Investigation of the Properties of an Aerial Line Transect Survey for Polar Bears in the Chukchi Sea Using Computer Simulation

By

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For

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INTRODUCTION
The US Fish and Wildlife Service (FWS) is responsible for managing the polar bear populations that at least seasonally occupy US territories and territorial waters. To date, little is known about the number of polar bears in many of the subpopulations currently recognized by the International Union for the Conservation of Nature and Natural Resources (IUCN) Polar Bear Specialist Group (PBSG; Aars et al. 2006), including the subpopulation occupying the Chukchi Sea. In August of 2000, the FWS conducted a pilot survey in the eastern Chukchi and western Beaufort seas to assess the logistical feasibility of using ship-based aerial line transect (distance; Buckland et al. 2001) surveys to estimate polar bear densities (Evans et al. 2003). Although results from the pilot study were encouraging, precision was lower than desired (coefficient of variation [CV] = 37%). In addition, the survey covered only a small portion of the Chukchi Sea thus may not have been representative of the entire region.

In 2006, WEST was contracted by the FWS to provide initial recommendations for conducting an aerial line transect survey to estimate the number of polar bears occupying the Chukchi Sea. WEST’s recommendations, along with discussion of potential logistical constraints, are documented in the memo titled “Recommendations for an aerial survey of polar bears in the Chukchi Sea”, by WEST, Inc. 2006 for the FWS (hereafter cited as WEST, Inc. 2006). Based on these recommendations, the FWS requested that WEST conduct an intensive computer simulation to assess the potential accuracy and precision of an aerial line transect survey of polar bears in the Chukchi Sea. In 2007 and 2008, WEST developed a simulation analysis to mimic realistic survey conditions and logistical constraints in order to investigate the accuracy and precision of several estimators for the total number of polar bears occupying the Chukchi Sea in the late summer and early fall. Specifically, the simulation was performed to develop the best methods for conducting the aerial survey, to develop and test analytical methods for the resulting data, and to determine the minimum sample size (number of transects, as determined by the length of the survey) to obtain an unbiased population estimate with a CV ≤ 20%.

Our simulation incorporated changing sea ice conditions during the anticipated survey period of 15 September – 14 November based on historical data from 1987 – 1994, and investigated use of a resource selection function (RSF), similar to the one developed by Durner et al. (2006), for estimating population size. Our simulation was based on recommendations from the following sources: analysis recommendations in WEST, Inc. (2006), logistical constraints observed during a pilot survey conducted in 2000 by the FWS (Evans et al., 2003), personal communications with Tom Evans, David Douglas (USGS), and George Durner (USGS), and the properties of the RSF developed by Durner et al. (2006).

STUDY AREA
The study area for the simulation and future surveys mimic that used by Durner et al. (2006). The region ranged from 156° W to 170° E, and 66° 30’ N to 80° N (Figure 1).
Boundaries were chosen to represent the extent of Chukchi Sea ice conditions and typical historical polar bear movements on the sea ice during 15 September – 14 November.

Within this study area, regions where simulated aerial surveys were flown were further restricted by two factors. First, the RSF (see below) and sea ice data used in this simulation were based on passive microwave imagery (SSMR, SSM/I; National Snow and Ice Data Center, Boulder, Co.). These data were in a raster format with a pixel size of 5 × 5 km. Durner et al. (2006) found only a small portion (~1%) of bear locations > 50 km south of the 15 % ice concentration contour during 15 September to 14 November during years 1987 – 1994. Because passive microwave data are not reliable along shorelines (Cavalieri et al. 1990), and to be consistent with Durner et al. (2006) we excluded passive microwave pixels that were within 25 km of land, and pixels where sea ice concentration estimates were <15 % or within 50 km south of the 15 % ice concentration contour. A rasterized land mask (1:10-scale Digital Chart of the World; Defense Mapping Agency, 1992) with a 25 km buffer effectively removed most of the coastal pixels.

Second, the surveyed area was allowed to vary by day depending on sea ice extent. Polar bears cannot forage effectively in open water, and because polar bears swimming in large expanses of open water are likely enroute to ice covered areas or land, we defined the southern boundary of the survey area for each day as the southern extent of sea ice on that day. Open water regions were not considered as available habitat so simulated polar bear locations were not placed south of the ice edge. The 5 × 5 km resolution of historical microwave satellite imagery meant that some pixels classified as ‘open water’ may have contained undetected sea ice.

**AERIAL LINE TRANSECT SURVEYS**

We envisioned an aerial line transect survey for polar bears from a helicopter stationed on an ice breaker in the Chukchi Sea. This survey would involve 2 observers on each side of the aircraft in the rear seats, and one or more of the pilots in the front seats ‘guarding’ the transect line and area directly below the aircraft that isn’t visible to the back seat observers. Using the pilot(s) to detect polar bear groups directly below the aircraft will go a long way toward ensuring that no animals go undetected directly below the aircraft and detection on the transect line is 100% (Jon Aars, personal communication), a primary assumption of distance sampling (Buckland et al. 2001).

WEST, Inc. (2006) recommends that global positioning system (GPS) technology be used to direct the pilot(s) along sampled transects and mark locations on the transect line when polar bear groups are detected and directly below or perpendicular to the aircraft. In addition, laser range finders (e.g., Laser Technologies, Inc., 7070 S. Tuscan Way, Centennial, CO 80112) with built-in clinometers should be used to measure perpendicular distances of observed polar bear groups from the transect line. Laser range finders are highly precise (1-3 meters), and should be easy to use while hovering or flying at slower speeds (< 88 knots) at an Above Ground Level (AGL) of up to 400 m. When necessary, the aircraft should hover to allow collection of accurate distance measurements. When
bears flush or run in response to the helicopter, distances should be measured to the location where first sighted. (WEST, Inc. 2006).

Groups detected by the observers and pilot(s) will need to be recorded during the survey, along with the size of each bear group, the side of the transect (left or right) where the group was located, and the group’s perpendicular distance from the transect line. In addition, survey conditions (e.g., weather, speed, survey height) and the names and positions of each observer in the aircraft should be recorded for each transect flown. Information on survey conditions and/or observers may be used as covariates, or for post-stratification purposes, during analysis of the actual survey data, but this type of information was not directly investigated in our simulation. For more details on WEST’s recommendations for a line transect survey protocol in the Chukchi Sea, see the 2006 memo (WEST, Inc. 2006).

Standard distance analysis begins by fitting a detection function to the distances of observed groups, and proceeds by integrating that function over the search width (0 to \( W \)), where \( W \) = right truncation distance) to estimate the average probability of detection (\( \hat{P} \)). \( \hat{P} \) is then used to inflate the number of animals detected to obtain an estimate of the density of bear within the area searched (Buckland et al. 2001),

\[
\hat{D} = \frac{n\hat{E}(s)}{2WL\hat{P}}
\]

where \( n \) is the number of observed groups of animals, \( \hat{E}(s) \) is the expected group size, and \( L \) is the total length of transects flown (\( 2WL \) is total area searched). More details on the theory and application of distance sampling can be found in (Buckland et al. 2001; 2004).

**SIMULATION**

**Overview of Simulation Approach**

Our simulation was designed to mimic historic sea ice conditions, practical survey protocol, and realistic logistical constraints. The general approach was as follows (details follow):

- Simulated surveys occurred during 15 September to 14 November.
- Historical sea ice conditions from 1985 – 1994 that Durner et al. (2006) used to create the RSF were used in our analysis to simulate the location of future habitat.
- For each of the 500 repetitions in the simulation, a year from 1985 – 1994 was drawn at random, along with a random starting date that allowed for completion of an 8, 6, or 4 week survey by 14 November. The daily sea ice data from subsequent dates in that year were then used as the observed ice conditions, in order to mimic realistic changes in sea ice.
- Simulated surveys began on the western edge of the study area, and the icebreaker moved in a general NW to SE direction along the 50% ice contour. The icebreaker was restricted to daily travel of <80 km.
- Transects were randomly sampled near the ice breaker’s daily location and oriented south to north, with the southern ends \( \leq 16 \text{ km} \) from the ice breaker in
order to minimize ‘dead-head’ travel between the ice breaker and transect lines, and to increase safety.

- An average of 3 transects were surveyed each day (1 sortie on odd days, and 2 on even days: 1 sortie = 2 transects), which is similar to the constraints experienced during the pilot study (Tom Evans, personal communication).
- Transect lengths were randomly sampled with replacement from the lengths flown in the pilot study (Evans et al. 2003).
- Polar bear groups were randomly placed on the daily sea ice within the study area boundaries in proportion to the RSF developed by Durner et al. (2006). Specifically, polar bear groups were placed in 5 x 5 km cells covering that day’s sea ice, in accordance with the results of a model validation exercise performed by Durner et al. (2006). Polar bear group sizes were based on those observed in the pilot study.
- Probability of detecting a polar bear group along a sampled transect and within the search width was based on the group’s perpendicular distance from the transect line and an assumed detection function obtained from the pilot study’s data.
- Radio collars were randomly assigned to individual polar bears. Numbers of radio collared bears considered were 30 and 45.
- Population sizes considered were 500, 1000, 2000, 2500, and 3000 polar bears.
- The simulation began with the largest number of polar bears (3,000), the longest survey period (8 weeks), and the largest number of collared bears (45). Population size, survey period length, and number of collared bears were further reduced until bias or loss of precision was deemed large enough to preclude further investigation.
- The usual assumptions of distance sampling methodology were employed in the simulation: (1) detection rates on the transect line, or \( g(0) \), were 1; (2) perpendicular distances from the transect line were measured accurately; and (3) movement of animals on a transect immediately prior to observation was negligible.

**Sea Ice Conditions and Polar Bear Habitat**

Characteristics of sea ice and its extent can change dramatically during late-summer and early-fall (Durner et al. 2006, 2008) within the Chukchi Sea. Sea ice conditions appear to drive the movement of polar bears during this period (Durner et al. 2006), as the bears look for food and safety. To ensure our simulation mimicked historical reality, we used two types of historical data files in the simulation, both of which were provided to WEST by the USGS. Both files were generated for all days in the survey period (15 September – 14 November), from data collected during 1987 – 1994.

The first data file contained the shortest distance (m) from each 5 x 5 km cell’s center to the 50% ice contour for that day. The coordinates of each 5 x 5 km cell were given in Universal Transverse Mercator (UTM), relative to Zone 2. To ensure that ramifications of partitioning the study area into 5 x 5 km cells in UTM coordinates from a polar stereographic projection were minimal, David Douglas (personal communication)
estimated that the true size of every 5 x 5 km cell in the data did not differ from 25 km² by more than 1% (0.25 km²).

The second file contained daily relative probability of selection for each cell as predicted by the RSF developed by Durner et al. (2006). Polar bear habitat quality was quantified as the predicted relative probability of selection using the following equation from Durner et al.:

\[
RSF = \exp(-0.01116 \times D_{50} + 0.0000107 \times D_{50}^2 + 0.0003442 \times \text{Bathymetry} + 0.06377 \times N_{Tice} - 0.0006086 \times N_{Tice}^2),
\]

where \(D_{50}\) was the distance (km) to the 50% ice concentration contour, \(\text{Bathymetry}\) was the ocean depth (m), and \(N_{Tice}\) was the total ice concentration (%).

Durner et al. (2006) used all polar bear locations between 15 September to 14 November 1987 – 1994 to assess the RSF. The RSF map for each day was divided into 20 RSF intervals based on percentiles of the distribution of predictions. Hence, the highest RSF interval (#20) was comprised of the 5 x 5 m cells with the uppermost 5% of the daily RSF values. The lowest RSF interval (#1) which was comprised of the lowest 5% of RSF values for that day, and so forth. The results of this assessment indicated that over half (54%) of the polar bear locations occurred within the upper 2 combined RSF intervals, suggesting that approximately half of the bears in the Chukchi Sea were distributed across about 10% of the study area (Figure 2). The proportion of polar bear occurrences increased to 68% within the upper 3 combined intervals (~15% of the area), and to 77% within the upper 4 combined intervals (~20% of the area).

These daily RSF intervals were used to place hypothetical polar bear groups within the study area on each survey day. This was done by sampling 5 x 5 km cells in the study area, with replacement, using a non-equal probability sampling scheme where sampling weights were proportional to the mean RSF value with each RSF interval. Thus, polar bear locations were clumped and not uniformly distributed across the sea ice. Exact locations of polar bear groups were random within the sampled cells. Polar bear locations changed each day in the simulation, but we did not attempt to simulate a travel route for each polar bear during the study period according to some movement model. Incorporating a movement model into the simulation will not change results, and we felt it would unnecessarily complicate the simulation.

Polar bear group sizes were generated by adding 1.0 to a random value from a Poisson distribution with a mean of \(\lambda = 0.16\). Under this scenario, average group size was 1.16 bears (SD = 0.374); the same as observed in the pilot study (Evans et al. 2003). The algorithm for assigning group sizes and locations to groups was developed so the exact number of polar bears in the entire study area equaled the desired population size for the survey.

A small number (30 or 45) of the simulated polar bear individuals were designated as a female polar bear equipped with GPS radiotelemetry collar. Locations of these bears
were used in the analysis of the simulated survey data to extrapolate the number of polar bears within the study area but outside of the region surveyable by a helicopter stationed off an icebreaker (see below).

**Sea Ice Conditions and Survey Progress**

Sea ice conditions limit accessibility of much of the study area during the potential survey period. Although icebreakers are built to travel through seas where ice is present, we cannot expect an ice breaker to travel into waters dominated by sea ice (Tom Evans, personal communication). To mimic this limitation, we programmed the ice breaker to begin the survey on the western edge of the study area and follow the 50% ice contour, in a general west to east direction. Surveying near the 50% ice contour has the added benefit of increasing the number of observations of polar bears for estimating a detection function, since the RSF developed by Durner et al. (2006) indicates polar bears exhibited a preference for these areas throughout the season. However, restricting the survey areas around the 50% ice contour also means the survey is not spatially representative of the entire study area, and requires specialized adjustments to standard distance sampling analysis (see below).

In the simulation, sea ice data from the NSIDC was used as a basis to move the ice breaker each night in preparation for surveying the next day’s transects. We used sea ice data from day \(i\) to determine where the ice breaker would move that night and be stationed on day \(i+1\). On the first day of a simulated survey the ice breaker was randomly placed in a cell along the 50% ice contour within 8 km of the western ice edge. The distance the ice breaker traveled each day (or night) in our simulation was based on the west-east (horizontal) distance of the ice breaker to the eastern most cell on the 50% ice contour, and the number of remaining survey days. For example, if the distance from the ice breaker to the eastern most 50% ice contour cell was 1000 km, and there were 19 more days left in the survey, the ice breaker was moved 1000 / (19 + 1) = 50 km to the east in one night and as close to the 50% ice contour as possible. However, the maximum allowable travel distance in any one day was 80 km (Tom Evans, personal communication). This algorithm had the added benefits of moving the ice breaker at a somewhat consistent pace, preventing the ice breaker from reaching the eastern edge of the study before completion of the survey, and providing a sample of transects that had good spatial coverage, in the west to east direction, across the study area (Figure 3). However, we had to eliminate 1994 from simulations due to difficulty in moving the ice breaker along the 50% ice contour around Wrangel Island. The 50% ice contour near Wrangel Island was different in 1994 than in any other year in that it was south of the island during the first few weeks of the survey, and our simulation algorithm placed survey transects directly over the island.

**Survey Transects**

In the simulation an average of 3 transects were flown each day; 2 transects were flown on odd days, and 4 transects were flown on even days. A random sample of transects near the ice breaker’s daily location was drawn by randomly sampling (2 or 4) transects from all available transects \(\leq 16\) km from the ice breaker in an east-west direction that had not been previously sampled. Transects began at the southern edge of the row of
cells just north of the cell that contained the ice breaker. Since ice breaker locations were considered to be in the center of a 5 x 5 km cell, this resulted in transects starting 2.5 km north of the ice breaker’s northing position. The surveyed length of transect pairs was determined by randomly sampling from transect lengths observed during the pilot study (Figure 4). Transects flown during the pilot study had a mean length of 81.8 km, with SD = 41.4 km. Although 100 km was the targeted transect length during the pilot study, weather, logistical, and mechanical constraints resulted in shorter transects. In the simulation transect lengths were selected in pairs to better mimic actual survey conditions where transects sampled out and back would have the same length when the aircraft was turned around due to weather, logistical or other mechanical constraints. Limiting transect start locations to be <16 km of the ice breaker ensured the helicopter was never substantially >200 km away from the ice breaker, a safety requirement for the survey (Tom Evans, personal communication).

All but one polar bear group detected in the pilot study were ≤675 m from the transect line. The furthest detected polar bear group was 980 m away, and treated as an outlier in our simulation. In the simulation, probability of detecting a polar bear group with a perpendicular distance ≤675 m was based on a kernel-estimated detection function fit to the pilot study data. For example, a polar bear group 200 m east or west of a transect was ‘observed’ in the simulation based on a random draw from a binomial distribution with probability equal to the probability of detection at 200 m (i.e., \( p = 0.61 \) in this situation) obtained from the observed pilot study detection function.

**Statistical Analysis**

Generally, analysis of line transect data is performed in the program DISTANCE (Thomas et al. 2005) due to the ease with which a suite of detection functions can be fitted to observed perpendicular distances to estimate \( \hat{P} \) (equation [1]). Because we could not program our entire simulation in DISTANCE, and the difficulty and time required to run the simulation in 2 or more programs, we chose to model the probability of detection using a kernel estimator (Wand and Jones 1995). The kernel method has been used successfully to estimate detection functions for line transect data in other surveys (Chen 1999, 2000, Good et al. 2008). The general kernel density estimator is

\[
\hat{f}(x) = (nh)^{-1} \sum_{i=1}^{n} K \left( \frac{x - x_i}{h} \right),
\]

where \( x \) is a perpendicular distance within the range of observed distances, \( x_i \) is one of the \( n \) observed distances, \( h \) is a smoothing parameter, or ‘bandwidth’, and \( K \) is a kernel function satisfying the condition \( \int K(x)dx = 1 \). In all simulations, we used the Gaussian kernel function (Wand and Jones 1995) because of its popularity and the smoothly declining weights it induces. To estimate the smoothing parameter \( h \), we employed the direct plug-in (Sheather and Jones 1991) method because it is regarded as the best compromise between bias and variance among all available methods (Wand and Jones 1995, Venables and Ripley 2002). An additional advantage of the non-parametric kernel method over the semi-parametric methods used by DISTANCE is that the kernel method
requires fewer assumptions and allows greater flexibility in shape of the detection function.

Perpendicular distances from line transects have a boundary at or near the transect line (i.e., there are no observations less than the minimum observable sighting distance). Because the kernel density estimator performs better when no sharp boundaries, or discontinuity, exist, we followed the recommendations of Chen (1999) and Venables and Ripley (2002) by reflecting the observed distances to both sides of the transect line prior to density estimation. Following kernel estimation, the negative portion of the density function was discarded, the positive portion of detection function was scaled so that probability of detection on the line was 1.0, and area under the function was calculated (by numerical integration) to estimate $\hat{P}$.

Prior to survey simulation development, we completed a separate simulation to compare the properties of the kernel-based line transect analysis to the analyses available in DISTANCE. This comparison indicated that kernel-based analyses of detection data similar to those obtained by Evans et al. (2003) can be expected to perform as well or better (e.g., lower bias and variance) than analyses in DISTANCE. Details and results of this comparison are provided in Appendix I.

Polar bear group sizes detected by Evans et al. (2003) were not correlated with distance from the transect line ($r = -0.12$; 95% confidence interval from -0.49 to 0.25), so probability of detection was simulated to be independent of group size. Average group size, $\hat{E}(s)$ (equation [1]), was estimated using all polar bear groups observed during a simulated survey. The right truncation distance, $W$ (equation [1]) was set equal to 675 meters for all transects in the simulation.

Two issues related to conducting a line transect survey over sea ice complicate the analysis. First, assuming the number of polar bears in the study area is constant during a survey period, polar bear density is expected to decrease during the survey due to expansion of sea ice–i.e., the sea ice surface becomes larger, so density decreases. As an example, the extent of ice in the study area almost doubled (92% increase) from 15 September to 15 November in 1993 (Durner et al. 2006). In a ‘standard’ analysis of line transect data the density of objects is assumed to be constant during the study period (Buckland et al. 2001). Second, we cannot expect to obtain a spatially representative sample of transects throughout the study area due to limitations of the ice breaker and helicopters. This presents a major hurdle in estimation of the number of polar bears in the Chukchi Sea, because polar bear density is expected to be higher in the surveyable areas and decrease with distance from the 50% ice contour.

To overcome the issue of an increasing sea ice extent and the resulting decrease in polar bear density during the survey period we divided the survey period into 3-day segments or survey periods (i.e., days 1 – 3, days 4 – 6, etc.), and estimated the number of polar bears in the study area during each period. We used all observations to estimate $\hat{P}$ and $\hat{E}(s)$ in a simulated survey, but the total number of detected polar bear groups ($n$), and
total length of transect lines flown during a 3-day period were used to obtain an estimate of the density of polar bears in the area searched (2WL) during those three days. We then estimated the total number of polar bears occupying the sampled region during the 3-day period by connecting the northern and southern endpoints of each transect covered during the 3-day period (e.g., Figure 5). This polygon constituted the sampled region, and total bears were estimated by multiplying the size of this polygon by estimated density. The number of observations declined with both a reduction in the length of the survey and size of the population being considered. In cases where 10 or fewer observations were available for the survey, the observations from the pilot study were added to the survey observations to estimate \( \hat{P} \). Without this data pooling, it would not have been possible to estimate \( \hat{P} \) in many of the simulated surveys. If 10 or fewer observations are obtained during the actual surveys, the same technique (i.e., pooling data from multiple similar surveys) can be applied.

Finally, we investigated two methods to extrapolate the number of polar bears beyond the region sampled (polygon) during each 3-day period. The first method used the expected ratio of collared bears in the sampled region, and the total number of polar bears in the study area. This estimator was

\[
\hat{N}_{\text{total}} = \hat{N}_{sr} \times \hat{E}(c / c_{in}),
\]

where \( \hat{N}_{sr} \) was the estimated number of polar bears in the 3-day sampled region (polygon), and \( \hat{E}(c / c_{in}) \) was the average proportion of collared bears found in the sampled polygon across the three days.

The second method used to extrapolate beyond the region sampled in a 3-day period involved using the area under the RSF surface during the middle day (day 2). Using this method, the total number of polar bears in the study area was estimated as

\[
\hat{N}_{\text{total}} = \hat{N}_{sr} \times \frac{\sum_{in} \text{RSF}}{\sum_{\text{RSF}}},
\]

where \( \sum_{in} \text{RSF} \) was the sum of the RSF values for all 5 x 5 km cells within the sampled polygon, and \( \sum \text{RSF} \) was the sum of the RSF values for all 5 x 5 km cells across the entire study area.

After estimating the total number of polar bears on the sea ice within the study area for each 3-day period, we averaged the 3-day period estimates across the study area for our final estimate of the total population size. Bootstrapping was used to estimate the standard errors of the population totals. The 3-day periods were sampled, with replacement, for each of 200 bootstrap samples. Each bootstrap sample contained the original number of 3-day periods in the simulated survey. New estimates of \( \hat{P} \), \( E(s) \), and \( \hat{N}_{\text{total}} \) were generated for each sample. The standard error of \( \hat{N}_{\text{total}} \) was estimated as the standard deviation of the 200 bootstrap estimates.
We began our simulation using the largest number of hypothetical polar bears considered (3,000), the longest survey period attainable (8 weeks; which corresponds to sample size), and the most radio-collared bears (45). We calculated the coefficient of variation \( CV = 100 \times \frac{\hat{N}}{SE(N)} \), and the percent coverage of a 90% confidence interval \( CI = \hat{N} \pm 1.645 \left( SE(N) \right) \) for each combination of population size, survey period length, and number of radio-collared bears. Fish and Wildlife Service desires a CV \( \leq 20\% \), and we want to see a 90% CI contain the true population total approximately 90% of the time. We continued to run simulations while reducing the sample size (survey length) and/or population size and/or number of radio-collared bears until the CV and CI coverage became substantially undesirable at which point we suspended simulations.

**RESULTS**

Simulation results of primary interest (population estimates) are presented in Table 1. In general, the population estimator based on the area under the RSF surface in the sampled region (RSF estimator) was generally as expected and much better than the estimator based on the expected ratio of collared bears in the sampled region (collared bear estimator). Confidence interval coverage was acceptable for the RSF estimator for all sample sizes and populations \( \geq 1,000 \). Performance of the ratio of collared bears estimator was poor under the conditions simulated (Table 1). The ratio of collared bears estimator was biased low by approximately 30% when population size was \( \geq 2000 \) and number of survey weeks was \( \geq 6 \), while coverage of the 90% confidence interval was very low regardless of the number of weeks surveyed (38% to 74% coverage when population size \( \geq 2000 \)). Bootstrapping appeared to provide accurate standard error estimates for both estimators of population total (Figures 6 and 7) under most conditions simulated.

An additional simulation (not shown in Table 1) was run with an average of 3 sorties per day (6 transects) over a 4-week period with a population size of 2,000 polar bears (45 collared), to emulate a doubling of sampling intensity within a shorter survey period. The results from this simulation were similar to that for an 8-week survey with an average of 1.5 sorties per day (i.e., 90% CI Coverage = 87%, CV = 26%).

Tables 2 and 3 highlight additional simulation results. As expected, the mean distance the icebreaker moved increased and the total number of transects surveyed decreased with a decrease in survey length. The mean transect length was consistent across survey lengths (83.9 – 85.3) and similar to that observed in the pilot study (mean = 81.8 km, with SD = 41.4 km). The mean number of polar bears observed in the simulation decreased as both population size and the survey length decreased (Table 3). The mean number of bears observed decreased with a decrease in population size.

**DISCUSSION**

There are several advantages to initially approaching a problem through computer simulation. The most important is that simulation allows one to isolate individual factors or combinations of factors and investigate their influence on the characteristics of interest, while holding potentially confounding factors constant and thereby eliminating
their influence. In addition, sample sizes are virtually unlimited. This simulation also allowed us to investigate different extrapolation techniques. While real time passes only once, the outcomes of computer models can be replicated numerous times; the range, variation, and mean of outcomes observed across replications can be informative with respect to the reliability of predictions. This advantage is also a limitation of simulation; a simulation is a caricature of reality rather than reality itself, and the utility of a simulation usually depends on the validity of the assumptions made during its construction.

We considered two options for completing the computer simulation, generate the distance data in R and complete the distance analysis using DISTANCE, or complete the entire simulation (generating the distance data and completing the distance analysis) in R. Our comparisons of the two different approaches indicated that the kernel method implemented in R performed much better than DISTANCE at the low densities we expected in the simulations. (Appendix I). Thus, we feel comfortable with our approach of developing and running the simulation completely within R.

It is unreasonable to expect polar bears in the Chukchi Sea to stay within the bounds defined by our study area during any substantial length of time. Polar bears are known to generally move with the sea ice in order to find food sources, safety on the sea ice, and avoid confrontations with other bears. However, it would be impossible for the FWS or any single entity to survey the entire arctic in any one season, and the large-scale movement of polar bears between seasons and years precludes sequentially surveying various regions to produce an unbiased estimate of the total population size in the arctic.

Our simulation did not consider polar bears occupying land or areas within 25 km of the shoreline. The methodology we employed necessarily omitted the nearshore coastal zone owing to the coarse resolution of the sea ice concentration data. Consequently, the RSF model domain does not address the occupancy of habitats adjacent to the coastline, yet a considerable proportion of the Chukchi Sea polar bear population is known to utilize coastal areas during autumn (Durner et al. 2006). Durner et al. (2006) estimated that 13.2% of the polar bear locations during 15 September – 14 November in 1987 – 1994 were within 25 km of shore (some up to 5 km inland). However, these locations were not used to build the sea ice RSF for the Chukchi Sea due to the coarse resolution and unreliable nature of the sea ice data in this region. This poses a problem for extrapolation of estimates in these areas to the entire Chukchi Sea study area.

It is not known if polar bears use coastal habitats throughout the fall season, or mostly when the 50% ice edge is close to shore. If most polar bears are located some distance away from the shoreline at the beginning of the survey period and move south with the 50% ice edge during the fall they should have the opportunity to be observed during the survey. However, if a portion of the population uses areas within 25 km of shore during the entire survey period, a second survey in near-shore locations should be conducted at the same time as the survey staged off the ice-breaker in order to include this portion of the population in the overall population estimates. Thus, we recommend a separate land-based line transect survey be conducted simultaneously to any sea ice based survey in order to estimate the total number of bears occupying the entire arctic region.
Alternatively, a new and as yet unknown method for reliable extrapolation of near shore and off shore estimates could be employed. If such a method were found, both near shore and off shore area could be surveyed by a helicopter staged off an ice-breaker.

Similarly, we did not consider polar bears in the open water due to safety regulations enforced on the helicopter flights. Durner et al. (2006) found only a small portion (~1%) of bear locations > 50 km south of the 15% ice concentration contour during 15 September to 14 November during years 1987 – 1994. However, radiotelemetry collars were not expected to work well when submerged, so this estimate may be biased low.

The RSF estimator performed well overall. The estimator was nearly unbiased (bias <1%) for population sizes ≥2000 regardless of the number of weeks spent surveying. The estimator became positively biased as population size or survey weeks decreased (~4.5% bias for 1000 bears, ~100% bias for 500 bears). However, confidence interval coverage was usually close to target. The 8 week simulation with 3,000 bears had the best performance, with a CV of 21% and a 90% CI Coverage of 89%. Decreasing the sample size (fewer survey weeks) resulted in an increase of the CV (23% for 6 week survey, 29% for 4 week survey) and a slight decrease in the 90% CI Coverage (87% coverage for 6 week survey, 86% coverage for 4 week survey). Similarly, decreasing the population size resulted in poorer performance as indicated by an increase in the CV and a decrease in the 90% CI Coverage.

The collared bear estimator did not perform well overall. When population size and number of survey weeks was large (≥2000 and ≥6 weeks, respectively), the estimator was approximately 30% too low on average. Coverage of the 90% confidence interval in these situations was unacceptably low, ranging from 38% to 64%. The poor performance of this estimator was likely due to its reliance on two small ratios: the ratio of collared to un-collared bears in the population, and the ratio of collared bears inside and outside any given 3-day study area. The small proportion of collared bears in the population meant that in many 3-day survey periods, there were no collared bears observed and a population estimate could not be calculated. For a given survey, we rarely obtained a population estimate for every 3-day survey period (i.e., 10 for 4 weeks, 14 for 6 weeks and 19 for 8 weeks) and often only had from one to three survey period estimates from which to calculate the population estimate. The collared bear estimate appears to improve as the sample size decreases (number of weeks). This is due to an increase in the size of the sampled region and an increase in the proportion of the population that was collared. During shorter surveys the ice breaker moved more quickly and covered more area during a 3-day period which meant that more 3-day survey periods had observations of collared bears thus a population estimate could be calculated resulting in more survey periods contributing to a given survey population estimate.

Although simulation results indicate that an 8-week survey is preferable to a shorter length survey, the resulting sample size (number of transects flown) in the simulation was a function of the number of sorties flown per day. Flying more sorties (possibly by using 2+ helicopters) can increase the number of transects flown during a shorter period. We expect that a 4-week survey using 2 helicopters flying an average of 6 transects per day
would result in estimates of population size similar to those obtained using a helicopter during an 8-week survey.

A 20% CV seems to be a difficult objective to reach on many population surveys. Based on our experience with line transect surveys and mark-recapture studies for polar bears, moose, elk, golden eagles, and other species we believe a CV in the range of 30% to 40% is adequate for many purposes and more realistic, and should not preclude attempts to estimate the number of polar bears in the region. If line transect surveys were repeated on an annual or semi-annual basis, we would still expect power to detect trends in the population to be quite high.

In simulations where surveys lasted eight weeks, the ice breaker moved between 11.2 and 79.1 kilometers each day (median=25.0). In simulations of six week surveys, the ice breaker moved between 20.0 and 79.1 kilometers each day (median=32.0). For four week surveys, the ice breaker moved between 30.4 and 79.1 kilometers each day (median=47.2).

The two population size estimators considered in the simulation can both be viewed as estimators for a stratified survey area. The estimator based on the ratio of collared bears is akin dividing the study area into 2 strata – surveyed and not surveyed. The estimator based on the volume under the RSF surface is akin to dividing the study area into a large number of strata – one for each RSF 5 x 5 km cell in the GIS. The need to extrapolate estimates of the number of polar bears outside the surveyable region, the changing sea ice conditions, and the limitations of only being able to survey regions close to the 50% ice contour preclude the use of pre-survey stratification typical to other population surveys.

Our simulation incorporated observed sea ice conditions in years 1987 – 1994. Polar bear locations and the estimators themselves were based on the RSF developed by Durner et al. (2006) using radiotelemetry locations of sampled female polar bears obtained 1987 – 1994. Although contemporary sea ice data (1995 – present) is available, we did not include these years in our simulation because Durner et al. (2006) found a weaker relationship between RSF intervals and observed polar bear locations from years 1997 – 2005. It is unclear if this weaker relationship is due to the fact that data used for the evaluation came from polar bears captured and collared in the Beaufort Sea that wandered into the Chukchi Sea study area (i.e., they may not act like typical polar bears in the Chukchi Sea population), or a result of drastically different sea ice conditions. Sea ice conditions have drastically declined since 1994, and are expected to further decrease into the 21st century (Durner et al. 2008). These realized and potential future changes in the quantity and quality of available sea ice habitat for polar bears in the Chukchi Sea warrant further investigation to determine if resource selection habits of polar bears can be expected to change prior to any future aerial line transect survey conducted by the FWS. In addition, the logistical constraints experienced during the pilot survey conducted by Evans et al. (2003), and those anticipated in our simulation, may not mimic actual constraints presented in future years. For these reasons, we recommend validating the RSF developed by Durner et al. (2006) using contemporary radiotelemetry locations of polar bears in the Chukchi Sea. If there is indication that sea ice selection by polar
bears in the region has changed since 1987 – 1994, or that future sea ice conditions will substantially alter the logistical constraints and further hinder the ability of the FWS to conduct an aerial survey in a manner similar to that used in our simulation, we recommend developing a more contemporary RSF and possibly re-running the simulation to investigate potential changes in the expected properties of the survey method and estimators described in this report.
REFERENCES


Table 1. Average estimate of the number of polar bears in the Chukchi Sea, percent coverage of a 90% confidence interval (CI), and the average coefficient of variation (CV = SE/estimate) for 2 estimators of population size, for each hypothetical population size and number of survey weeks considered in the simulations. Simulations had 45 bears equipped with radiotelemetry collars, and flew an average of 1.5 sorties (3 transects) per day. A 90% confidence interval should contain the true population size 90% of the time (i.e., CI Coverage = 90%).

<table>
<thead>
<tr>
<th>Population Size</th>
<th>Number of Survey Weeks</th>
<th>Ratio of Collared Bears</th>
<th>RSF Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\tilde{N}$</td>
<td>CI Coverage</td>
</tr>
<tr>
<td>3,000</td>
<td>8</td>
<td>1,958</td>
<td>38%</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>2,161</td>
<td>54%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2,719</td>
<td>73%</td>
</tr>
<tr>
<td>2,500</td>
<td>8</td>
<td>1,592</td>
<td>36%</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1,857</td>
<td>56%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2,218</td>
<td>72%</td>
</tr>
<tr>
<td>2,000</td>
<td>8</td>
<td>1,405</td>
<td>54%</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1,550</td>
<td>64%</td>
</tr>
<tr>
<td></td>
<td>4</td>
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<td>72%</td>
</tr>
<tr>
<td>1,000</td>
<td>8</td>
<td>856</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>966</td>
<td>79%</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1,246</td>
<td>80%</td>
</tr>
<tr>
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<td>630</td>
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<tr>
<td></td>
<td>6</td>
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<tr>
<td></td>
<td>4</td>
<td>887</td>
<td>61%</td>
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</table>
Table 2. Summary statistics describing movement of the icebreaker and number of transects flown across all simulations repetitions for eight, six and four week surveys.

<table>
<thead>
<tr>
<th>Number of Survey Weeks</th>
<th>Minimum Distance (km)</th>
<th>Maximum Distance (km)</th>
<th>Mean Distance (km)</th>
<th>Total Number of Transects</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>11.2</td>
<td>79.1</td>
<td>25.0</td>
<td>167</td>
</tr>
<tr>
<td>6</td>
<td>20.0</td>
<td>79.1</td>
<td>32.0</td>
<td>126</td>
</tr>
<tr>
<td>4</td>
<td>30.4</td>
<td>79.1</td>
<td>47.2</td>
<td>84</td>
</tr>
</tbody>
</table>
Table 3. Mean number of bears observed per survey, per transect and per day across all simulations repetitions for eight, six and four week surveys.

<table>
<thead>
<tr>
<th>Population Size</th>
<th>Number of Survey Weeks</th>
<th>Mean Number of Bears Observed Per Simulation</th>
<th>Per Transect</th>
<th>Per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,000</td>
<td>8</td>
<td>84</td>
<td>0.50</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>65</td>
<td>0.51</td>
<td>1.53</td>
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<td></td>
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<td>42</td>
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<td>2,500</td>
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<td>69</td>
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<td>6</td>
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<td>0.43</td>
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<td>4</td>
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<td>1.24</td>
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<td>8</td>
<td>57</td>
<td>0.34</td>
<td>1.00</td>
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<td></td>
<td>6</td>
<td>43</td>
<td>0.34</td>
<td>1.01</td>
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<td></td>
<td>4</td>
<td>28</td>
<td>0.33</td>
<td>0.99</td>
</tr>
<tr>
<td>1,000</td>
<td>8</td>
<td>28</td>
<td>0.17</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>21</td>
<td>0.16</td>
<td>0.50</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>14</td>
<td>0.17</td>
<td>0.50</td>
</tr>
<tr>
<td>500</td>
<td>8</td>
<td>15</td>
<td>0.08</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>11</td>
<td>0.08</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>7</td>
<td>0.08</td>
<td>0.24</td>
</tr>
</tbody>
</table>
Figure 1. Boundary of the full Chukchi Sea study area used in the simulation sea ice occupying offshore (>25 km) waters between 190°W (-170°) to 156°E (-156°) and 66°N to 80°N within the red rectangle.
Figure 2. Frequencies of pelagic polar bear locations within 20 equal area RSF intervals along an increasing RSF-value gradient (Fig. 8 in Durner et al. 2006). Polar bear data from 15 September-15 November, 1987-1994.
Figure 3. Example images of 50% ice contour with simulated ice breaker locations, transects and sampled region (3-day survey period polygon) for an 8 week survey. Note that the survey appears to deviate from the 50% ice contour during the last image. This is due to the change in the sea ice in time. The underlying surface for each image is for the middle date of the current 3-day survey period (sampled region).
Figure 4. Transect lengths flown in the pilot study (Evans et al. 2003), and used in the simulation.
Figure 5. Example sampled region (survey period polygon) with ice breaker locations and transects for one simulated 3-day survey period. Transects surveyed from a given ice breaker location are those that start at the same latitude as the ice breaker.
Figure 6. Average standard error and standard deviation of the 500 estimates of polar bear population size in the simulations, based on the ratio of collared bears in the regions surveyed. A 1-to-1 relationship is represented by the dashed line.
Figure 7. Average standard error and standard deviation of the 500 estimates of polar bear population size in the simulations, based on the area under the RSF surface in the regions surveyed. A 1-to-1 relationship is represented by the dashed line.
APPENDIX I

A computer simulation using pilot study observations (Evans et al. 2003) was used to compare properties of kernel-based line transect analyses to properties of the semi-parametric analyses available in DISTANCE.

We used R to generate distance datasets for two densities (0.05 bears/km² and 0.00667 bears/km²), for each replication in the simulation. The lower density was the same as the density of polar bears estimated in the pilot study (Evans et al. 2003). Because estimators can perform much better (e.g., lower bias and higher precision) at higher densities, we used the higher density to illustrate the performance of the two analyses when low density was not a consideration.

Polar bear mean group size, location, and transect length were simulated the same way as in the main report. We completed 250 repetitions for each of the simulated datasets as defined by the two densities. The simulated datasets were output to .csv files for distance analysis in R and DISTANCE.

In R we modeled the probability of detection using the kernel-based detection function (equation [2] in report). In DISTANCE we chose to model the probability of detection using model averaging for two detection functions: a Uniform key function with cosine expansion and a Half-normal key function with cosine expansion. The number of expansion terms (0 – 5) in each model was determined by a stepwise model building process that used model AICc values to determine the most parsimonious model (Burnham and Anderson 2002). These two semi-parametric functions were chosen because they encompassed three of the four models used by Evans et al. in the pilot study, had high AICc weights accounting for 91% of the weight used in their model averaging, and allowed us to complete model averaging at the bootstrap level within DISTANCE. These models are also considered flexible, can yield model robust estimates, and can satisfy the shape criterion described by Buckland et al. (2001).

Since all but one polar bear group detected in the pilot study were ≤675 m from the transect line (Evans et al. 2003) we chose to truncate the data at 675 for the analyses. Truncation of distance data deletes outliers and results in a more robust estimation of the detection function (Buckland et al. 2001). Bootstrapping was used to estimate the standard errors for the densities (Manly, 2005) in both R and DISTANCE. New estimates of \( \hat{P} \), \( \hat{E}(s) \), and \( \hat{D} \) were generated for each sample. Standard errors of \( \hat{P} \) and \( \hat{D} \) were estimated as the standard deviation of 200 bootstrap estimates. Since the proposed aerial survey will assume a \( g_0 = 1 \) by using the pilot(s) to detect polar bear groups directly below the aircraft (Jon Aars, personal communication) we elected to use \( g_0 = 1 \) in the simulation even though Evans et al. (2003) used a \( g_0 = 0.667 \) which had come from an earlier polar bear aerial survey (McDonald et al. 1999).
Both the kernel (in R) and standard distance (in DISTANCE) analyses performed well when density was higher (i.e., when 0.05 bears/km$^2$, Table A.I.1). When density was set at its higher level, detection probability estimates ($\hat{P}$) were different (average $\hat{P}$=0.485, average SE($\hat{P}$) = 0.4975 for R and average $\hat{P}$=0.349, average SE($\hat{P}$) = 0.04491 for DISTANCE), but these differences did not translate into substantially different properties for the overall estimates of density. The average density estimate from R ($\hat{D}$ = 0.04975) was closer to the true population density (0.05) than the DISTANCE density estimate ($\hat{D}$ = 0.04491). Bias in the density estimate was 5% for the kernel method implemented in R, while bias of the usual distance analyses implemented in DISTANCE were twice as high (bias = 10.2 % for DISTANCE). In addition, standard errors were slightly larger using the standard distance analysis than when using the kernel method (SE($\hat{D}$) = 0.0077 for DISTANCE and SE($\hat{D}$) = 0.0060 for kernel method).

<table>
<thead>
<tr>
<th>Density</th>
<th>Program</th>
<th>$\hat{P}$</th>
<th>SE($\hat{P}$)</th>
<th>$\hat{D}$</th>
<th>SE($\hat{D}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>R</td>
<td>0.485</td>
<td>0.0475</td>
<td>0.04975</td>
<td>0.0060</td>
</tr>
<tr>
<td></td>
<td>Distance</td>
<td>0.349</td>
<td>0.0481</td>
<td>0.04491</td>
<td>0.0077</td>
</tr>
<tr>
<td>0.00667</td>
<td>R</td>
<td>0.537</td>
<td>0.1301</td>
<td>0.00629</td>
<td>0.0020</td>
</tr>
<tr>
<td></td>
<td>Distance</td>
<td>0.395</td>
<td>0.0583$^a$</td>
<td>0.00561</td>
<td>0.0016$^a$</td>
</tr>
</tbody>
</table>

a. Estimates based on Delta method. Bootstrap results not available due to program failure.

When true (simulated) density was lower, the kernel method out-performed standard distance analyses. When true density was set to 0.00667 bears/km$^2$, detection probability estimates were again different (average $\hat{P}$=0.537, SE($\hat{P}$) = 0.1301 for R and average $\hat{P}$=0.395, SE($\hat{P}$) = 0.0583 for DISTANCE), but overall density estimates were also different. The kernel based density estimate from R ($\hat{D}$=0.00629) was closer to the true population density of 0.00667 than the semi-parametric DISTANCE density estimate ($\hat{D}$=0.00561). Bias in the density estimate was 5.7% for the kernel method and 15.9% for DISTANCE.

In summary, the density estimates implemented in R that modeled the probability of detection using a kernel-based estimator more closely approximated the true population densities than did density estimates obtained from DISTANCE using model selection with semi-parametric detection functions. As density decreased, the disparity between the two estimates increased with the estimates from R remaining closer to the true population density than the estimates from DISTANCE. The bias in density estimates
from R remained fairly constant between the two different simulations (high density bias = 5.0% and low density bias = 5.7%) while the bias in density estimates from DISTANCE was both higher than R and increased as the density decreased (high density bias = 10.2% and low density bias = 15.9%). In addition, fatal errors caused DISTANCE to terminate pre-maturely during bootstrap analysis at the lower density.