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Estimating Potential Effects of Hypothetical Oil Spills on Polar Bears

By: S.C. Amstrup, G.M. Durner, T.L. McDonald¹, and W.R. Johnson²

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¹ Western Ecosystems Technology, Inc. 2003 Central Ave., Cheyenne, WY, 82001, USA ² Minerals Management Service, 381 Elden St. MS 4041, Herndon, VA, 20170, USA

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ABSTRACT

Much is known about the transport and fate of oil spilled into the sea and its toxicity to exposed wildlife. Previously, however, there has been no way to quantify the probability that wildlife dispersed over the seascape would be exposed to spilled oil. Polar bears, the apical predator of the arctic, are widely dispersed near the continental shelves of the Arctic Ocean, an area also undergoing considerable hydrocarbon exploration and development. We used 15.308 satellite locations from 194 radiocollared polar bears to estimate the probability that polar bears could be exposed to hypothetical oil spills. We used a true 2-dimensional Gausian kernel density estimator, to estimate the number of bears likely to occur in each 1.00 km² cell of a grid superimposed over near shore areas surrounding 2 oil production facilities: the existing Northstar oil production facility, and the proposed offshore site for the Liberty production facility. We estimated the standard errors of bear numbers per cell with bootstrapping. Simulated oil spill footprints for September and October, the times during which we hypothesized effects of an oil-spill would be worst, were estimated using real wind and current data collected between 1980 and 1996. We used ARC/Info software to calculate overlap (numbers of bears oiled) between simulated oil-spill footprints and polar bear grid-cell values. Numbers of bears potentially oiled by a hypothetical 5912 barrel spill (the largest spill thought probable from a pipeline breach) ranged from 0 to 27 polar bears for September open water conditions, and from 0 to 74 polar bears in October mixed ice conditions. Median numbers oiled by the 5912 barrel hypothetical spill from the Liberty simulation in September and October were 1 and 3 bears, equivalent values for the Northstar simulation were 3 and 11 bears. In October, 75% of trajectories from the 5912 barrel simulated spill at Liberty oiled 9 or fewer bears while 75% of the trajectories affected 20 or fewer polar bears when we simulated an October spill at the Northstar site. Northstar Island is nearer the active ice flaw zone than Liberty. Simulations suggested that oil spilled at Northstar would spread more effectively and more consistently into surrounding areas. Also, polar bear densities are consistently higher near Northstar. Oil spills simulated for the Liberty site were more erratic in the areas they covered and the numbers of bears impacted, and numbers of bears hypothetically exposed were usually smaller. Methods described here are broadly applicable to other dispersed marine wildlife.

Key words: Arctic, Beaufort Sea, clustering, kernel, management, oil spill, polar bears, population delineation, radiotelemetry, satellite, smoothing, *Ursus maritimus*

INTRODUCTION

The polar bear is the apical predator of the arctic ecosystem and perhaps the universal symbol of the Arctic. The distribution of polar bears is tied to that of sea ice in the Beaufort Sea region. They are most common in areas near the continental shelf where active ice over the deep water of the polar basin meets the shallow shelf water, and where there are persistent leads and openings suited to hunting seals. The continental shelf also is an important region for oil exploration and development (Stirling 1990). Spilled oil from continental shelf projects could foul some of the most important foraging habitats of polar bears.

Oil and other chemicals, can be fatal to exposed bears (Oritsland et al. 1981, Amstrup et al. 1989, St. Aubin 1990). Bears are known to consume foods (and non-food items) fouled with petroleum products, and they groom intensively when their fur and environment are fouled. Spilled oil may be concentrated in pools on the ice surface and accumulate in leads and openings that occur during spring break-up and autumn freeze-up (Neff 1990). Such mechanical concentration of spilled oil would increase the probability that polar bears and their principal prey (ringed seals, *Phoca hispida*) will be directly oiled. Also, the oiling of their prey suggests bears could be secondarily exposed to oil by consuming fouled prey. In short, we can expect that a spill in the waters and ice of the continental shelf will result in contamination of polar bears and other animals dependent upon the air-ice-water interface.

There previously has not been a way to determine how many bears, or other animals dispersed over the seascape, might be exposed to oil contamination. Models describing the movement and deterioration of oil in the environment have been developed and extensively tested (Smith et al. 1982, National Academy of Sciences 1985, Galt et al. 1996, French 2001). The life and health threats to animals exposed to oil also are well described, and much has been written about the toxicological effects of oil on birds and mammals (National Academy of Sciences 1985, Geraci and St. Aubin 1990, Loughlin 1994). Similarly, the mechanisms of contact, e.g. surface exposure, inhalation, ingestion, frequently have been discussed (Oritsland et al. 1981, National Academy of Sciences 1985, Geraci and St. Aubin 1990, Loughlin 1994). Despite abundant information on all of these topics, however, there previously has been no probabilistic way to quantify the numbers of animals that could be exposed to oil in the event of a spill.

Without a probabilistic method to estimate numbers exposed, there is no link between knowledge of the fate and transport of spilled oil and knowledge of the toxicity of oil to wildlife. Previous studies have identified methods for estimating probabilities that certain "high value targets" may be oiled (Galt et al. 1996, National Oceanic and Atmospheric Administration, National Ocean Service, Office of Response and Restoration 2005). Targets commonly are headlands, reefs, or other coastal features known to be important as rookeries or other terrestrial refugia for marine animals. Such methods cannot quantify impacts to wildlife resources scattered over broad ocean areas. French (2001) described, in a hindcasting context, how models might be used to estimate impacts on scattered resources, but the source and nature of resource data was not clear, and estimates were presented without measures of uncertainty. Hall (2002) showed intersections between point observations of marine birds and probability contours of oil spill trajectories. Hall's (2002) results, however, also were shown without expressions of the uncertainty in estimates of exposure. Similarly, Bodkin and Udevitz (1994) developed an intersection method to assess potential exposure of sea otters (*Enhydra lutris*) to spilled oil, but it too lacked the necessary quantitative information on distribution of the animal resource, to make probabilistic estimates or predictions.

Numbers of animals exposed, and hence mortality levels that could be caused by oil spills have yet to be projected. Without such projections, preparations for and responses to spills will be inadequate. Here, we describe a method for making those projections by expressing wildlife distributions as probabilities of occurrence and oil spills as projected trajectories. We provide methods for estimating uncertainty for both data streams. For demonstration, we use location data from polar bears in the Beaufort Sea and two offshore oil production facilities (one operational, and one proposed) near Prudhoe Bay Alaska.

METHODS

General Strategy

The two sites chosen for this simulation exercise were the existing Northstar oil production island located 15 km northwest of Prudhoe Bay, Alaska, and the original site proposed for the Liberty oil production facility located 27 km east of Prudhoe Bay (Figure 1). An alternative onshore site is currently being explored for the Liberty development, but that alternative was considered after our calculations were performed. Radio-telemetry data collected during September and October were converted into estimates of density within the area surrounding each simulation site. We used methods developed by NOAA (National Oceanic and Atmospheric Administration, National Ocean Service. Office of Response and Restoration 2005) and the U.S. Minerals Management Service (Smith et al. 1982) to generate paths of hypothetical oil spills. The general strategy used in this study was to: 1) calculate the probabilistic distribution of polar bears in our study area, 2) map the "footprints" of a series of oil-spill scenarios originating from each location, and 3) use GIS layering to overlap the simulated oil-spill footprints with polar bear distributions to estimate the numbers of bears that would be exposed to oil in each scenario.

Spill Size, Timing, and Duration

Large oil releases from the production islands, which could enter the offshore waters were considered less likely than those from pipelines (Minerals Management Service, Alaska Outer Continental Shelf Region 2001). Leaks stemming from pipeline failures, which were thought to be plausible risks, ranged from 125-5912 barrels (Minerals Management Service, Alaska Outer Continental Shelf Region 2001). Total compromise of the sub-sea pipeline, from any cause, was estimated to result in the loss of 1580 barrels of crude oil (Minerals

Management Service, Alaska Outer Continental Shelf Region 2001: Volume III, Appendix A). Failures, of under ice detection systems, to detect chronic leaks could result in loss of as much as 5912 barrels of oil depending on the failure scenario (Minerals Management Service, Alaska Outer Continental Shelf Region 2001: Volume III, Appendix J). Release of trapped oil by thaw or autumn storm event would be equivalent to the catastrophic loss of these large volumes of oil. Therefore, because we were interested in evaluating significant oil-spill scenarios, we treated the largest anticipated spill of catastrophic origins (1580 barrels) and the largest anticipated chronic spill (5912 barrels) as if they both were instantaneous discharges. We hypothesized that smaller spills would cover less area, be less environmentally damaging, and expose fewer polar bears.

When the southern Beaufort Sea (SBS) is covered by solid ice, spilled oil would remain trapped in the ice very near the source of release. Solid ice entrapment would guarantee minimal spread, and also maximize opportunities for clean-up and recovery of spilled oil. By way of contrast, we hypothesized that maximum oil-spread would occur in open water. Polar bears, although less common than when ice is present, still occur near shore during largely open water periods. Finally, bear densities near shore are at their highest during the autumn broken ice period, and although hampered somewhat by ice, oil still could travel great distances. We therefore hypothesized the effects of an oil-spill would be most severe during the open water period of maximum potential oil spread and during the mixed ice period of maximum polar bear density. So, we modeled oil-spills occurring during both summer and autumn time frames. The summer time frame, 22 August – 30 September, coincided with the maximum extent of open water in the Southern Beaufort Sea, and should have allowed greatest spread of oil released from our modeled locations. The mixed ice autumn time frame, 1 October – 9 November, coincided with the highest densities of bears in the near-shore environment.

All oil-spill trajectories simulated instantaneous release and 10 days of travel for the oil after the time of release. We concluded that although we could follow simulated oil spill paths almost indefinitely, the likelihood that our models would mimic real oil behavior undoubtedly diminished rapidly beyond the first several days post-spill. Also, oil weathering processes suggested that the nature of the oil product remaining beyond 10 days would be quite different than newly released oil (Neff 1990, Reed et al. 2000, Buist et al. 2003). Beyond 10 days, therefore, we concluded that spreading of spilled oil could follow different rules than fresh crude, and would not be adequately represented by our model. Clearly, however, movement of oil, for more than 10 days, would cause more damage and probably oil more bears than were oiled in the first 10 days. Similarly, a long-lasting as opposed to an instantaneous release might result in greater damage. We simply did not have the oil movement and weathering data to realistically evaluate such eventualities.

Estimates of Where an Offshore Oil Spill May Go

Oil spill trajectories are represented by the Lagrangian motion that a particle on the sea surface might take under given wind, ice, and ocean current

conditions (Galt et al. 1996). We simulated between 360 and 500 trajectories each composed of 500 Lagrangian elements (called spillets) to give a statistical representation of possible oil transport. Each spillet moves under the influence of the range of wind, ice, and ocean-current conditions that exist in an area during a particular time-frame. We simulated movement of spilled oil by two circulation models. An Inshore Model covered the area predominantly influenced by wind in summer and covered by shore-fast ice during winter. An Offshore Model covered the areas offshore of the zone influenced by shore-fast ice. Inshore was defined as the area lying approximately between the twenty-meter bathymetric contour and the shoreline. This area is characterized by the most stable ice along this portion of the Beaufort Sea coast. Because both of our simulated release sites were within this inshore region; all of our spill simulations began their trajectories under Inshore Model conditions.

Current vectors in the inshore region were simulated using a 2dimensional hydrodynamic model developed by the National Oceanic and Atmospheric Administration (NOAA) (Galt 1980, Galt and Payton 1981). This inshore model, which is based on wind forcing and the continuity equation, was originally developed to simulate wind-driven shallow water dynamics in lagoons and shallow coastal areas with complex shorelines. Iterative solutions balance wind forcing friction, pressure gradients, coriolis accelerations, and bottom friction and incorporate the barrier islands as well as the coastline. This method is implemented in the General NOAA Oil Modeling Environment (GNOME, National Oceanic and Atmospheric Administration, National Ocean Service, Office of Response and Restoration 2005) which is currently used for oil spill modeling nationwide. Oil spills stopped when they contacted the mainland coastline, but were allowed to move around coastlines of the small offshore islands. An example of the near-shore currents simulated by this model for a 10meter/second wind is shown in Figure 2. Model results were similar to available current meter velocities during summer open water conditions (Hachmeister et al. 1987) with many events coinciding in time. This coincidence suggested that currents derived from the NOAA model generally correspond with real-world currents.

The Inshore model does not have an ice module associated with it. We added an ice mask between shore and the 20-meter water-depth contours to simulate the observed shorefast ice zone. The ice mask had a 100% ice concentration. During the time the mask is applied, from November 1-June 15, the model allows neither ice nor spilled oil to move. When the mask is removed, oil moves within this zone as if in open water.

We simulated spreading of spilled oil throughout offshore regions with the Oil-Spill-Risk Analysis model (OSRA) (Smith et al. 1982). The OSRA model uses information about the physical environment, including wind, ice, and current data to predict the likely paths of oil spills. For cases where the ice concentration was below 80%, each trajectory was constructed using vector addition of the ocean current field and 3.5% of the instantaneous wind field—a method based on work

done by Huang and Monastero (1982); Smith et al. (1982); and Stolzenbach et al. (1977). The current vector and the oil drift vector were simulated using a 3dimensional coupled ice-ocean hydrodynamic model (Hedström 1994, Hedström et al. 1995). The Offshore Model is based on the semispectral primitive equation ocean model of Haidvogel et al. (1991), and the ice model of Hibler (1979). For cases where the ice concentration was 80% or greater, the model ice velocity was used to transport the oil. Equations 1 and 2 show the components of motion that were simulated and used to describe the oil transport for each spillet:

$$U_{\rm oil} = U_{\rm current} + 0.035 \ U_{\rm wind} \tag{1}$$

 $U_{\rm oil} = U_{\rm ice}$

(2)

where: $U_{oil} = oil drift vector$

 U_{current} = current vector (when ice concentration is less than 80%)

 U_{wind} = wind speed at 10 meters above the sea surface

 $U_{\rm ice}$ = ice vector (when ice concentration is greater than or equal to 80%)

The wind drift factor was estimated to be 0.035 of the wind speed, with a variable drift angle ranging from 0° to 25° clockwise. The drift angle was computed as a function of wind speed according to the formula in Samuels et al. (1982). (The drift angle is inversely related to wind speed.) Wind input for OSRA was derived from the TIROS Operational Vertical Sounder (TOVS) which has flown on NOAA polar-orbiting satellites since 1978. TOVS data from 1980 through 1996 were available for this modeling exercise. The TOVS Pathfinder (Path-P) dataset provides observations of areas poleward of latitude 60° N at a resolution of approximately 100 x 100 kilometers (Chedin et al. 1985). The dataset is centered on the North Pole and has been gridded using an equal-area azimuthal projection, a version of the Equal-Area Scalable Earth-Grid (EASE-Grid) (Armstrong and Brodzik 1995). For the Beaufort Sea, the $U_{current}$ and U_{ice} are simulated using the two models described above. A random vector component was added to represent sub-grid scale uncertainty associated with turbulence or mixing processes that are not resolved by the physical transport processes of the general circulation model. This assures that each spillet moves differently than others despite being released at the same time and place, and being subjected to the same modeled ice, current, and wind conditions.

The ocean and ice models are forced by the fluxes of momentum and heat, estimated from the daily surface geostrophic winds and monthly thermodynamic fields. The location of each trajectory at each time interval was used to select the appropriate ice concentration. The pack ice was simulated as it grows and melts. The edge of the pack ice is represented on the model grid. Depending on the ice concentration, either the ice or water velocity with wind drift from the stored results of the coupled ice-ocean model (Haidvogel et al. 1991) is used. A major assumption used in this analysis was that the ice-motion velocities and the ocean daily flows calculated by the coupled ice-ocean model adequately represented the flow components. Sensitivity tests and comparisons with data illustrate that the model does capture the first-order transport and the dominant flow (Hedström et al. 1995).

Our models did not simulate cleanup scenarios of any kind. Therefore, oil transport was assumed to occur without human intervention. The effects of any oil discharge prevention and contingency plans must be analyzed separately, and are not addressed in this paper.

Estimation of Polar Bear Numbers

Field Procedures

We captured and radio-collared adult female polar bears in the Beaufort Sea and adjacent areas, during spring and autumn 1985—2003, for the purpose of deploying satellite (PTT) radio collars. Captures were accomplished by injecting immobilizing drugs with projectile syringes fired from helicopters (Larsen 1971, Schweinsburg et al. 1982, Stirling et al. 1989). We did not radio-collar male polar bears because their necks are larger than their heads, and they do not retain radio collars. Capture protocols were approved by independent animal care and welfare committees. Collars we deployed were ultra high frequency (UHF) platform transmitter terminals (PTT's) that were relocated by satellite. Data retrieved from PTT's were processed by the Argos Data Collection and Location System(ADCLS)(Fancy et al. 1988).

Analyses

We generated a population distribution based on locations of satellite radio-collared polar bears and estimates of polar bear population size for bears in western Canada, the southern Beaufort Sea, and the Chukchi Sea (Amstrup et al. 2004). Location data for polar bears equipped with PTTs in the Beaufort and Chukchi Sea were collected from 1985 to 2003 by USGS in Alaska and by the Canadian Wildlife Service in western Canada. We used only high quality radiolocations that were within < 1 km of the true location of the bear. PTTs had duty cycles that varied according to research objectives, ranging between a daily position fix to a weekly position fix. To standardize location data among different duty cycles, we selected only one high quality observation per week per satellite collar. Total population size for the study area was calculated as the sum of the population estimates for the northern Beaufort Sea (1200 bears), southern Beaufort Sea (1800 bears), and the Chukchi Sea (2000 bears) in Lunn et al. (2002). Population estimates were used only to convert scaled probability densities to estimates of the relative numbers of bears in each cell of our grid. The important aspect of these estimates is not their absolute population levels, but rather that the ratios of one population size to another were sensible; and that estimates for each population were of comparable quality. Also, implicit in our computations was the assumption that un-collared bears move and use space similarly to collared bears. This was justified because we were aware of no reason why behavior of unmarked females in any of the populations would be fundamentally different from that of collared females. In addition, available

evidence suggests little or no difference in movement patterns and space use between male and female polar bears (Stirling et al. 1980, Schweinsburg et al. 1981, Lentfer 1983, Stirling et al. 1984, Amstrup et al. 2001).

We estimated the number of polar bears present in each cell of the grid by smoothing and scaling the raw frequencies (i.e., the actual radio-tracking locations) in each cell with a 2-dimensional Gaussian kernel density estimator with fixed elliptical bandwidth (Wand and Jones 1995, Kern et al. 2003, Amstrup et al. 2004). Kernel smoothing made it possible to use the location data for predictive purposes without presuming any particular statistical distribution for individual locations (Worton 1995). In effect, the kernel smoother converted frequency counts in each cell in the grid to an expected intensity of use for each cell. Unlike other smoothing protocols, we used a true 2-D approach that allowed the major and minor axes of the smoother to differ in length (bandwidth) and orientation (Kern et al. 2003, Amstrup et al. 2004).

We converted raw frequencies into density or intensity of use values by scaling the mean frequency counts such that they summed to one. Variation inherent in estimated intensity values was computed using bootstrap methods (Manly 1997, Kern et al. 2003) where individual bears were randomly re-sampled with replacement. Each bear identification number was selected for re-sampling by bootstrapping along with its associated collection of locations. This non-standard bootstrap sampling insured that time dependencies (i.e., auto-correlation), if present in the original data, also were present in each bootstrap sample. Because numbers of locations for each bear differed, each bootstrap sample was a different size. Once a bootstrap sample was selected, the entire estimation procedure was performed using the bootstrap data. We computed standard errors for each cell in the grid from the 1000 bootstrap calculations of relative intensity of use. We then had point and interval estimates of the number of bears in each cell of our grid.

We used the ARC/INFO (ver. 9.0, ESRI, Redlands, CA) GENERATE command to produce a point coverage of the coordinate file. Attribute data were read into an INFO template with the INFO ADD FROM command. The INFO template was then merged to the point coverage with the ARC/INFO JOINITEM command. The final point coverage of polar bear density included a point attribute table of density and Standard Error (SE). This point coverage of density and associated standard errors included a region of 3300 × 3300 km with a 5000 m distance between points and covered the entire Beaufort and Chukchi Sea (Amstrup et al. 2004: Figure 1).

The originally proposed Liberty island was centered at 70°16'45.36" N and 147°33'29.09" W. Northstar island is centered at 70°29'27.08" N and 148°41'51.74" W. For each location, we overlaid a grid with 1024 by 256, or 262,144 total cells (cell size 1000 m), where each grid was centered over its respective oil production island. Hence, each grid was slightly offset from the other (Figure 1). Grids extended approximately from the Mackenzie River delta, Canada, west to Point Lay, Alaska, and from 100 – 280 km north of the coast. These study areas then, were subsets of the Beaufort Sea, and represented a

portion of the total range of 3 polar bear populations that occur in the southern Beaufort Sea (Amstrup et al. 2004). To estimate the monthly distribution of polar bears in our study areas, we needed to determine how many of the bears from each of the 3 populations were present in the two smaller regions.

ARC/INFO polygon coverages of each study area were created with the GRIDPOLY command. Population size of each region within the study area was determined by producing a new point coverage of bear density with the INTERSECT command, where all points that fell within the region polygon boundary were included in the new point coverage. We used the STATISTICS command to summarize the density values of each new point coverage and derive a population estimate for each region. We generated a new set of polar bear satellite radio-locations (see above description) that fell within each region during each period for which we simulated spills. We then calculated a population density based on the estimated number of bears and the distribution of radio-collared bears within each region by reapplying the Gaussian Kernel smoother to the data in each smaller grid. This produced an ARC/INFO point coverage of bear density for both the Liberty and Northstar study areas. Finally, we used the POINTGRID command to create a grid of bear densities and a grid of associated standard errors, for both the Liberty and the Northstar regions.

Spillets moved with winds and currents, as if they were simple points, but they represented volumes of oil that have mass. Therefore, spillet arcs were converted to polygons by incorporating the expected spreading, over the surface of sea water, for that volume of oil. Table 1 illustrates the diameters over which spillets of different volumes would be expected to spread (Fay 1971, Lehr 2001). For example, each of the 500 spillets from a spill of 1580 barrels would represent 3.16 barrels of oil and would spread to a diameter of ~27 m (Table 1). Oil spillet paths used in our simulations were estimated to have a maximum spread diameter of 47 m. Therefore, only a small proportion of any 1 km polar bear density cell would be intersected by the narrow spillet path, and we felt it would be unreasonable to count an entire 1 km² density cell as oiled. To prevent this possible overestimation, our density and SE grids were further partitioned to assure that the portion of a cell across which a spillet moved, rather than the entire cell, might be counted as oiled. We used ARC/INFO GRID module commands to subdivide each cell. We performed 2 subdivisions. We first generated a grid in which each 1 km² cell was divided into 400 smaller (50 \times 50 m, or 2500 m²) cells. This approximated the 47 m width of each spillet in the 5912 barrel spill. Then we further subdivided the 1 km² cells into 1600 cells measuring 25 x 25 m to approximate the 27 m spillet width from the 1580 barrel spill.

Intersection of Oil-Spill Trajectories and Bear Densities

Modeled oil-spill trajectories were linear paths or arcs showing how wind and current forcing moved each spillet through the study area. By overlaying the paths of spillets with our grid of bear densities and standard errors, we could determine the number of grid cells and the number of bears that oil would contact. To simulate spillet paths that incorporated the diameters of the two spillets sizes in which we were interested, we used the LINEGRID command to convert line coverages, of oil spill trajectories, to individual raster grids with 25 m and 50 m cell sizes. We used GRID commands to create a bear density grid and a SE grid for each trajectory by assigning density and SE values to trajectory grid cells. We assigned values by matching each cell center of the trajectory grid with the closest cell center from the bear density or SE grid (Figure 3). Density and SE values of each trajectory grid were exported as an ASCII text file for analysis.

Each path of the 500 spillets was composed of hourly arc segments. The arc attribute table (AAT) of trajectory coverages included: ID (identifies an hourly arc segment of a spillet by the trajectory number, spillet number, and hourly increment); TRAJ (the trajectory identifier); SPILLET (spillet identifier); YEAR (year of data used to generate the oil spill scenario); JDAY (julian day of data used to generate the oil spill scenario); HOUR (hour of the day, from 1 – 24); and ICE_PCT (percent ice coverage for that particular spillet segment). We used the INFO command REDEFINE to create a new field of hourly increments in the AAT. This new field (labeled INTERVAL), allowed us to select trajectories falling entirely in a targeted timeframe. Individual trajectory swere extracted from the master coverage and saved as individual trajectory line coverages.

Estimation of the number of polar bears potentially affected by each of our simulated oil spills required the polar bear density grid, the polar bear standard error grid, and the grids of spillet paths. All polar bear grid cells that were touched or crossed by one or more cell of a rasterized spillet path were considered 'oiled' by a simulated spill (Figure 3). Each polar bear grid cell could be oiled only "once" per trajectory. The bears estimated to populate each grid cell were considered to be killed. That is, there were no partial effects of oiling allowed. Partial effects of oil exposure certainly are possible. A scale of relative degree of oiling, based upon numbers of spillets hitting each grid cell (Bodkin and Udevitz 1994), could be seamlessly incorporated into our procedure. However, the findings of Oritsland et al. (1981) make it clear that sublethal effects are unlikely even with the presence of monumental medical intervention. Assuming all exposures are lethal allows managers to err on the side of conservation, and is also the most realistic outcome. Similarly, our method does not address chronic post-spill exposure to hydrocarbons (Peterson et al. 2003). Clearly, there is risk of chronic exposure. However, there are no data on the extent or nature of such exposures in the ice covered waters of the Arctic. The inability to estimate this component of the risk is further justification to make the conservative judgment that all bears exposed to oil at the time of the spill are killed.

One estimate of the number of polar bears impacted by one oil spill resulted from each overlap of a rasterized trajectory with the polar bear density grid. Because each trajectory was simulated under different and independent weather and sea state conditions, the 500 trajectories were regarded as a simple random sample of oil spills from a larger (infinite) population of oil spills that might occur in the future.

Random errors inherent in the oil spillet paths which composed modeled trajectories were independent and variation across independent trajectories

correctly incorporated variation in spillet paths. Five hundred records of the overlap of density grids and trajectories revealed the variation (in numbers of polar bears potentially oiled) that resulted from differing wind, current, and ice conditions, among spill occasions (trajectories). These 500 trajectories, however, could not elucidate the variation contributed by the standard errors in estimation of polar bear cell values. We evaluated the contribution of those errors with Monte Carlo simulation as follows: Assuming m_{ij} represents the estimated mean density of polar bears in cell i,j and s_{ij} represents the estimated standard error of m_{ij}, the Monte Carlo simulations estimated the contribution of variation within bear cells using the following scheme:

- For each cell hit by oil during a single spill, a random deviate from a gamma distribution with mean m_{ij} and standard deviation s_{ij} was generated. Let g_{ij} represent this gamma deviate.
- 2. The random gamma deviates were summed over all cells hit by oil to estimate number of impacted bears.
- 3. For each trajectory, steps 1 and 2 were repeated 10 times providing 10 Monte Carlo realizations of the number of potentially impacted polar bears for each trajectory.

The 5000 Monte Carlo trajectories (10 iterations of 500 trajectories) allowed us to determine the portion of the variance, in estimated number of bears affected by an oil spill, which resulted from differences within and among trajectories.

We assumed the gamma distribution for mean densities because: (1) the gamma distribution does not allow negative density values to be generated, and (2) the gamma distribution is uni-modal resembling a normal distribution when its standard error is small relative to its mean. An alternative choice of distribution for average bear density was the normal distribution, but the normal distribution admits negative densities. To investigate the sensitivity of estimated standard errors to the assumed distribution of average density, we also calculated standard errors assuming the normal distribution. Normal deviates below zero were truncated to zero for this comparison.

Spatial correlation among locations in neighboring grid cells was accounted for and used in the smoothing process that estimated average densities. The smoothing process accounted for spatial correlation in locations by averaging cell values in a local neighborhood of cells to arrive at density estimates. While the density estimates, m_{ij}, were spatially correlated, the error inherent in estimating the m_{ij} was not expected to be correlated with errors in adjacent cells. Spatial dependency of estimation error, and of the g_{ij}, was not incorporated into the Monte Carlo estimate of standard error. Each g_{ij} was generated independently of every other g_{ij}.

To illustrate error computations, consider the hypothetical grid of estimated polar bear densities and standard errors and the indication of which cells were oiled in Table 2. The estimated number of polar bears exposed in this example is the sum of polar bear densities from the five oiled cells, or 0.065 bears (=0.015+0.02+0.01+0.005+0.015). Three iterations of the Monte Carlo variance estimation procedure are contained in Table 3. Each Monte Carlo iteration generated gamma deviates only for those cells that were oiled. The estimated number of impacted bears from the 3 iterations were 0.0634, 0.0604, and 0.0633. The reported standard error for the estimated number of impacted bears was the standard deviation of these three numbers, 0.0017.

Once Monte Carlo simulations were complete, the total variation in number of oiled bears was partitioned into two sources following standard ANOVA methods for random effects models. Total variation in oiled bears was partitioned into a component due to variation across trajectories and a component due to variation within trajectories. Following Neter et al. (1990: equations 26.16a through 26.1d), total sum-of-squares was computed as

$$SSTO = \sum_{i=1}^{t} \sum_{j=1}^{n} Y_{ij}^{2} - \left(Y_{..}^{2} / tn\right)$$

where t= number of trajectories, n= number of Monte Carlo iteration per trajectories, Y_{ij} = the estimate of number of bears oiled by the *i*-th trajectory during the *j*-th Monte Carlo simulation, and

$$Y_{..} = \sum_{i=1}^{t} \sum_{j=1}^{n} Y_{ij}$$
.

The sum-of-squares attributable to variation among trajectories was computed as

$$SSA = \sum_{i=1}^{t} Y_{i.}^{2} / n - \left(Y_{..}^{2} / tn\right)$$

where

$$Y_{i.} = \sum_{j=1}^n Y_{ij} \; .$$

The proportion of variation due to trajectories (R²) was computed as SSA/SSTO. If SSA was a large proportion of SSTO, variation across trajectories was large and variation within trajectories was small.

RESULTS

Estimation of Polar Bear Density

We utilized 15,308 satellite locations from 194 polar bears collared between 1985 and 2003 to establish distributions of polar bears in the Beaufort Sea. Of those, 360 observations of 72 polar bears and 276 observations of 68 polar bears respectively, were used to estimate the distribution of polar bears in the Liberty and Northstar study areas during the open water period of 22 August to 30 September (hereafter called September). Similarly, we used 536 observations of 92 polar bears, and 552 observations of 98 polar bears to generate the 1 October to 9 November (hereafter called October) distribution of polar bears in the Liberty and Northstar areas.

Kernel smoothing of these observations provided probabilistic distributions of polar bears to overlay with the oil-spill trajectories. Final products depicting polar bear distributions in the study area included the estimated number of bears (actually fractions of a bear) and the standard error of those estimated numbers in each cell of our grid. For presentation and interpretation purposes, we developed contour bands showing variation in monthly intensity of polar bear use over the whole study area. The distribution was not uniform during either the open water or October time frames (Figures 4, 5).

During September, polar bears generally were more scattered than they were in October. Pockets of relatively high density, such as near Barter Island, reflected areas where polar bears frequent the beach in open water times (Figures 1, 4). As our empirical observations suggested, numbers of bears in the study area were higher during October. Overall, near shore densities of polar bears were 2 to 5 times greater in October than in September (Figures 4, 5). Near-shore densities in February and June were intermediate between those of October and September. Densities near shore also were lower in February and June. These results verified that the times of greatest impact from an oil spill were likely to be summer and fall.

Oil-Spill Trajectories

Footprints of our nearly 2000 modeled oil spill trajectories were highly variable (Tables 4, 5; Figures 4, 5,). Trajectories of the hypothetical oil spills were used to calculate the area swept by the spill (Figure 3). Trajectories simulating the 5912 barrel spill from the Liberty simulation site in September, covered as little as 3.1 km² and as much as 1645 km² during the 10-day timeframe specified for the spill (Table 4, Figure 6). The mean area affected was 357 km², while the median value was 188 km². The same simulated spill from the Northstar simulation site covered between 352 and 2170 km² with a mean and median of 472 km² and 339 km² (Table 5, Figure 14) In October, minimum and maximum footprints of a 5912 barrel simulated spill from the Liberty simulation site were 2.8 km² and 1534 km² (Table 4, Figure 10). The mean and median were 238 km² and 89 km² respectively. The October minimum, maximum, mean and median areas covered for the Northstar simulations were: 4.8 km², 2730 km², 359 km², and 251 km² (Table 5, Figure 18). As expected, smaller spills contacted smaller areas. However, it should be noted that reducing the simulated spill volume by nearly ³/₄ reduced spillet diameter only by half, and reduced the oiled area by less than 1/3rd (Tables 4, 5; Figures 6, 8, 10, 12, 14, 16, 18, 20). On average, oil drifted somewhat farther and covered more area in September than it did in October, possibly reflecting the influence of reforming sea-ice on oil movement in October (Tables 4, 5; Figures 6, 8, 10, 12, 14, 16, 18, 20). The most extensive simulated spill, however, occurred in October. This reflected a severe, protracted storm that occurred in October of 1981.

Intersection of Oil-Spill Trajectories and Bear Densities

Variable footprints from simulated oil-spills translated into varying numbers of polar bears potentially affected by each spill trajectory. The high densities of polar bears projected for the near coastal regions of the SBS in October occasionally corresponded with large numbers of bears being exposed to oil (Tables 4, 5). Because the distribution of polar bears in the study area was not uniform, the relationship between spatial coverage and number of bears affected was not linear. Depending upon which direction and how far a particular trajectory traveled, numbers of bears affected varied greatly (Tables 4,5; Figures 7, 9, 11, 13, 15, 17, 19, 21). Trajectories simulating the 5912 barrel spill from the Liberty simulation site in September, oiled as few as 0.01 bears and as many as 23 bears. The mean number affected was 4.2 bears, while the median value was 1 bear. September trajectories from the Northstar simulations oiled between 0.01 and 27 bears with mean and median of 5.0 and 2.6. In October, minimum and maximum numbers of bears oiled by the 5912 barrel Liberty spill simulation were 0.06 and 55. The mean and median were 8 and 2.7 bears respectively (Table 4). The equivalent numbers for Northstar were: 0.18, 74, 13.4, and 10.6 (Table 5). Smaller simulated spill volumes affected fewer bears, but as in comparisons of spatial coverages the change in numbers of bears affected was not linearly related to the change in volume (Tables 4, 5; Figures 7, 9, 11, 13, 15, 17, 19, 21).

We used two Monte Carlo simulations to examine the variation in the bear cell values. One was based upon a gamma distribution and the other on a Normal distribution truncated at zero. In all cases, no practical differences were seen between standard errors calculated assuming a gamma distribution and those calculated assuming a normal distribution. These estimates typically differed in their 3rd decimal place only, and we report only the gamma distributions here. The variation in our estimates of numbers of bears oiled was due almost entirely to variation among trajectories. Variation within trajectories did not contribute except at the 10,000th or 100,000th decimal place (Table 6).

DISCUSSION

The method described here allows managers to link oil spill trajectory knowledge (Smith et al. 1982, National Academy of Sciences 1985, Galt et al. 1996, French 2001), mechanisms of exposure to oil (Oritsland et al. 1981, National Academy of Sciences 1985, Geraci and St. Aubin 1990, Loughlin 1994), and animal distribution data from telemetry or survey studies (Loughlin 1994, Minerals Management Service, Alaska Outer Continental Shelf Region 2001: Appendices A and J, Amstrup et al. 2004). With this method, managers can develop probabilistic estimates of how many wild animals dispersed over a seascape, might be exposed to oil contamination if there were a spill in the marine environment. Such estimates allow calculation, for the first time, of reasonable assessments of risks to the wildlife in question.

In the case of polar bears in the Beaufort Sea, maximum numbers potentially oiled during both the September open water and October broken ice scenarios were large (27 and 74 at Northstar and 23 and 55 at Liberty). During both scenarios, however, simulated oil-spill trajectories affected small numbers of bears far more often than they affected larger numbers of bears (Tables 4, 5; Figures 6-21). The distribution of numbers of bears oiled in our simulations was highly skewed to the right, with median numbers of bears oiled much smaller than mean numbers. For example, in October, our models indicated that the median number of bears exposed to a 5912 barrel simulated spill at the Liberty and Northstar simulation sites respectively was only 3 and 11, and 75% of the trajectories simulating a 5912 barrel spill contacted 9 or fewer bears in the Liberty simulation and 20 or fewer bears in the Northstar simulation (Tables 5, 6).

Our estimates of the numbers of bears that might be oiled by simulated spills released at the existing Northstar oil production island or the proposed Liberty oil production island incorporated geographic uncertainty in our estimates of polar bear probability of occurrence. Monte Carlo simulations verified that the uncertainty due to the probabilistic distribution of polar bears was inconsequential. Essentially all variation in our results was due to variation in oil trajectories, but in cases where the data do not allow animal occurrence estimates as precise as ours, significant variation could be introduced by that additional uncertainty in animal distributions. This procedure allows the investigator to appreciate that additional source of variability and to incorporate it into model outcomes and management decisions.

Estimates of numbers of bears oiled included measures of uncertainty in relative abundance, but they did not include measures of the uncertainty in population estimates. Both of our study areas are within the range of the SBS polar bear population. Amstrup et al. 2004 have shown that the number of bears from the Northern Beaufort Sea, and the Chukchi Sea populations that could be within the portions of our 2 study areas affected by spills, at any time, is small. However, McDonald and Amstrup (2001) have shown that the population of the SBS might be as small as 1000 or as large as 2300. Therefore, it would be fair to conclude that the population in question might be as small as 55% or as large as 128% of the value (1800 for this exercise) we used in our computations. Those multipliers could be applied directly to the quantile values shown in tables 5 and 6 to obtain a crude estimate of the affect of uncertainty in estimated numbers of bears. For example, the median number of bears oiled by a simulated 5912 barrel spill from the Northstar simulation in October was 10.6. Multiplying that by 0.55 and 1.28 would suggest the median number of bears oiled could be as large as 13.5 bears or as small as 5.8.

Estimates presented here are based upon real weather data gathered between 1980 and 1996. During the late 1990's and early 2000's, greater summer time ice retreats have occurred and open water has persisted in the southern Beaufort Sea for longer periods (Rigor et al. 2001, Comiso 2002; 2003, Belchansky et al. 2004, Comiso and Parkinson 2004, Stroeve et al. 2005). Whereas our polar bear distribution data reflect these changing ice conditions, the oil movement models do not. Clearly, if recent weather trajectories continue, future modeling of the intersection of hypothetical oil spills and wildlife will need to take advantage of new weather data. Similarly our modeling exercises did not include oil weathering, such information, if available could be built into the process. In fact, the flexible method described here can seamlessly incorporate improved data on oil transport, weathering, animal numbers, movements and distribution, into estimation efforts.

Depending upon prevailing environmental conditions at the time, our simulations suggest that the spilling of 2956 or 5912 barrels of crude oil from the proposed Liberty or Northstar Island could pose significant risks to polar bears, or essentially no risk at the population level. In short, managers are faced by the very low probability that a large number of bears might be affected and the high probability that a low number of bears might be affected.

Ultimately, the calculation of risks to polar bears from an oil spill must incorporate not only the risk to bears once a spill occurs, but the probability of occurrence of a spill. In Alaska, oil production is accompanied by stipulations for clean-up efforts. The strength of those stipulations and the realistic assessment of their effectiveness also must be included in any adequate risk analysis. With the probabilistic assessments of wildlife/oil interactions provided here, industry and agency managers are one step closer to being able to perform risk assessments based upon objective probabilities rather than subjective and unquantifiable opinions. With the methods described here, managers dealing with potential oil-spill exposures to any dispersed marine resource have objective ways to assess their risks. More objective decision making can only improve management of polar bears and other wild species, and the human activities that could affect them.

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Table 1. Diameters of oil spillets used for modeling the movement of oil released from the proposed Liberty island. Each of approximately 500 spill trajectories was composed of 500 Spillets that represented equal aliquots of oil from that spill. Hence, each of the 500 spillets from a 1500 barrel spill would be 3 barrels in size (Fay 1971, Lehr 2001).

Spill Size in Barrels	Il Size Spillet Calculated		Thickness in Meters		
	Barrels	Diameter in Meters			
125	0.25	9.437208	0.000543		
715	1.43	19.4299	0.000726		
925	1.85	21.63061	0.000757		
1,500	3	26.45743	0.000821		
1,580	3.16	27.03648	0.000828		
2,956	5.912	35.09968	0.000919		
5,912	11.824	46.85245	0.001032		

Row #	Column #								
	1	1 2 3							
1	0.010	0.015	0.020	0.015					
	(0.001)	(0.002)	(0.010)	(0.005)					
2	0.010	0.005	0.010	0.015					
	(0.009)	(0.002)	(0.004)	(0.008)					
3	0.015	0.005	0.010	0.020					
	(0.005)	(0.001)	(0.005)	(0.014)					
4	0.010	0.010	0.015	0.010					
	(0.008)	(0.006)	(0.007)	(0.006)					

Table 2: A hypothetical grid of estimated polar bear densities and standard errors. Standard errors are in parentheses. Bold text indicates cells (1,2; 1,3; 2.1; 2,2; and 3,1) that were oiled in an example illustrating computation of number of impacted polar bears.

Table 3: Estimating the standard error in numbers of bears exposed to spilled oil. Values in each of 3 example Monte Carlo iterations were generated from a gamma distribution of the number of bears oiled in the example shown in Table 2. The standard deviation of the "total" row illustrates the portion of the variation in numbers of bears oiled which is due to uncertainty in bear counts in each cell.

Cell	Monte Carlo Iteration						
	1	2	3				
1,2	0.0133	0.0146	0.0146				
1,3	0.0119	0.0224	0.0149				
2,1	0.0161	0.0041	0.0089				
2,2	0.0052	0.0048	0.0043				
3,1	0.0168	0.0145	0.0207				
Total:	0.0634	0.0604	0.0633				
Standard deviation: 0.00 [°]							

Table 4. Summary of numbers of bears and areas potentially contacting oil during simulated spills in the proposed Liberty Island area of the southern Beaufort Sea. We ran 500 trajectories for each scenario or time frame. Each trajectory was comprised of 500 spillets or Lagrangian elements. Numbers of bears oiled by each trajectory were resampled with Monte Carlo methods 10 times. Note that in all scenarios, the vast majority of trajectories influenced relatively small numbers of bears. Particularly in October, however, a small number of trajectories oiled very large numbers of bears.

	Area Oiled by Spills from Liberty Island (km ²)									
Trajectory	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	5%	10%	95%	Std. Dev.
Sept. 1580 bbl.	2.67	29.93	165.21	290.81	493.72	1193.41	10.07	11.80	826.58	292.29
Sept. 5912 bbl.	3.05	33.77	188.31	357.36	601.46	1645.30	11.25	13.18	1001.64	373.02
Oct. 1580 bbl.	2.32	24.62	74.32	198.00	232.04	1110.07	7.06	9.18	972.55	279.58
Oct. 5912 bbl.	2.84	27.34	88.86	238.05	270.05	1533.99	7.85	10.20	1171.33	343.68
			Number	s of Bears	Oiled by	Spills fro	n Liberty	Island		
Sept. 1580 bbl.	0.01	0.17	1.05	3.38	6.40	16.34	0.05	0.06	12.86	4.14
Sept. 5912 bbl.	0.01	0.20	1.26	4.18	7.65	22.94	0.06	0.07	15.52	5.23
Oct. 1580 bbl.	0.05	0.64	2.24	6.63	7.90	46.06	0.14	0.19	27.73	9.26
Oct. 5912 bbl.	0.06	0.70	2.69	7.96	9.24	55.22	0.16	0.21	33.47	11.26
				Number	of Bears (Diled/km ²	Oiled			
Sept. 1580 bbl.	0 0045	0 0058	0 0064	0.0116	0.0130	0 0137	0 0049	0 0052	0.0156	
Sept. 5912 bbl.	0.0046	0.0058	0.0007	0.0117	0.0127	0.0130	0.0040	0.0052	0.0155	
Oct 1580 bbl	0.0040	0.0056	0.0007	0.0117	0.0127	0.0139	0.0049	0.0052	0.0100	
Oct 5012 bbl	0.0202	0.0259	0.0301	0.0335	0.0340	0.0415	0.0199	0.0210	0.0285)
	0.0205	0.0258	0.0303	0.0334	0.0342	0.0360	0.0198	0.0210	0.0286	

Table 5. Summary of numbers of bears and areas potentially contacting oil released during simulated spills in the North Star Island area of the southern Beaufort Sea. We ran 500 trajectories for October scenario and 360 for September scenario. Each trajectory was comprised of 500 spillets or Lagrangian elements. Numbers of bears oiled by each trajectory were re-sampled with Monte Carlo methods 10 times. Note that in all scenarios, the vast majority of trajectories influenced relatively small numbers of bears. Particularly in October, however, a small number of trajectories oiled very large numbers of bears.

			Are	ea Oiled by	/ Spills fro	om North	Star Islan	d		
Trajectory	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	5%	10%	95%	Std. Dev.
Sept. 1580 bbl.	2.82	35.97	284.47	383.49	634.89	1570.57	9.65	12.91	1129.72	385.09
Sept. 5912 bbl.	3.52	42.01	339.23	472.05	777.06	2170.28	10.83	14.32	1500.97	484.74
Oct. 1580 bbl.	4.16	59.50	192.00	267.79	385.51	1758.80	9.58	18.19	794.49	269.29
Oct. 5912 bbl.	4.80	70.30	251.29	359.23	518.94	2729.67	10.76	19.95	1114.86	386.93
			Numbers	of Bears C	Diled by S	pills from	North Sta	ar Island		
Sept. 1580 bbl.	0.01	0.17	2.08	4.05	6.56	22.47	0.04	0.05	13.22	4.71
Sept. 5912 bbl.	0.01	0.20	2.58	5.02	7.83	27.34	0.04	0.06	16.62	5.91
Oct. 1580 bbl.	0.16	2.58	8.50	10.17	15.35	49.46	0.38	0.74	26.81	8.91
Oct. 5912 bbl.	0.18	2.99	10.63	13.44	20.41	73.73	0.41	0.83	37.41	12.61
				Number	of Bears	Oiled/km ²	Oiled			
Sept. 1580 bbl.	0.0038	0.0047	0.0073	0.0105	0.0103	0.0143	0.0039	0.0040	0.0117	,
Sept. 5912 bbl.	0.0039	0.0047	0.0076	0.0106	0.0101	0.0126	0.0040	0.0040	0.0111	
Oct. 1580 bbl.	0.0384	0.0434	0.0443	0.0380	0.0398	0.0281	0.0399	0.0408	0.0337	,
Oct. 5912 bbl.	0.0379	0.0425	0.0423	0.0374	0.0393	0.0270	0.0382	0.0417	0.0336	5

Table 6. Sources of variation in estimated numbers of polar bears affected by different sizes and time frames of oilspills. Mean and standard error of approximately 5000 simulation runs (Only 3600 were possible for North Star in September). Note that the variation among trajectories explains almost all of the variation observed. Variation in polar bear numbers for each cell values for contributes essentially nothing to the variation among spill trajectories.

Trajectory	No.	Mean Gamma	S.D. Gamma	SS Across Trajectories	SS Within Trajectories SS Total		% Due to Trajectories
Liberty Area							
September 1580 Barrel Spill	5000	3.376	4.137	85573.01	0.00769	85573.02	99.999991
September 5912 Barrel Spill	5000	4.179	5.223	136382.90	0.04138	136382.94	99.999970
October 1580 Barrel Spill	4950	6.629	9.256	424013.28	0.02142	424013.31	99.999995
October 5912 Barrel Spill	4950	7.956	11.247	626027.60	0.10419	626027.70	99.999983
North Star Area							
September 1580 Barrel Spill	3600	4.045	4.705	79679.88	0.00832	79679.89	99.999990
September 5912 Barrel Spill	3600	5.021	5.900	125280.14	0.04598	125280.18	99.999963
October 1580 Barrel Spill	4990	10.170	8.899	395052.96	0.03031	395052.99	99.999992
October 5912 Barrel Spill	4990	13.442	12.595	791461.20	0.16929	791461.37	99.999979



Figure 1. North Star and proposed Liberty locations where oil releases were simulated. Boundaries and corner locations of the study areas surrounding each spill site, and place names used in the text also are shown.



Figure 2 Nearshore surface currents simulated by the NOAA model for a wind from the East at 10meters/second.



Figure 3. Spillet paths or arcs were represented as vectors (A). Vectors were rastorized to give the paths physical width (B). Bear numbers in each grid cell of comparable width (C) to spillet paths were overlain on spillet paths (D) revealing which cells were actually oiled. Numbers of bears exposed to oil is then the sum of the values in all oiled cells.



Figure 4. Three hypothetical oil spill trajectories originating at the existing North Star oil production island near Prudhoe Bay, Alaska, during September. Contours show relative polar bear population densities in the spill areas (bears/100 km²). Simulation numbers and numbers of bears oiled in each simulated spill were: 1. #4082, 4; 2 #4387, 12; and 3. #4428, 23. Note high density of bears along coast at eastern end of figure. Barter Island is located just east of the edge of the frame.



Figure 5. Three hypothetical oil spill trajectories originating at the proposed Liberty oil production island near Prudhoe Bay, Alaska, during October. Contours show relative polar bear population densities in the spill areas (bears/100 km²). Simulation numbers and numbers of bears oiled in each simulated spill were: 1. #4566, 25; 2 #4663, 4; and 3. #4999, 13.

Figure 6. Areas contacted by simulated oil spills from the proposed Liberty site during the month of September. Shown here is the frequency histogram resulting from 500 simulated spills (trajectories) of 5912 barrels of crude oil. September conditions were predominated by open water and low coverage of sea ice.



Liberty Site: Area Oiled by 5912 Barrel September Spill

Figure 7. Numbers of bears estimated to be oiled by simulated oil spills from the proposed Liberty site during the month of September. Shown here is the frequency histogram resulting from 500 simulated spills (trajectories) of 5912 barrels of crude oil. September conditions were predominated by open water and low coverage of sea ice.

0.4 0.3 Probability 0.2 0.1 0.0 10 0 5 15 20 Number of oiled bears

Liberty Site: #Bears Oiled by 5912 Barrel September Spill

Figure 8. Areas contacted by simulated oil spills from the proposed Liberty site during the month of September. Shown here is the frequency histogram resulting from 500 simulated spills (trajectories) of 1580 barrels of crude oil. September conditions were predominated by open water and low coverage of sea ice.



Liberty Site: Area Oiled by 1580 Barrel September Spill

Figure 9. Numbers of bears estimated to be oiled by simulated oil spills from the proposed Liberty site during the month of September. Shown here is the frequency histogram resulting from 500 simulated spills (trajectories) of 1580 barrels of crude oil. September conditions were predominated by open water and low coverage of sea ice.



Liberty Site: #Bears Oiled by 1580 Barrel September Spill

Figure 10. Areas contacted by simulated oil spills from the proposed Liberty site during the month of October. Shown here is the frequency histogram resulting from 495 simulated spills (trajectories) of 5912 barrels of crude oil. October conditions were predominated by open and refreezing sea-water and mixed new and older ice.



Liberty Site: Area Oiled by 5912 Barrel October Spill

Figure 11. Numbers of bears estimated to be oiled by simulated oil spills from the proposed Liberty site during the month of October. Shown here is the frequency histogram resulting from 495 simulated spills (trajectories) of 5912 barrels of crude oil. October conditions were predominated by open and refreezing sea-water and mixed new and older ice.



Liberty Site: #Bears Oiled by 5912 Barrel October Spill

Figure 12. Areas contacted by simulated oil spills from the proposed Liberty site during the month of October. Shown here is the frequency histogram resulting from 495 simulated spills (trajectories) of 1580 barrels of crude oil. October conditions were predominated by open and refreezing sea-water and mixed new and older ice.

0.006 Probability 0.004 0.002 0.0 200 600 0 400 800 1000 Oiled area (square km)

Liberty Site: Area Oiled by 1580 Barrel October Spill

Figure 13. Numbers of bears estimated to be oiled by simulated oil spills from the proposed Liberty site during the month of October. Shown here is the frequency histogram resulting from 495 simulated spills (trajectories) of 1580 barrels of crude oil. October conditions were predominated by open and refreezing sea-water and mixed new and older ice.

Liberty Site: #Bears Oiled by 1580 Barrel October Spill



Figure 14. Areas contacted by simulated oil spills from the North Star site during the month of September. Shown here is the frequency histogram resulting from 360 simulated spills (trajectories) of 5912 barrels of crude oil. September conditions were predominated by open water and low coverage of sea ice.



NorthStar Site: Area Oiled by 5912 Barrel September Spill

Figure 15. Numbers of bears estimated to be oiled by simulated oil spills from the North Star site during the month of September. Shown here is the frequency histogram resulting from 360 simulated spills (trajectories) of 5912 barrels of crude oil. September conditions were predominated by open water and low coverage of sea ice.



NorthStar Site: #Bears Oiled by 5912 Barrel September Spill

Figure 16. Areas contacted by simulated oil spills from the North Star site during the month of September. Shown here is the frequency histogram resulting from 360 simulated spills (trajectories) of 1580 barrels of crude oil. September conditions were predominated by open water and low coverage of sea ice.



NorthStar Site: Area Oiled by 1580 Barrel September Spill

Figure 17. Numbers of bears estimated to be oiled by simulated oil spills from the North Star site during the month of September. Shown here is the frequency histogram resulting from 360 simulated spills (trajectories) of 1580 barrels of crude oil. September conditions were predominated by open water and low coverage of sea ice.



NorthStar Site: #Bears Oiled by 1580 Barrel September Spill

Figure 18. Areas contacted by simulated oil spills from the North Star site during the month of October. Shown here is the frequency histogram resulting from 499 simulated spills (trajectories) of 5912 barrels of crude oil. October conditions were predominated by open and refreezing sea-water and mixed new and older ice.

0.0025 Probability 0.0015 0.0005 0.0 500 1500 0 1000 2000 2500 Oiled area (square km)

NorthStar Site: Area Oiled by 5912 Barrel Oct Spill

Figure 19. Numbers of bears estimated to be oiled by simulated oil spills from the North Star site during the month of October. Shown here is the frequency histogram resulting from 499 simulated spills (trajectories) of 5912 barrels of crude oil. October conditions were predominated open and refreezing sea-water and mixed new and older ice.



NorthStar Site: #Bears Oiled by 5912 Barrel October Spill

Figure 20. Areas contacted by simulated oil spills from the North Star site during the month of October. Shown here is the frequency histogram resulting from 499 simulated spills (trajectories) of 1580 barrels of crude oil. October conditions were predominated by open and refreezing sea-water and mixed new and older ice.

NorthStar Site: Area Oiled by 1580 Barrel October Spill



Figure 21. Numbers of bears estimated to be oiled by simulated oil spills from the North Star site during the month of October. Shown here is the frequency histogram resulting from 499 simulated spills (trajectories) of 1580 barrels of crude oil. October conditions were predominated by open and refreezing sea-water and mixed new and older ice.



NorthStar Site: #Bears Oiled by 1580 Barrel October Spill