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Ryan R. Wilson
U.S. Fish and Wildlife Service, ryan_r_wilson@fws.gov

Craig Perham
U.S. Fish and Wildlife Service, craig.perham@boem.gov

Deborah P. French-McCay
RPS-ASA, Debbie.McCay@rpsgroup.com

Richard Balouskus
RPS-ASA, Richard.Balouskus@rpsgroup.com

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Potential impacts of offshore oil spills on polar bears in the Chukchi Sea☆

Ryan R. Wilson [a, *], Craig Perham [a, 1], Deborah P. French-McCay [b], Richard Balouskus [b]

[a] U.S. Fish and Wildlife Service, 1011 E Tudor Rd., Anchorage, AK 99503, USA
[b] RPS-ASA, 55 Village Square Dr., South Kingstown, RI 02879, USA

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ABSTRACT

Sea ice decline is anticipated to increase human access to the Arctic Ocean allowing for offshore oil and gas development in once inaccessible areas. Given the potential negative consequences of an oil spill on marine wildlife populations in the Arctic, it is important to understand the magnitude of impact a large spill could have on wildlife to inform response planning efforts. In this study we simulated oil spills that released 25,000 barrels of oil for 30 days in autumn originating from two sites in the Chukchi Sea (one in Russia and one in the U.S.) and tracked the distribution of oil for 76 days. We then determined the potential impact such a spill might have on polar bears (*Ursus maritimus*) and their habitat by overlapping spills with maps of polar bear habitat and movement trajectories. Only a small proportion (1–10%) of high-value polar bear sea ice habitat was directly affected by oil sufficient to impact bears. However, 27–38% of polar bears in the region were potentially exposed to oil. Oil consistently had the highest probability of reaching Wrangel and Herald islands, important areas of denning and summer terrestrial habitat. Oil did not reach polar bears until approximately 3 weeks after the spills. Our study found the potential for significant impacts to polar bears under a worst case discharge scenario, but suggests that there is a window of time where effective containment efforts could minimize exposure to bears. Our study provides a framework for wildlife managers and planners to assess the level of response that would be required to treat exposed wildlife and where spill response equipment might be best stationed. While the size of spill we simulated has a low probability of occurring, it provides an upper limit for planners to consider when crafting response plans.

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The extent of summer sea ice in the Arctic Ocean has been greatly reduced over the past decade due to global warming (Overland and Wang, 2013; Stern and Laidre, 2016). Further declines are expected in the coming decades until sea ice is nearly absent during summer months in the Arctic (Laliberté et al., 2016; Overland and Wang, 2013). As a result, the Arctic Ocean ecosystem is anticipated to experience extensive ecological change (Post et al., 2013) including population reductions (Kovacs et al., 2011; Regehr et al., 2016), and the northward range expansion of marine species (Wassmann et al., 2011). Reduced summer sea ice extent will also increase human access to the Arctic Ocean. Shipping routes that were once impassible due to sea ice will soon become viable (Smith and Stephenson, 2013) and areas once inaccessible for offshore oil and gas development will soon be ice-free long enough to allow for development (Harsem et al., 2015; National Research Council, 2014). These anthropogenic activities increase the potential for oil spills to impact the marine ecosystem.

While economic opportunities in the Arctic Ocean are increasing, there is concern that the ability to respond to marine oil spills is insufficient given the limited infrastructure in the region (Knol and Arbo, 2014; National Research Council, 2014). Thus, if an offshore spill were to occur, it is unlikely that it could be contained early enough to limit exposure to wildlife. There is currently limited information on what impact an offshore oil spill would have on marine mammal populations in the Arctic (Huntington, 2009). The information that does exist suggests varying levels of impact across species (Geraci and Smith, 1976; Hurst et al., 1991; Øritsland et al., 1981).

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* Corresponding author.
E-mail addresses: ryan_r_wilson@fws.gov (R.R. Wilson), craig.perham@boem.gov (C. Perham), Debbie.McCay@rpsgroup.com (D.P. French-McCay), Richard.Balouskus@rpsgroup.com (R. Balouskus).
[1] Present address: U.S. Bureau of Ocean Energy Management, 3801 Centerpoint Dr., Suite 500, Anchorage, AK 99503.

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Given the potential negative consequences of an oil spill on marine wildlife populations in the Arctic, it is important to develop and maintain plans on how to respond to oiled wildlife in the event of a spill. This requires an understanding of how habitat could be affected, what areas are most likely to be contaminated, and how many animals might be exposed to sufficient oil to require capture and decontamination. Such proactive assessments will help those responsible for clean-up efforts anticipate the level of response and equipment that will be required, and where that equipment should be stationed for efficient deployment during oil spill response efforts. This information would also help provide wildlife managers with an understanding of the population-level effects on a species if an offshore spill occurred.

Most studies examining impacts to wildlife from energy development are retrospective (Northrup and Wittemyer, 2013) and thus unable to help mitigate the impact if an accident occurs. Indeed, few studies have attempted to understand the magnitude of impact an offshore oil spill in the Arctic would have on wildlife, although Amstrup et al. (2006) conducted a study to determine how many polar bears (*Ursus maritimus*) might be exposed to oil if a spill were to occur in the Beaufort Sea. They estimated 0–74 polar bears (with a skew towards lower values) could be exposed to oil from a 5900 barrel spill in September or October. While there have been planning efforts initiated for how to respond to an oil spill in the Chukchi Sea by management agencies (U.S. Fish and Wildlife Service, 2015), a similar analysis to Amstrup et al. (2006) has not occurred in the adjacent Chukchi Sea even though there have been offshore exploratory activities in recent years and increased interest in the oil potential of the region (Verzhbitsky et al., 2012).

In this study we attempt to understand the impact to polar bears in the Chukchi Sea from a worst case discharge (WCD) oil spill and inform management agencies of the magnitude of impact such a spill might have. Companies are required to develop WCD scenarios as part of any offshore oil and gas development in U.S. federal waters. Although unlikely to occur, they represent a reasonable worst case scenario to estimate potential impacts to wildlife. Therefore, our objectives were to simulate WCD oil spills at two different sites in the Chukchi Sea to determine, 1) the probability of oil reaching different areas of the Chukchi Sea, 2) how long it would take for oil to reach those regions, 3) the amount of important polar bear habitat that could be exposed to oil, and 4) what proportion of the polar bear population might come into contact with oil. Our goal was not to estimate the actual number of animals or area of habitat that would be affected by an offshore oil spill, but rather to determine what levels might be reasonable to expect if a WCD spill were to occur.

1. Materials and methods

1.1. Oil spill modeling

We modeled hypothetical oil spills at two locations in the Chukchi Sea (Fig. 1). Exploratory drilling occurred near the first site (i.e., within ~20 km), Crackerjack (N71.13, W166.14), in the 1980s and was also listed as a site for exploration drilling by Shell Gulf of Mexico Inc. in their 2010 exploratory drilling program (Minerals Management Service, 2009). The second site was located within the Yuzhno Chukotsky Lease block southeast of Wrangel Island in Russian waters (N70.20, W175.56; Fig. 1). This location was created under a cooperative agreement with Rosneft and ExxonMobil as part of a plan to develop hydrocarbon resources in the Russian Arctic shelf (Exxon Mobil, 2013). In recent years, there has been increased interest in offshore drilling in the Russian Arctic, including lease areas in the Chukchi Sea (Tippee, 2013). While neither site we analyzed is currently being actively developed, the waters adjacent to the sites provide important habitat to polar bears (Rode et al., 2015; Wilson et al., 2014). It is therefore an opportune time to determine what level of impact an offshore spill at each site could have on polar bears to help inform future offshore drilling plans in the region and response efforts in the event a large oil spill ever occurred.

A full description of the oil spill modeling efforts we employed are detailed in French-McCay et al. (2017a). Here we provide a brief synopsis. To model oil spills at these locations, we used results of modeling by French-McCay et al. (2017a), which employed the OILMAPDEEP model (Crowley et al., 2014; Spaulding et al., 2000) to calculate the behavior and dilution of the released oil and gas mixture in the buoyant plume from such a discharge near the release site. Those model results indicated that the plume from discharges at both locations would surface within an hour of release. Thus, the oil spill model was initiated from just below the water surface (1m) with a median droplet size of 1817 microns (French-McCay et al., 2017a). To model the transport, fate, and distribution of oil, we used the Spill Impact Model Application Package (SIMAP; French-McCay, 2004; French-McCay et al., 2017a). The SIMAP model has been validated with numerous actual oil spills (French-McCay et al., 2017b, 2004; French and Rines, 1997; McCay, 2003) and has been used in many risk assessment studies (French-McCay et al., 2005), including in the Arctic (French-McCay et al., 2014; French-McCay et al., 2017b). In the model, the distribution and fate of oil was primarily affected by wind, ocean currents, and sea ice. Oil moves with the surface currents and wind for water with no ice, or that has sea ice with a concentration <30%. If sea ice concentration is $\geq 30\%$, however, ice is assumed to have ample spatial coverage to trap oil between floes and oil is transported with the ice using ice-movement velocities. If oil came into contact with land fast ice (i.e., ice that is affixed to land and does not move), the model assumed the oil became entrapped and remained immobile until the ice melted and pack ice retreated north. In the presence of sea ice, oil weathering processes (e.g., evaporation and emulsification) and physical processes such as spreading and entrainment are slowed proportionate to the degree of ice coverage. See Appendix S1 for details on sources of environmental data (e.g., currents, ice, and wind) used in the SIMAP model.

We simulated spills as underwater blowouts releasing 25,000 barrels of Prudhoe Bay crude oil per day for 30 days beginning in October during autumn (i.e., the transition period between open water and the ice-covered seasons). This discharge scenario represents the WCD described in the Chukchi Sea Regional Exploration Program Oil Spill Response Plan (Shell Gulf of Mexico Inc., 2015). Worst case discharges are defined by the Bureau of Ocean Energy Management (BOEM) as the daily rate of an uncontrolled flow of oil from all producible reservoirs into the open wellbore. Because a similar WCD analysis was not conducted for the simulated Wrangel spill site, we used the same WCD scenario as defined for the Crackerjack site.

We tracked the fate and distribution of released oil for a period of 76 days after the initial blowout. We employed a stochastic approach to estimating the probable trajectory and distribution of spills from each site by sampling 100 random start times in October between 2008 and 2014 and using water current, ice, and wind data that corresponded to the period of the selected start date (see below). The random start time allowed for the same type of spill to be analyzed under varying conditions. We therefore were able to estimate probabilities of the distribution of oil based on a range of realized environmental conditions. The output of the model was the daily distribution of individual spillets (i.e., discs with a given radius and mass of oil). We then synthesized these spillets to obtain the daily mass of oil within a grid of 1 km^2 pixels.

We classified oil into two different classes (i.e., medium and

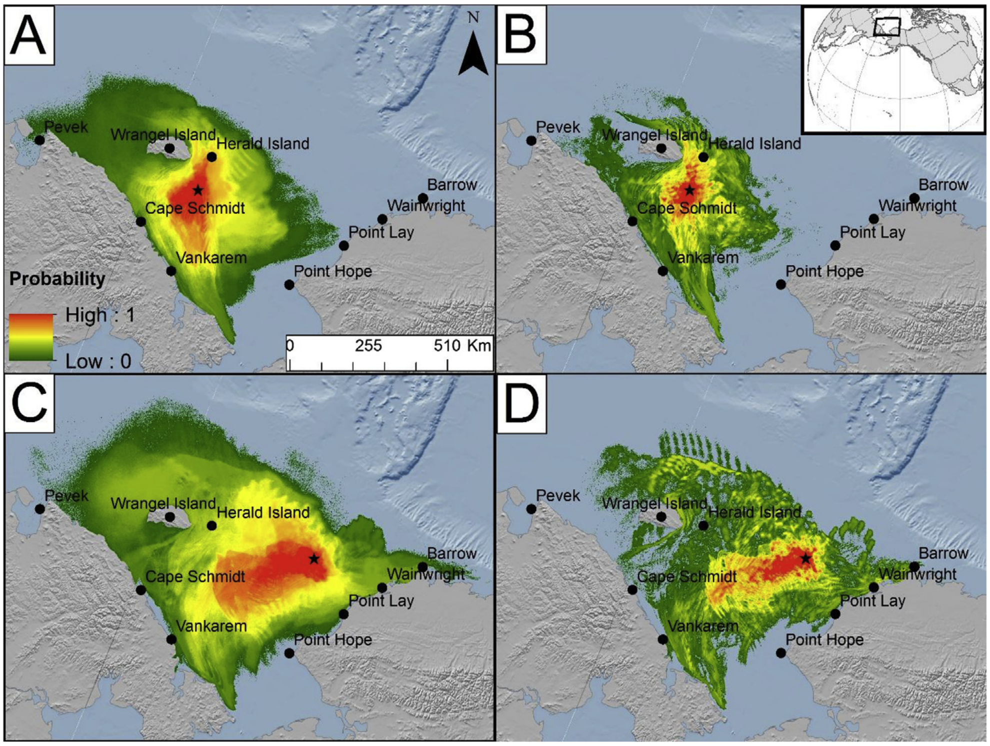

Fig. 1. Maps depicting the probabilities of medium (i.e., $\geq$1.0 g/m^2) and high density oil (i.e., $\geq$10.0 g/m^2) reaching different regions of the Chukchi Sea after a 30 day underwater blowout monitored for a 76 day period; medium density oil from Wrangel (A) and Crackerjack (C) spill sites, high density oil from Wrangel (B) and Crackerjack (D) spill sites. Each spill site is depicted with a star.

high oil densities) as it relates to the oil's potential to cause harm to wildlife (French-McCay, 2016). We defined a pixel as having reached a medium oil density threshold if the density of oil was $\geq$1 g/m^2. This density of oil is considered to potentially have sub-lethal effects on marine mammals (French-McCay, 2016), for example via ingestion of toxins through grooming of the pelage (Engelhardt, 1984; Geraci and St. Aubin, 1988). We defined pixels with a density of oil $\geq$10 g/m^2 as having reached a high oil density threshold. Oil density greater than this threshold is considered to have potentially lethal effects on marine mammals (French-McCay, 2016) which, for polar bears, could lead to thermoregulation problems caused by the coating of fur, hair loss (Derocher and Stirling, 1991), or renal failure (Øritsland et al., 1981).

1.2. Impacts to polar bears

During the period of our simulated spills, >60% of polar bears in the Chukchi Sea are on sea ice (Rode et al., 2015). Of those bears using land, the average date they return to sea ice is early November (Rode et al., 2015). While bears are on ice, the majority of their time is spent out of the water, but they have been observed in the water 17% of the time (Pagano et al., 2017). Thus, if oil is in water adjacent to ice polar bears are using, there is a reasonable chance that they could be exposed to oil, potentially fouling their fur.

To estimate the potential impacts to polar bear habitat from the simulated spills, we used resource selection estimates for bears in the Chukchi Sea (Wilson et al., 2016) to develop daily maps of polar bear habitat conditions. Using the coefficient estimates provided in Wilson et al. (2016), we developed maps of polar bear resource selection for dates corresponding to the dates of the simulated spills. Following the Wilson et al. (2016) study, resource selection maps were derived based on spatial layers of ice concentration, spatial variation in sea ice concentration, ocean depth, and the presence/absence of landfast ice. We then overlaid the daily spill trajectories with the daily polar bear resource selection maps to determine how much 'high-quality' polar bear habitat would come into contact with oil. We defined 'high-quality' habitat as any area that had a probability of polar bear use $\geq$0.80 (Durner et al., 2009; Wilson et al., 2016). The predicted habitat maps corresponded with conditions present during the same date of the simulated spill.

Given the large proportion of the Chukchi Sea polar bear population that occurs on shore in autumn (Rode et al., 2015), we examined the probability of different areas of coastal habitat being impacted by the simulated spills. We estimated the probability that medium and high density oil would come within 10 km of communities along the Chukchi Sea coast as well as Wrangel and Herald islands (Fig. 1). We also estimated the average time it would take for oil to reach these locations after the spill occurred. Our assessment of the time for oil to reach communities not only served to identify times for oil to reach different regions, it also informs communities of the potential risks to their subsistence activities and how much time they have to prepare for an actual spill.

We estimated the cumulative proportion of polar bears in the study region that could potentially be exposed to oil by relating empirical data on polar bear movements to each simulated spill trajectory. Between 2008 and 2016, 103 adult female polar bears were captured and instrumented them with satellite tracking collars collecting either Argos or global positioning system (GPS) locations at intervals ranging from every 2 h to every four days. Captures occurred on the sea ice south and southeast of Point Hope (Fig. 1). Of those instrumented bears, 46 had location data that overlapped the period of simulated spills (i.e., Oct–Jan). Given differences in location acquisitions rates and location error across collars, and the need to have polar bear locations match the daily oil spill time-steps, we used the continuous time correlated random walk (CRAWL; Johnson et al., 2008) model to estimate polar bear locations at daily intervals. The CRAWL model allows users to account for uncertainty in animal locations and to estimate locations at unobserved times based on the set of observed locations. Because there is uncertainty in animal locations as well as the path animals moved between two locations, the CRAWL model also allows for multiple path realizations to be obtained, helping to account for the overall uncertainty in where bears traveled during the period of the spill. To implement the CRAWL model, we used the 'crawl' package (Johnson, 2017) in program R (R Core Development Team, 2016). We handled location errors with the CRAWL model the same as described in (Rode et al., 2015). See Appendix S2 for an example of how this analysis worked. Polar bear movement data used for this component of the analysis were largely derived from the same set of individuals that Wilson et al. (2016) used to estimate resource selection patterns. However, data from bears obtained between 2013 and 2016 were not included in the Wilson et al. (2016) analysis, but were added to the data set used in the current analysis.

2. Results

Worst case discharge oil spills from both sites have the potential to expose a large area of the Chukchi Sea, with spills from both sites crossing the international boundary between the U.S. and Russia (Fig. 1). While the ultimate trajectory of a spill would be uncertain given variable environmental conditions, our results show that some areas of the Chukchi Sea would have high probabilities of being exposed to oil during any spill (Fig. 1). For the oil spill originating near Wrangel Island, areas to the north and southwest of the spill site had high probabilities of being exposed to oil by both medium and high oil densities (Fig. 1). Locations that had a ≥80% probability of being exposed to oil from the Wrangel spill site covered an area of 23,109 km^2 and 7430 km^2 for medium and high oil densities, respectively. The Crackerjack spill led to areas west of the release site having the highest probability of exposure (Fig. 1). Locations that had a ≥80% probability of being exposed to oil from the Crackerjack spill site covered an area of 44,500 km^2 and 6546 km^2 for medium and high oil densities, respectively.

2.1. Polar bear impacts

The average area of high value polar bear habitat exposed to oil increased for approximately 10–20 days after the 30 day release period for both scenarios (Fig. 2). During the 76 days that oil was tracked from the Wrangel spill site, the average maximum area of high value polar bear habitat exposed to oil was 5289 km^2 (SD = 2269; 95% CI = 4844–5734) and 923 km^2 (SD = 473; 95% CI = 830–1016) for medium and high old densities, respectively. These areas represent approximately 3–10% and 1–2% of available high value polar bear habitat for medium and high oil densities, respectively (Wilson et al., 2016). The Crackerjack spill affected slightly higher levels of polar bear habitat than the Wrangel spill, with medium density oil affecting a maximum of 6055 km^2 (SD = 3182; 95% CI = 5431–6679) of high value polar bear habitat and high density oil affecting 706 km^2 (SD = 311; 95% CI = 645–767).

As a result of the Wrangel spill, we estimated that 38% (SD = 10; 95% CI = 36–40), and 13% (SD = 9; 95% CI = 11–15) of polar bears in the Chukchi Sea could be exposed to oil of medium and high densities, respectively, 76 days after the spill first occurred (Fig. 3). The Crackerjack spill resulted in an estimated 27% (SD = 13; 95% CI = 25–30) of polar bears exposed to medium oil density and 5% (SD = 4; 95% CI = 5–6) exposed to high oil density (Fig. 3).

The two spill scenarios differed in their probabilities of reaching sites along the U.S. and Russian coasts (Table 1). Simulated spills from the Wrangel site never reached U.S. coastal communities, whereas spills from the Crackerjack site reached locations in both countries during the 76 days spills were tracked (Table 1). For both spill scenarios and densities of oil, Wrangel and Herald islands had the highest probabilities of being exposed to oil compared to all other sites considered (Table 1). The communities of Vankarem and Cape Schmidt had the highest probabilities of being exposed to oil from a spill originating at the Wrangel site (Table 1). In the U.S., the communities of Barrow and Wainwright had the highest probabilities of being exposed to oil from a spill originating at the Crackerjack site (Table 1). For both spill scenarios, medium-density oil took, on average, 3–5 weeks to reach coastal regions (Table 1). High-density oil responded similarly, taking an average of 3–6 weeks to reach coastal regions (Table 1).

3. Discussion

Our results suggest that a WCD oil spill in the Chukchi Sea during autumn could expose large numbers of bears to oil. The number of bears we estimated to potentially come into contact with oil could range from 100 to 800 bears based on a population of 2000 polar bears found in the Chukchi Sea (Obbard et al., 2010) and our estimates of the proportion of bears in the study area possibly exposed to oil. This level of exposure occurred even though only a small fraction of preferred sea ice habitat was exposed to oil during the spills because of the behavioral habits of bears being concentrated on the ice edge as it moves back over the shallow waters of the continental shelf (Durner et al., 2009). It is possible that the actual number of bears exposed to oil would be much lower because our estimate only reflects those bears that were in the vicinity of oil (i.e., within a 1 km^2 grid cell with oil). There are conflicting observations about whether polar bears would voluntarily enter water with oil (Derocher and Stirling, 1991; Øritsland et al., 1981). Food, however, might provide an adequate incentive (Øritsland et al., 1981; St. Aubin, 1990) and their hunting behavior could increase the probability of exposure to oil (Stirling, 1990). At a minimum, these results highlight the potential need to decontaminate a large number of polar to avoid reduced survival associated with compromised thermoregulation due to fouling of fur (Hurst et al., 1991; Øritsland et al., 1981) or physiological effects associated with ingestion of oil through grooming (Øritsland et al., 1981; Stirling, 1990).

As is the case with any oil spill, early containment of discharged oil and a quick cessation of the blowout are imperative to limiting exposure to wildlife. We found that most polar bears, and their preferred habitat, would not be exposed to oil until 2–3 weeks after the initial release of oil. Therefore, meaningful efforts to contain a spill, or limit the duration oil is actively released, could lead to a significant reduction in the number of polar bears exposed. This is mostly due to fact that in October, the sea ice in the Chukchi Sea is still a significant distance (~400 km) from our spill sites. This time lag, as well as the lag between release and oil contact with key onshore habitat (e.g., Herald and Wrangel islands) indicates there may be some time to mount efforts to contain the spill, or attempt to keep it from reaching important areas. A quick response to a spill during autumn is also important given the challenges of oil cleanup in Arctic waters. For example, in situ burning of oil can remove >90% of oil on the water surface, but must be initiated quickly as it becomes less effective as the water content of the oil emulsion increases or in the presence of slush ice (Potter and Buist, 2008). Mechanical recovery of oil or the placement of booms could also become more difficult once sea ice is present due to the challenges of operating boats in icy waters (National Research Council, 2014).

The Bureau of Ocean Energy Management estimated there is a 75% chance of one or more large spills (i.e., >1000 barrels)

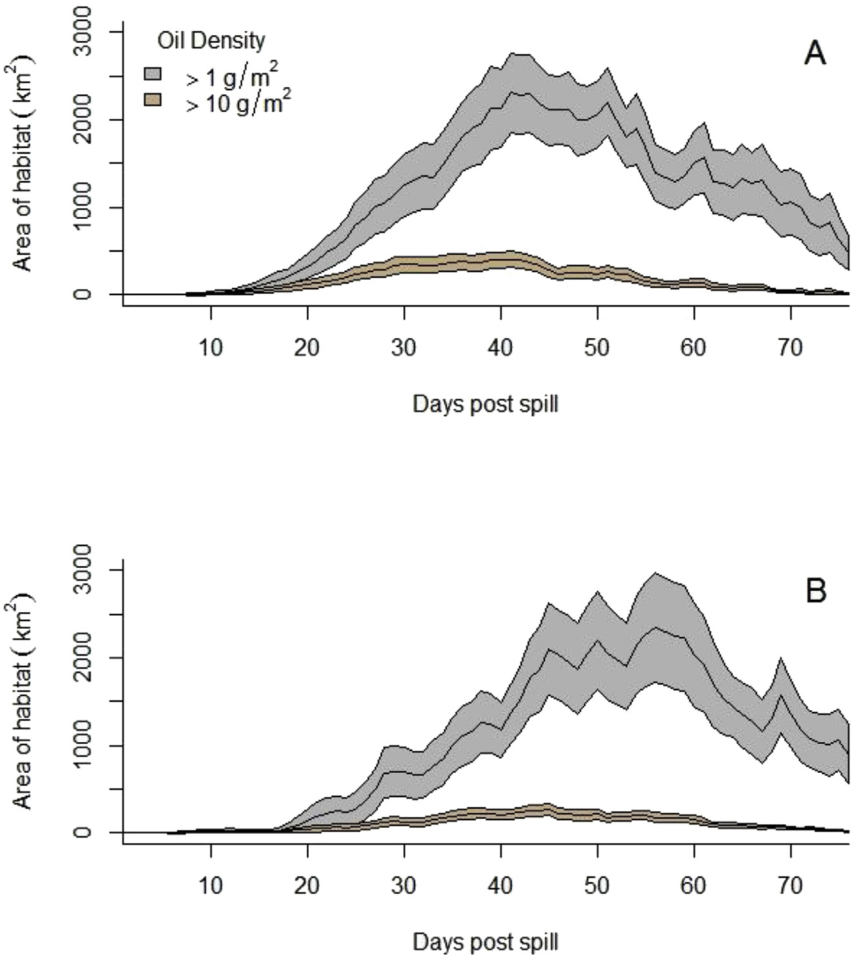

Fig. 2. Areas of high-value polar bear habitat exposed to medium (i.e., $\geq$1.0 g/m^2) and high density oil (i.e., $\geq$10.0 g/m^2) at the Wrangel (A) and Crackerjack (B) spill sites throughout the 76 day period oil was monitored after the initial simulated spill. Gray and tan polygons represent the 95% CI around the mean (i.e., center lines of polygons).

occurring during the production life of offshore platforms, pipelines, and wells in the Chukchi Sea (Bureau of Ocean Energy Management, 2015). Our simulations released a total of 750,000 barrels, significantly larger than what BOEM considered a large spill. However, in their Supplemental Environmental Impact Statement, BOEM considered there was at least some probability (albeit very low; ~10^{-5}) of a very large oil spill occurring in the Chukchi Sea Planning Area that could release 2,160,200 bbl after a 74 day period (Bureau of Ocean Energy Management, 2015). Even though the risk of the WCD spill is likely extremely small we wanted to highlight a scenario used by industry (Shell Gulf of Mexico Inc., 2015) to understand the potential magnitude of impact a spill could have on polar bears in the region. We also wanted our scenarios to reflect the current lack of infrastructure in the Arctic to respond to spills and challenges of containing oil in icy waters (National Research Council, 2014). Thus, our results do not reflect the actual probability of a spill occurring nor the likely magnitude of a spill if one were to occur. Clearly, a shorter duration spill, or one that was contained sooner than 30 days would lead to lower levels of exposure of bears and other marine mammals. Indeed, our results indicate that most bears would not get exposed to oil until at least three weeks after the initial spill although this was mostly due to sea ice not yet being adjacent to the spill sites in October.

We only estimated how many bears might be exposed to oil from a spill. Additional effects of an oil spill (e.g., consumption of contaminated prey), however, could have prolonged impacts on polar bears beyond the immediate effects of oil exposure, such as consumption of contaminated prey and the potential for longer-term issues such as bio-accumulation of contaminants. While ringed seals exposed to oil or forced to consume contaminated prey generally fared well (Geraci and Smith, 1976), it remains unclear what impact consumption of contaminated prey would have on polar bears. Research has suggested that bio-accumulation or magnification of contaminants from ringed seals (*Pusa hispida*) to polar bears can occur, but that its magnitude varies across contaminant type (Letcher et al., 2009). Large amounts of oil directly consumed through grooming is detrimental to polar bears (Øritsland et al., 1981), but what levels of oil bears might be expected to consume through contaminated prey is unknown, as are the long-term consequences of eating contaminated prey. There is some evidence to suggest that other forms of contamination can lead to population-level effects of polar bears (Derocher et al., 2003), so it is reasonable to suspect that oil-contaminated prey might also be problematic for bears.

Our use of empirical movement data to estimate potential exposure of bears to oil has a variety of assumptions that if violated could significantly alter our estimates. First, it assumes that bears captured in the region southeast of Point Hope exhibit representative movements of other bears in the region. This is generally thought to be the case because bears caught in this area exhibit annual movements that cover the entire range of the population

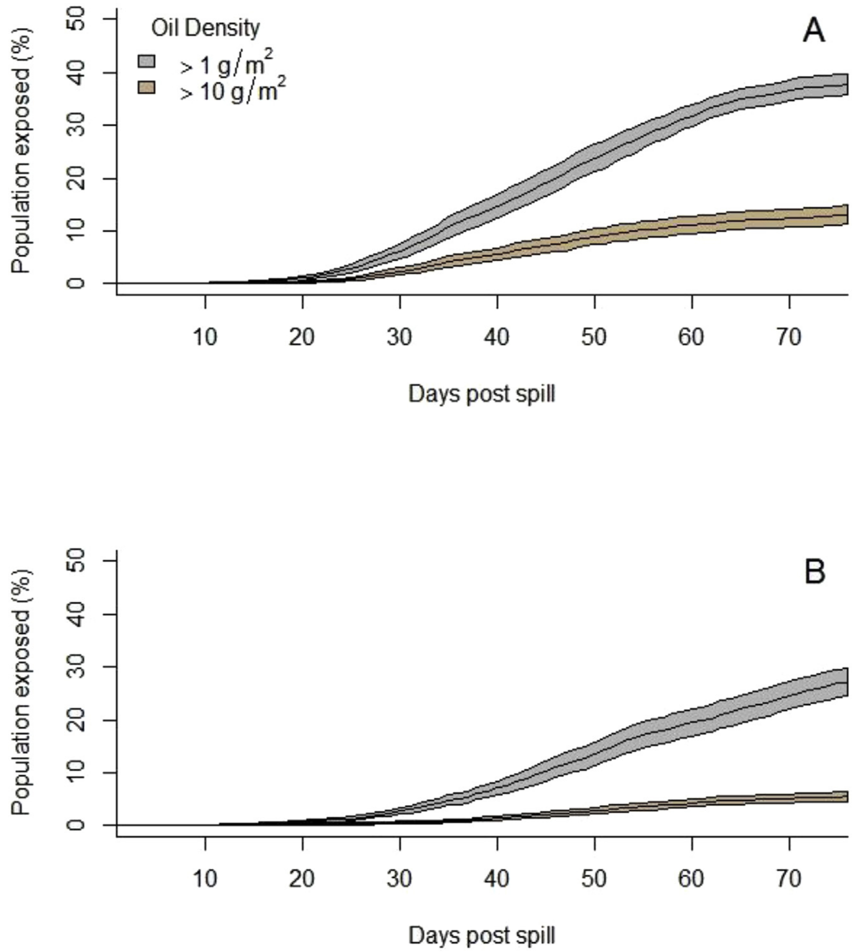

Fig. 3. Cumulative percent of polar bears in the Chukchi Sea exposed to medium (i.e., $\geq$1.0 g/m^2) and high density oil (i.e., $\geq$10.0 g/m^2) at the Wrangel (A) and Crackerjack (B) spill sites throughout the 76 day period oil was monitored after the initial simulated spill. Gray and tan polygons represent the 95% CI around the mean (i.e., center lines of polygons).

Table 1
Summary of time for oil of medium (i.e., $\geq$1.0 g/m^2) and high density (i.e., $\geq$10.0 g/m^2) to reach shore at varying locations in Russia and the U.S. after a 30 day uncontrolled underwater blowout at two different simulated spill sites; Wrangel and Crackerjack. The probability (*P*) of oil reaching each location across 100 stochastic simulations is also presented.

Sites	Spill Scenario							
	Wrangel				Crackerjack			
	Oil Density				Oil Density			
	Medium		High		Medium		High	
	P	Days ($\bar{x}$ ± SD)	*P*	Days ($\bar{x}$ ± SD)	*P*	Days ($\bar{x}$ ± SD)	*P*	Days ($\bar{x}$ ± SD)
Russia								
Wrangel Island	.61	25 ± 14	.54	32 ± 16	.35	22 ± 12	.28	36 ± 12
Herald Island	.82	27 ± 13	.61	33 ± 13	.41	20 ± 9	.22	45 ± 18
Pevek	.00	–	.00	–	.00	–	.00	–
Cape Schmidt	.17	22 ± 10	.07	14 ± 5	.01	25 ± –	.00	–
Vankarem	.20	36 ± 7	.07	45 ± 6	.05	19.8 ± 3	.04	22 ± 4
U.S.								
Pt. Hope	.00	–	.00	–	.00	–	.00	–
Pt. Lay	.00	–	.00	–	.12	22 ± 8	.09	21 ± 6
Wainwright	.00	–	.00	–	.23	25 ± 10	.22	26 ± 10
Barrow	.00	–	.00	–	.22	34 ± 16	.18	34 ± 14

(see Fig. 1 in Wilson et al., 2014). We also assume that our sample of movement data from 48 bears provided sufficient information to capture the variation in movement patterns exhibited by the population. Our approach assumes that our sample of adult female movements is also representative of male movements. While not specifically addressed for polar bears in our study region, Laidre et al. (2013) found that males and females of two separate polar bear populations exhibited similar habitat selection patterns and 4–

day displacement distances. Finally, our approach assumes that polar bears will not avoid areas with oil. While there are few observations of polar bears interacting with oil, the general consensus is that polar bears would not avoid an oil spill and instead likely investigate them (Derocher and Stirling, 1991).

This study highlights the need for coordination between the U.S. and Russia on oil spill response planning in the event of an oil spill in either country's waters. The U.S. and Russia currently have a bilateral agreement on responding to oil spills, but there have been no joint spill response drills between the two countries which are important for identifying problems before a real spill occurs (National Research Council, 2014). Such coordination currently exists between Norway and Russia and has been successful in ensuring there is adequate dialogue and planning to responding to a spill if one were to occur (Sydnes and Sydnes, 2013). Regardless of which country a spill occurs in, our study shows there is a significant probability for oil, sufficient to cause biological contamination, to reach both countries. Additionally, given the high probability of oil reaching Herald and Wrangel islands, and their importance to polar bears (Rode et al., 2015), it would be prudent to station spill containment equipment at each location once oil extraction begins. Given the potentially large number of polar bears that could be exposed to oil, the difficulty of finding and capturing bears on the sea ice, the logistical challenges of reaching bears with traditional means (e.g., land-based helicopters) due to their distances from shore, and the limited capacity to clean contaminated bears, oil spill planning should focus on how to best limit exposure of bears to oil rather than relying on post-hoc cleanup efforts.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.envpol.2017.12.057.

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