil spill trajectories modelled for periods of up to one year may be improved by doing the modelling directly within coupled ice-ocean models, forced with reanalysis data for hindcasting, or coupled to an atmospheric model for forecasting applications. Nudds et al. (2013) used the ARC118 ice-ocean model driven by climatology from the CORE2 (Common Ocean-ice Reference Experiments) dataset to model trajectories of Lagrangian particles representing spilled oil in the ocean surface and sea ice. Packets containing an arbitrary number of particles were released every day for ten days from a site on the continental slope in the Canadian Beaufort Sea, in the same area as the Beaufort Sea Continental Slope location introduced in Section 2.3. Particles are released at the beginning of January, April, July, and October, and are tracked for three months in both the ocean and sea ice. Gravitational and turbulent spreading of oil into a slick is simulated by assigning a diffusion coefficient to the particles, though no clear relationship is established between the value of this diffusion coefficient and the volume of oil and its properties. The largest simulated extent of contamination results from the particle release on July 1st. Trajectories show primarily northeastward drift towards Banks Island for all cases, except for the Oct 1st release, where particles drifted westward towards Alaska. The simulated contamination in the sea ice and ocean is not co-located, with contamination in ice being less extensive. To quantify inter-annual variability, the experiments were repeated using CORE2 forcing for the years 1998–2000. The results for these three runs were neither a close match with each other, nor with the results derived using climatology. The authors concluded that using climatology to calculate oil spill trajectories does not produce satisfactory results. Fine and Masson (2015) used a similar approach for assessing oil spill risks in the ice-free waters of northwestern British Columbia.

In this study, we present worst-case probability distributions of contamination in sea ice and surface waters, resulting from continuous oil spills at ten sites of current oil and gas activity in the Arctic Ocean. These are derived by representing oil as an Eulerian passive tracer in the surface ocean of a regional setup of the coupled ice-ocean Massachusetts Institute of Technology general circulation model (MITgcm) (Marshall et al., 1997a,b), forced with Japanese Re-analysis (JRA-25) atmospheric fields (Onogi et al., 2007). In lieu of considering various volumes of spilled oil, we calculate the maximum extent to which an arbitrary discharge of oil may be transported over the course of one year. Oil spills are represented by a constant presence of a nominal amount of passive tracer at the spill site at the ocean surface, starting on November 1st of each year from 1980–2010. The transport of this tracer away from the spill site is then tracked for one year. The evolution of the passive tracer fields in the sea ice and surface ocean are calculated in two steps, since the MITgcm cannot consider passive tracers in sea ice in its current configuration. First the evolution of the weekly mean tracer fields in the surface ocean is calculated for each year of simulation using the MITgcm. These weekly mean passive tracer fields (analogous to weekly mean oil slick extents and positions) are then used to initialize parallel, offline Lagrangian tracking of oil in sea ice, in conjunction with weekly mean sea ice concentration and velocity fields output by the MITgcm. Where oiled sea ice melts, weekly mean ocean surface currents from the MITgcm are used to track the resulting contamination of the surface waters. The 31 simulated trajectories of contamination in the sea ice and surface waters are then used to derive the distributions of contamination probability.