Polar Biol
DOI 10.1007/s00300-008-0439-7

ORIGINAL PAPER

Effects of sea ice extent and food availability on spatial and temporal distribution of polar bears during the fall open-water period in the Southern Beaufort Sea

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Received: 7 August 2007 / Revised: 29 February 2008 / Accepted: 9 March 2008

Abstract We investigated the relationship between sea ice conditions, food availability, and the fall distribution of polar bears (*Ursus maritimus*) in terrestrial habitats of the Southern Beaufort Sea via weekly aerial surveys in 2000–2005. Aerial surveys were conducted weekly during September and October along the Southern Beaufort Sea coastline and barrier islands between Barrow and the Canadian border to determine polar bear density on land. The number of bears on land both within and among years increased when sea-ice was retreated furthest from the shore. However, spatial distribution also appeared to be related to the availability of subsistence-harvested bowhead whale (*Balaena mysticetus*) carcasses and the density of ringed seals (*Phoca hispida*) in offshore waters. Our results suggest that long-term reductions in sea-ice could result in an increasing proportion of the Southern Beaufort Sea polar bear population coming on land during the fall open-water period and an increase in the amount of time individual bears spend on land.

Keywords Polar bears · Sea ice · Distribution · Bear density

Introduction

Identifying the ecological factors affecting animal distributions can be important for predicting population-level responses to changing environmental conditions (Mills and Gorman 1997; Musiega et al. 2006; Sutherland 2006). Such predictions are increasingly needed in the Arctic where rapid changes in pack and land-fast ice associated with climate change (Dumas et al. 2006; Holland et al. 2006; Lemke et al. 2007) are expected to result in broad ecosystem-level impacts (Gitay et al. 2002; ACIA 2005; Parmesan 2006; Serreze et al. 2007). Species living at high latitudes or altitudes are restricted to occupying the most cold-extreme habitats and as a result are some of the first to

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exhibit responses to climate change (Walther et al. 2002; Parmesan 2006). However, detecting and definitively attributing population trends in long-lived species to changing environmental conditions has been constrained by the ability to detect major declines in abundance (Taylor et al. 2007) and the potential for additional ecological processes, such as density dependence, to play a role (Ginzburg et al. 1990; Ellis and Post 2004; Derocher 2005). Identifying and understanding the mechanisms by which environmental factors, such as those attributed with climate change, may affect wildlife populations and their distribution can aid in predicting potential long-term population-level responses (Parmesan 2006).

Polar bears (*Ursus maritimus*) and their primary prey, ringed seals (*Phoca hispida*), are both highly dependent on sea ice (Stirling and Derocher 1993; Amstrup 2003; Simpkins et al. 2003), raising concerns that both species may exhibit population-level responses to changing sea ice conditions (Derocher et al. 2004; Regehr et al. 2006; Stirling and Parkinson 2006; Schliebe et al. 2006). While the life-history of some polar bear populations, such as those in Western Hudson Bay and Baffin Bay, includes spending up to 4 months of the year on land during the fall open-water period (Stirling et al. 1977; Derocher et al. 1993; Ferguson et al. 1997, 2000), polar bears in Alaskan populations, including the Southern Beaufort Sea (SBS) and Chukchi Sea, and other open basin populations (e.g., Barents Sea, Laptev Sea, Franz Joseph, Svalbard, East Greenland) typically spend most of the year on the sea ice (Garner et al. 1990; Amstrup et al. 2000; Mauritzen et al. 2001; Durner et al. 2004). However, recent reports from bowhead whale (*Balaena mysticetus*) aerial surveys suggest an increase in polar bear use of land in the fall since around 1997 (Monnett et al. 2005; Gleason et al. 2006). In addition, polar bear sightings in the vicinity of onshore oil and gas facilities (C. Perham, unpublished data) and observations by Native villagers suggest that bears have been increasing their use of land during the fall open-water period in the Alaskan SBS. Furthermore, females in this population have exhibited a shift to denning more on land and less on the sea ice in recent years (Fischbach et al. 2007). These changes have occurred over the same time period as documented reductions in the summer extent of sea ice in the SBS (Rigor and Wallace 2004; Serreze et al. 2007). Similar reductions in sea ice in Western and Southern Hudson Bay have resulted in polar bears spending more time fasting on land and as a consequence, human–bear interactions have increased (Stirling and Parkinson 2006), and bear body condition and reproduction have declined (Stirling et al. 1999; Dowsley 2006; Obbard et al. 2006; Stirling and Parkinson 2006) ultimately resulting in population declines (Regehr et al. 2008). Though declines in body condition and cub survival have also been documented in the SBS, they have not yet been directly linked to changes in sea ice conditions (Regehr et al. 2006). To better understand polar bear responses to changing ice conditions in the SBS, we investigated temporal and spatial patterns of polar bear abundance along the north coast of Alaska during the fall open-water period in relation to sea ice conditions and food availability.

Polar bears that come on land in most areas typically consume minimal, if any, food and therefore, spend the duration fasting while they await the re-formation of ice needed to access and hunt seals (Derocher et al. 1993; Atkinson and Ramsay 1995). For this reason, longer ice-free periods in Western and Southern Hudson Bay, Canada, are more clearly linked to reduction in body condition and natality (Stirling et al. 1999; Dowsley 2006; Obbard et al. 2006). Adult female polar bears fitted with GPS collars and tracked in the Southern Beaufort have only occasionally been observed coming ashore in the fall (G. Durner, personal communication), though the proportion of the total SBS population coming ashore each year in the fall is unknown. Of those polar bears that do come ashore, at least some spend time foraging on subsistence-harvested bowhead whale carcasses. Three communities, Barrow, Nuiqsut, and Kaktovik (Fig. 1), on the North Slope of Alaska consistently harvest bowhead whales each fall, and as many as 65 polar bears have been observed feeding at a single bowhead whale carcass (Miller et al. 2006). Bowhead whale carcasses have been available to polar bears at these locations since the early 1970s (Koski et al. 2005). Identifying the distribution of polar bears on the coast in relation to availability of whale carcasses is important to understanding the potential implications of increased land use on polar bear body condition and the role whale carcasses may play in affecting land use by bears. Furthermore, estimates of the minimum number of bears using land in the fall is needed to better understand potential population-level effects.

In light of the apparent changes in polar bear use of the nearshore environment and its potential to have both ecological and management implications, our objectives were to (1) determine whether within and among-year variation in polar bear abundance onshore is related to seasonal and annual variation in the extent of the pack ice and density of ringed seals over the continental shelf, and (2) identify spatial patterns of polar bear abundance onshore in relation to proximity to pack ice, availability of subsistence-harvested whale carcasses, and distribution of ringed seals in offshore areas.

As the ice retreats to its minimum extent in mid-to-late September, we predicted that the number of polar bears occurring on land would increase as opportunities for bears to return to the sea ice decline (Stirling et al. 1999; Stirling and Parkinson 2006). Though only a portion of the SBS

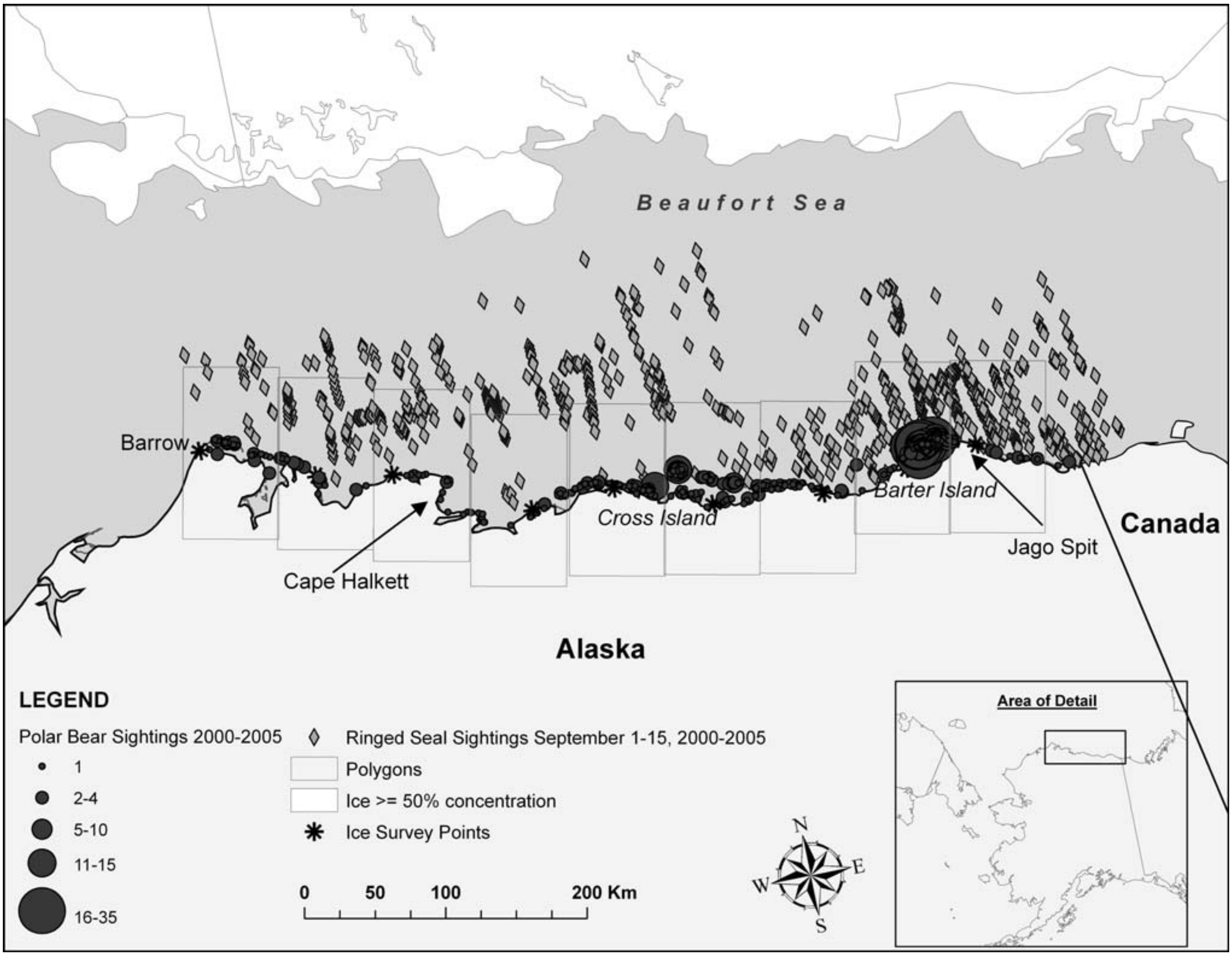

Fig. 1 Map of polygons, ice survey points (*asterisks*), and ringed seal sightings (*diamonds*) used to quantify offshore ringed seal density, polar bear density on land, and the distance to sea-ice on the Alaskan coast of the Southern Beaufort Sea. Sea-ice shown is an example of the data provided by the National Ice Center for 3 October 2005. Note that spatial patterns were examined only between 2003 and 2005 when surveys were flown between Barrow and the Canadian border

population appears to come to shore in the fall, we hypothesized that ice conditions would affect both within and among-year variation in the total number of polar bears on shore. We further hypothesized that the largest concentrations of polar bears would occur at the three areas where subsistence-harvested bowhead whale carcasses are deposited (Miller et al. 2006), particularly since access to polar bear preferred prey, ringed seals, is believed to be limited during the open-water period. We also investigated the possibility that, despite limited access to ringed seals during the open-water period, polar bear distribution on land may be a response to annual and spatial variation in ringed seal density over the continental shelf. Though ringed seals occur primarily in open-water areas in the fall in the SBS (Harwood and Stirling 1992), several studies have suggested that locations of polar bears during the open-water period were related to future opportunities to access ringed seals (Ferguson et al. 2000; Durner et al. 2004). Thus, our analyses of spatial and temporal patterns of near-shore polar bear abundance were examined relative to ice conditions, whale carcass availability, and ringed seal distribution and relative abundance.

Materials and methods

Aerial survey methods

Polar bear density estimates

Indices of polar bear density were determined by conducting weekly systematic aerial surveys along the coastline and barrier islands in the southern Beaufort Sea from mid-September to late-October 2000–2005 to identify seasonal

Table 1 Number of polar bears observed and distances surveyed for coastal aerial surveys conducted along the coast of the Alaskan Southern Beaufort Sea

	Total No. of bears observed	Total Distance Surveyed (km)
9/21/2000	49	914
9/28/2000	73	796
10/5/2000	72	856
10/12/2000	38	831
9/26/2001	29	960
10/3/2001	22	873
10/10/2001	30	842
10/17/2001	16	666
9/12/2002	43	839
9/19/2002	84	1,023
10/3/2002	114	943
10/17/2002	101	942
10/25/2002	41	806
9/17/2003	59	1,593
9/24/2003	61	1,667
10/6/2003	51	1,666
10/24/2003	32	1,452
9/15/2004	81	1,685
9/23/2004	106	1,791
10/6/2004	122	1,881
10/20/2004	55	1,650
9/12/2005	40	1,692
9/21/2005	82	1,688
10/5/2005	54	1,192
10/17/2005	21	1,488

Dates in bold are surveys conducted between Barrow and the Canadian border. All other surveys were conducted between Cape Halkett and Jago Spit (see Fig. 1)

changes (Table 1). During 2000–2002, the survey area extended from Cape Halkett to Jago Spit and in 2003–2005 from Barrow to the Canadian border (Fig. 1). Because polar bear activity in this area is concentrated along a relatively narrow band including the barrier islands and mainland coast, surveys were flown over these same areas each year similar to Stirling et al. (2004). Previous studies have shown perpendicular detection of polar bears from aerial surveys to remain high out to 500 m (McDonald et al. 1999; Wiig and Derocher 1999). As a result, the number of polar bears per km flown provides a "density" index for comparing temporal and spatial patterns of coastal use by bears relative to ecological conditions (Stirling et al. 2004). Since the methods were designed to generate a relative density index, we do not recommend extrapolating the values reported in this study to estimate total abundance of polar bears using the Alaskan north coast in any given year.

Surveys were flown in an Aero-Commander aircraft at an altitude of 91 m (300 ft) and a ground speed of 165–205 km/h. Two experienced observers recorded polar bear sightings. For each polar bear sighting, observers recorded sex and age of individual bears when possible. A designated observer continuously recorded changes in visibility and weather conditions. Only surveys conducted in fair to good viewing conditions were included in analyses. When necessary, animals were circled to verify counts, sex/age class, or presence/absence of cubs. However, because of our limited ability to reliably distinguish sex and age class of each bear observed, bears were further classified as either family groups or lone bears for analysis. Cubs-of-the-year could typically be distinguished from yearlings and 2-years old, but occasionally dependent young were classified as unknown age. A global positioning system (GPS; Garmin III+; Garmin International Inc., Olathe, KS, USA) recorded and time-stamped aircraft locations at 13–15 s intervals, as well as locations for all polar bear sightings. Flight tracks and polar bear sightings were entered into a Microsoft Access™ database and imported later into ESRI® ArcMap (Version 9.1; ESRI Inc., Redlands, CA, USA) to generate distribution maps.

Since distances flown varied slightly among surveys, the number of bears sighted was divided by the distance surveyed. Distances flown were determined by downloading waypoints from flights and converting point files to line files in ArcMap using Hawth's analysis tools (Version 3.06; Beyer 2004). Off-survey sections were omitted from line files and lengths of remaining lines were quantified using Hawth's tool. Distances spent circling to verify observations were not included in measures of survey distance.

Ringed seal density

Ringed seal density was determined from aerial surveys conducted (MMS, Anchorage, AK, USA) between 1 and 15 September 2000–2005 (Harwood and Stirling 1992). Aerial surveys consisted of randomized transect lines flown perpendicular to the coastline up to 200 km off the north coast of Alaska between Barrow and the Canadian border. Surveys were flown at an altitude of 457 m and a target groundspeed of 200–250 km/h (for further detail on survey design see Monnett and Treacy 2005). We included only data collected in Beaufort Sea states ≤ 2 (Beaufort scale winds of 4–6 knots, wave height 1/2–1 m, and small wavelets and unbreaking waves; Chapman 1977) and during good visual conditions (Harwood and Stirling 1992). Because standard deviation of daily ringed seal estimates showed a significant negative relationship with the total transect distance covered ($R^2 = 0.90$, $F = 35.3$, $P = 0.004$), only surveys that covered >600 km distance in a single day were included in estimates of ringed seal density. Similar to polar bear surveys, data collected on ringed seals were used as an index of spatial and temporal patterns of density and were not intended to represent population estimates.

Data selection and analysis

Factors affecting polar bear density within and among years

Analysis of both within and among year variation in polar bear density was based on counts of all bears excluding dependent young. Survey date was not included as a factor affecting polar bear density because we assumed that bears respond to ecological factors on a given date within a given year irrespective of the date itself. We hypothesized that both within and among year variation in polar bear density on land was related to the distance between land and pack ice edge. Therefore, we measured the distance to the pack ice edge using digital satellite-derived ice data in ArcMap (Version 9.1; ESRI Inc., Redlands, CA, USA). Nineteen points distributed roughly every 100 km along the coastline were created using ET Geowizards extension in ArcMap (Version 9.6; ET Spatial Techniques, Pretoria, South Africa; http://www.ian-ko.com) which selects points at equal intervals along a feature of choice specified by the user. Distances between points were calculated using measurements of the coastline and not straight line distances between points. Points located within bays or inlets were excluded so that “ice survey points” occurred only along the outer coast (Fig. 1). Ice data from the National Ice Center (http://www.natice.noaa.gov/) which includes spatial distribution and concentration of ice was used to identify areas of ice concentrations ≥50% which we defined as pack ice edge. The 50% threshold was chosen based on findings that polar bears in Western Hudson Bay and other eastern Canadian populations abandoned ice for shore when ice concentration drops below 50% (Stirling et al. 1999; Stirling and Parkinson 2006). Additionally, during autumn, radio-collared female polar bears in the SBS tend to use sea ice of 70–90% concentration (Durner et al. 2004). Distances from ice survey points to the pack ice edge of ≥50% concentration were quantified using the “Near” feature in ESRI® ArcToolbox (Version 9.1; ESRI Inc., Redlands, CA, USA) which measures the shortest linear distance between the survey point and the nearest ice of ≥50% concentration. Ice of this concentration was almost always part of the consolidated pack ice and landfast ice was excluded from measures, thus distances were essentially distances to the main pack ice, rather than randomly scattered fragments of 50% ice. Initially, we calculated mean distances across all survey points for every date in which ice data were available (typically every 3–4 days) between August and October of each year. Then, for each survey date, measures of ice conditions were calculated, including the mean and minimum distance of all ice survey points to the pack ice edge on the date of a survey. These values were then used to calculate (1) the mean distance to the pack ice edge from survey points for all dates during the month prior to the survey, and (2) the minimum distance to the ice edge for all dates during the month prior to the survey.

In addition to ice conditions affecting polar bear density on land, we investigated the role annual variation in ringed seal density over the continental shelf during the fall might play in affecting polar bear distribution in coastal areas. Ringed seal density was quantified as the number of ringed seals observed per 100 km surveyed between Barrow and the Canadian border. We also compared polar bear density on land at the minimum pack ice extent with polar bear density once land-fast ice formed. This allowed us to determine if polar bears leave land as soon as ice is available to access ringed seals offshore.

Spatial variation in polar bear density

Analyses of spatial patterns of polar bear density were restricted to only 2003–2005 when polar bears were surveyed over the larger geographic scale (from Barrow to the Canadian border). Spatial patterns were determined by quantifying polar bear density in relation to ringed seal density in nine rectangular polygon layers, 60 km wide × 120 km long, created in ArcMap® (Fig. 1). To create polygons that extended a similar distance offshore, the coastline was rotated to create the best straight line coast possible. From center point of the coastline in each polygon, a 60 km offshore area was included to encompass the continental shelf area delineated by the 25 m mid-depth bathymetry line (Schumacher 1976) where coastal, shore-fast ice forms in October, and where ringed seals are likely to be first available to polar bears after the open-water period (Durner et al. 2004). Several studies have documented this area as having the highest density of ringed seals during the fall open-water period in the SBS (Harwood and Stirling 1992; Frost et al. 2004). Ringed seal densities were quantified as the total number of ringed seals observed divided by the area of water within a polygon. Polar bear density was calculated as the number of polar bears sighted per km surveyed within each polygon. The proximity of ice to a single ice survey point located within each polygon was used to quantify spatial variation in ice proximity along the coast.

Statistical analyses

For all analyses, parametric-tests were conducted when assumptions of statistical tests could be met. Homogeneity of variance was confirmed prior to proceeding with all analysis of variance (ANOVA) and general linear model (GLM) analyses using either a Levene's test if data were not normally distributed or an F-test if data were normal. Normality was tested using an Anderson–Darling test. Means and standard deviations are provided unless otherwise stated. Because ANOVAs and GLMs are robust to non-normality, these tests were used even if normality could not be achieved (Green 1979). Three-way and two-way interactive terms were included initially in all GLM analyses. However, interactive terms were removed from the GLM if $P \geq 0.10$ in a stepwise fashion, such that three-way interactive terms were first removed, the GLM was re-run, and subsequent non-significant two-way interactive terms were removed. Thus, the final model results presented exclude any non-significant interactions. All statistical analyses were conducted in Minitab® (Version 13.32; Minitab, Inc., State College, PA, USA).

Factors affecting polar bear density within and among years

Because the area of the coast surveyed increased in latter years which could potentially bias polar bear density estimates, a paired t-test was used to compare (1) truncated data sets of polar bear surveyed between Cape Halkett and Jago Spit from 2003–2005 with (2) all data collected between Barrow and the Canadian border in 2003–2005. The results of this test were used to determine if data collected in all areas could be compared across all years or if only data collected between Cape Halkett and Jago Spit could be used. A Pearson's correlation matrix was generated to identify which of the two ice measures (i.e., the minimum or mean distance to the ice edge the month prior to a survey date) was most closely related to polar bear density. A GLM was used to determine whether the distance to ice from shore varied within and among years by including Julian date as a co-variate, year as a main effect, and year × date as an interactive term. A Pearson's correlation was used to examine within year patterns of ice distance and whale carcass use by correlating Julian date with mean distance to the ice edge and the proportion of bears onshore occurring within 15 km of subsistence-harvested bowhead whale carcasses.

A linear regression was used to examine the effects of ringed seal density offshore and mean distance to pack ice on annual variation in polar bear density. Ringed seal density for this analysis was quantified as the total number of ringed seals observed per 100 km of transect offshore between Barrow and the Canadian border. To incorporate daily variation in pack ice distance across the survey period of each year, the distance to pack ice was quantified as the area under the curve (AUC) of pack ice distance (distance of ice $\geq$ 50% concentration) versus date (Fig. 3) for the survey period each year. The AUC was then used in the regression analyses to determine if ice distance and ringed seal density were related to polar bear density among years. Subsistence-harvested whale carcasses were available to bears throughout the survey periods in all years at Cross and Barter Islands. Due to a lack of variation in whale carcass availability, it was not included as a factor affecting within or among year variation in polar bear density on land. A Friedman's repeated measures analysis was used to determine if the proportion of females with dependent young, cubs-of-the-year, and yearlings/2 year olds observed varied among years. A paired t-test was used to compare polar bear density between surveys conducted at the minimum extent of the pack ice in each year and surveys conducted in mid-to-late October when pack ice had extended near the continental shelf and land-fast ice had formed. We hypothesized that polar bears would move onto the sea ice from land once ice returned over the continental shelf.

Spatial variation in polar bear density

Analyses of the factors affecting spatial variation in polar bear density along the coast were conducted separately from analyses of the factors affecting temporal variation for two reasons. First, data was collected over the broadest geographic scale in 2003–2005 only, whereas temporal patterns were best examined across all years. Second, we hypothesized that different factors were driving temporal versus spatial variation in polar bear density. For example, the lack of year-to-year and within-year variation in bowhead whale carcass availability precluded the possibility that it was a factor driving temporal variation in polar bear density, whereas it could be an important factor affecting spatial variation. Furthermore, we were also interested in understanding the relationship between the ice edge distance and both spatial and temporal variation in polar bear density which we hypothesized might not necessarily act in the same direction (i.e., polar bear density would be higher in areas close to the ice edge but total density on land would be lower during years when the ice edge was closer to shore).

A GLM was used to determine if polar bear density differed between polygons with and without subsistence-harvested bowhead whale carcasses including distance to ice and ringed seal density offshore as co-variates. All interactions were examined, but were removed from the final model if $P > 0.10$. In addition, a Pearson correlation matrix was used to identify patterns of polar bear density, ringed seal density, and ice distance from west to east along the coast as well as relationships between polar bear density, ringed seal density, and ice distance. A regression analysis was conducted to determine if the number of polar bears observed at Barter Island accurately predicted the number of bears elsewhere on the coast in a given year.

Results

The maximum density of bears observed during any single survey was 8.6 bears/100 km or 122 bears total. Across all years and survey dates between mid-September and the end of October, an average of 4 ± 2 bears/100 km (57 ± 28 bears total) were observed. Thus, a maximum of 8.0% and an average of 3.7% of the estimated 1,526 bears in the SBS population (Regehr et al. 2006) were observed on land.

Factors affecting polar bear density within and among years

Number of bears observed per km of survey flown was higher (paired $t = -6.43$, $df = 10$, $P < 0.001$) between Cape Halkett and Jago Spit (3.87 ± 1.59 bears/100 km) than the area surveyed between Barrow and the Canadian border (2.88 ± 1.26) during the 2003–2005 surveys (Fig. 2). As a result, data used in all temporal analyses were restricted to only those surveys conducted between Cape Halkett and Jago Spit in 2000–2005 so that relationships could be examined among all years. The distance surveyed was related (Spearman's $r = 0.40$, $n = 25$, $P = 0.05$) to the number of bears encountered per km, but this relationship was not present once we removed a short survey conducted on 17 October 2001 ($r = 0.35$, $n = 24$, $P = 0.10$). This lack of relationship suggests that effort (survey length) was sufficient to accurately estimate polar bear density and that estimates were not biased by survey length.

Mean distance from shore to pack ice along the coast varied both within (Fig. 3; $F_{1,12} = 10.87$, $df = 1$, $P = 0.006$) and among years ($F_{5,12} = 5.32$, $df = 5$, $P < 0.008$). The distance to pack ice of $\geq$50% concentration was negatively correlated with date ($r = -0.688$, $df = 1$, $P < 0.0001$). Mean distance to $\geq$50% ice concentrations during the month prior to a survey was more closely related to polar bear density ($r = 0.75$, $n = 19$, $P = 0.0002$; Fig. 4) than any other ice measure. The distance to $\geq$50% ice concentration on the survey date was also related to polar bear density onshore ($r = 0.627$, $n = 19$, $P = 0.005$). In all years, the number of bears observed along the coast was higher (5.17 ± 2.37 bears/100 km) during the period of pack ice retreat (Fig. 2: ice distance of 208.2 ± 102.6 km) than after land-fast ice formed (2.58 ± 0.84 bears/100 km)($t = 3.87$, $df = 5$, $P = 0.012$) and the distance to offshore ice concentrations $\geq$50% declined (i.e., after October 12th ice distance: 84.4 ± 73.6 km)($F_{1,10} = 5.76$, $P = 0.037$). For all years, the proportion of bears using whale carcasses increased throughout the survey period (mid-September to mid-October; Fig. 5). Those bears that remained ashore after land-fast ice formation and pack ice formation advanced occurred almost exclusively near whale carcasses, whereas earlier in the season bears were more uniformly distributed along the coastline.

Annual variation in the density of adult and subadult bears onshore was directly related to the distance to pack ice. Annual variation in polar bear density during mid-September surveys was related to ringed seal density offshore during the 2 weeks prior to surveys (Fig. 6a). In addition, variation in the mean polar bear density across all surveys was related to the area under the curve for Fig. 3 (mean distance to 50% ice concentration between 1 September and 10 October; Fig. 6b). A step-wise regression that included both factors suggests that ice conditions, quantified as AUC, had the greatest effect on annual variation in polar bear density ($t = 3.32$, $P = 0.029$). Annual variation in ringed seal density was not correlated with distance to ice ($r = 0.609$, $P = 0.199$). There was no apparent trend in polar bear density with year ($r = -0.009$, $df = 1$, $P = 0.99$).

There was no difference among years in the proportion of females with dependent young (29.5 ± 8.9%) (Friedman's repeated measures: $F = 0.88$, $df = 5$, $P = 0.52$) or the

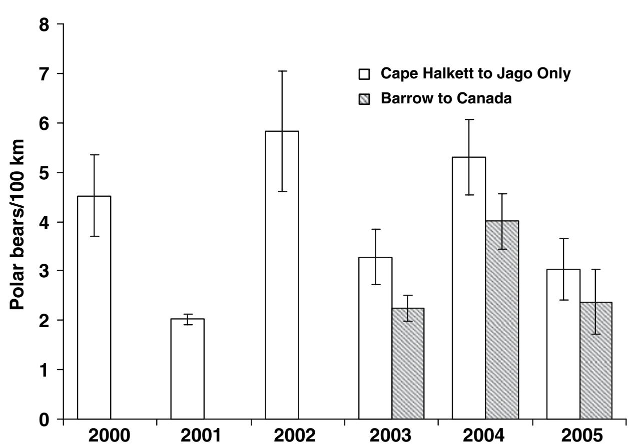

Fig. 2 Annual variation in the number of adult and subadult polar bears observed per 100 km during aerial surveys flown from Cape Halkett to Jago Spit only between 2000 and 2005 and flown from Barrow to the Canadian border between 2003 and 2005

Fig. 3 Seasonal variation in the mean distance from survey points along the north coast of Alaska between Barrow and the Canadian border to the edge of $\geq$50% ice concentration

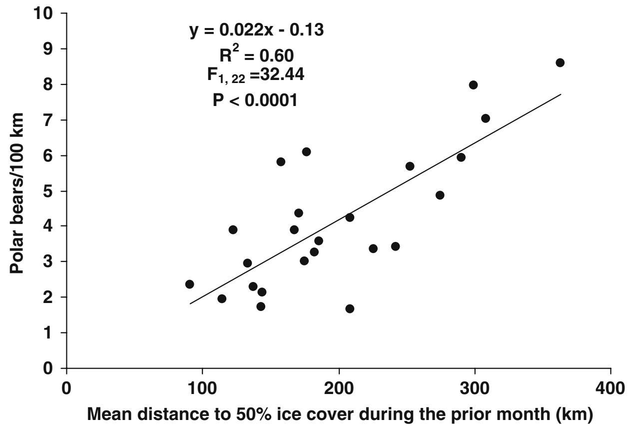

Fig. 4 The relationship between the polar bear density on the Alaskan coast of the southern Beaufort Sea and mean distance to the ice edge during the month prior to each survey date

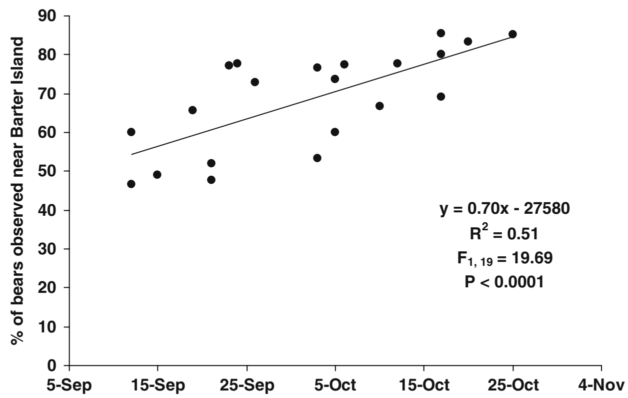

Fig. 5 Relationship between survey date and the percent of all adults and subadults observed on the survey that occurred within 15 km of subsistence-harvested bowhead whale carcasses at Barter Island, Alaska. Surveys were conducted weekly from 2000 to 2005. Dates in which greater than 50% of bears observed were recorded as unknowns were excluded

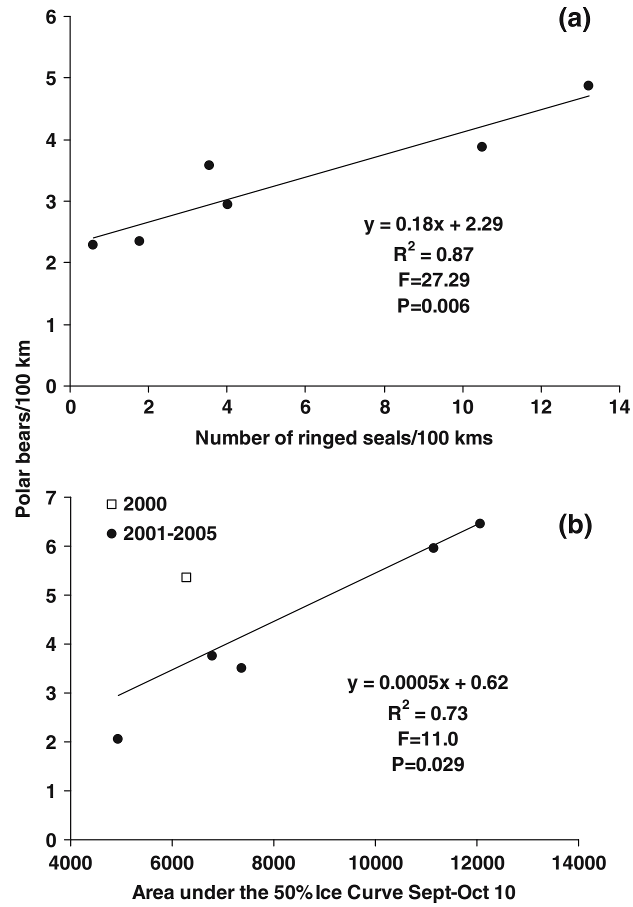

Fig. 6 Relationships between polar bear density onshore, ringed seal density offshore (**a**), and the area under the curve of mean distance to sea-ice of ≥50% concentration for each year surveyed (**b**). Ringed seal density was determined for 1–15 September over the continental shelf of the Alaskan Beaufort Sea and related to polar bear density onshore during the first survey of each year ranging between 12 and 26 September. The Area under the Curve was determined for September through October and related to the mean number of polar bears observed per km across all surveys for a year. Polar bear density is for Cape Halkett to Jago Spit only (see Fig. 1)

percent of dependent young (30 ± 6% of all bears observed)($F = 0.63$, $df = 5$, $P = 0.68$) observed in coastal surveys. Of the dependent young observed, the proportion of cubs-of-the-year (COY) and yearlings/2 years old were consistent across years (COY: 56.4 ± 19% of all dependent young; $F = 0.60$, $df = 5$, $P = 0.70$; yearlings: 41.6 ± 18.4%; $F = 0.94$, $df = 5$, $P = 0.49$).

Spatial variation in polar bear density

Polar bear density was higher (7.1 ± 8.1 bears/100 km) in polygons where subsistence-harvested whale carcasses were present compared to polygons where carcasses were absent (1.2 ± 1.2 bears/100 km) ($F_{1,23} = 6.25$, $P = 0.02$), but there was an interactive effect between ringed seal density over the continental shelf and whale carcass availability ($F_{1,23} = 8.5$, $P = 0.008$). Thus, the confounding effects of high ringed seal density ($F_{1,23} = 18.59$, $P < 0.0001$) and whale carcass availability could not be separated. Distance to pack ice was not a significant co-variate affecting polar bear density across polygons ($F_{1,21} = 0.97$, $P = 0.34$) and was excluded from the general linear model. Polar bear density was also related to ringed seal density across polygons ($r = 0.75$, $P < 0.0001$), but not to the distance to ice edge ($r = -0.12$, $P = 0.57$).

Ringed seal density within 60 km of the mainland coast increased ($r = 0.41$, $P = 0.032$) and distance to ice edge decreased($r = -0.41$, $P = 0.033$) from west to east along the coast. Ringed seal density was not correlated with the distance to ice edge ($r = -0.14$, $P = 0.49$). For the three communities that harvest bowhead whales, the density of polar bears in a polygon was not correlated with the number of whales harvested ($r = -0.5$, $P = 0.5$). Conversely, 80.5 ± 15.7% of all polar bears observed during aerial surveys occurred ≤15 km of whale carcasses; 68.9 ± 14.2% of polar bears observed on the coast occurred at Barter Island alone. The number of bears concentrated at Barter Island in a given year was not representative of trends in bear density along the rest of the coast as a whole ($R^2 = 0.10$, $F_{1,19} = 3.13$, $P = 0.09$).

Discussion

Polar bear density along the mainland coast and on barrier islands during the fall open-water period in the SBS was related to the distance between shore and the pack ice edge and the density of ringed seals over the continental shelf. The distance between pack ice edge and the mainland coast, as well as the length of time in which these distances prevailed as quantified by the AUC, was directly related to polar bear density onshore. In addition to ice proximity, we hypothesize that the distribution of ringed seals may be affecting polar bear density onshore throughout the fall open-water period by (1) encouraging bear movement on to land so they have access to seals that concentrate in open-water over the continental shelf when the pack ice retreats and, or (2) influencing bear distribution as they utilize areas of high ringed seal density to maximize future hunting opportunities in the fall once land-fast ice forms. The relationship between ringed seal density over the continental shelf in mid-September and concurrent bear density onshore suggests that the former hypothesis may be correct, while the relatively dramatic decline in polar bear density onshore in mid-October once land-fast ice forms supports the latter hypothesis. Thus, both ice conditions and ringed seal density may affect bear density on shore during the fall open-water period. If the extent of summer pack-ice continues to decline as predicted by many climate models (Zhang and Walsh 2006; Serreze et al. 2007; Stroeve et al. 2007), polar bears may be more likely to come ashore during this time to gain access to ringed seals over the continental shelf on recently frozen land-fast ice in the fall, rather than remain on the pack-ice where they may wait a longer period for ice to extend over the shelf.

Spatial patterns of polar bear density onshore appeared to be influenced by the presence or absence of subsistence-harvested bowhead whale carcasses. Polar bear density was over six times higher in areas where whale carcasses were available. However, this difference was largely driven by a major concentration of bears (69% of total bears onshore) at Barter Island (17.0 ± 6.0 polar bears/100 km). The two other native communities harvesting bowhead whales had much lower polar bear density (Barrow: 2.2 ± 1.8; Cross Island: 2.0 ± 1.8) despite both of these communities consistently harvesting higher numbers of bowhead whales (12.2 ± 4.9 and 4.2 ± 12 whales/year at Barrow and Cross Island, respectively) compared to the Kaktovik community on Barter Island (3.2 ± 0.4 whales/year; Suydam et al. 2000, 2001, 2002, 2003, 2004, 2005). Bowhead whales are typically harvested earlier on Barter and Cross Islands (mean date of harvests 7 and 8 September, respectively for 2000–2005) than at Barrow (mean date of harvest 7 October; Suydam et al. 2000, 2001, 2002, 2003, 2004, 2005) providing earlier foraging opportunities to land-based polar bears. However, the location of bears onshore coincides with areas where the distance to ice edge is shortest. The shorter distance to the pack ice edge and higher ringed seal density documented along the eastern edge of the study area where polar bear density was also highest is supported by other studies (Frost et al. 2004; Fischbach et al. 2007). Thus, bears at Barter Island not only avoid fasting by foraging on whale carcasses during the open-water period, they also maximize future hunting opportunities and earlier access to high densities of ringed seals once land-fast ice forms.

Overall, we did not detect an increasing trend in polar bear densities along the Beaufort Sea coast of Alaska during the six years of this study. Conversely, an increase in the proportion of female polar bears denning on land in the SBS (Amstrup 2000; Fischbach et al. 2007) and an apparent increase in the proportion of polar bears sighted on land compared to sea ice during the fall (Gleason et al. 2006) have been documented previously over a period of decades. Thus, either changes are occurring over longer time scales than we examined, or the trend has changed such that the density of polar bears on the coast is either undetectable or stable. Our study does, however, suggest that predicted reductions in the extent of summer sea ice (Hansen et al. 2005; Holland et al. 2006; Serreze et al. 2007), as well as potential for delayed formation of land-fast ice in the fall (Dumas et al. 2006) would likely result in an increase in the number of polar bears using land. Furthermore, in this study, bear density onshore declined only once the mean distance to ice concentrations ≥50% along the shore reached a distance of ≤100 km, suggesting the duration of time bears spend onshore could also increase. There was a strong relationship between annual variation in the number of bears onshore and the mean distance to pack ice edge during the fall open-water period. Duration of sea ice is predicted to decrease by 10 days by 2020 and 15–20 days by 2050 with additional thinning of land-fast ice (ACIA 2005; Dumas et al. 2006). In addition, a number of studies have suggested that recent changes will result in more bears coming ashore for longer periods (Derocher et al. 2004; Stirling and Parkinson 2006).

Factors attributed to within and among-year variation in polar bear density on land in this study were similar to patterns documented for polar bears on Wrangel Island, and along the Chukotka coast in Russia (Kochnev 2006). In these areas, the number of bears on land was correlated with the distance to ice edge and the availability of walrus (*Odobenus rosmarus*) carcasses during the open-water period. Polar bears in these areas congregate at walrus haulout sites where they feed on stampeded walrus during the ice-free period in the western Chukchi Sea. The opportunity for bears in the Chukchi Sea and SBS to feed during the fall open-water period differs from some Canadian populations, such as Western Hudson Bay, Davis Strait, and Baffin Bay which are entirely ice-free seasonally and resulting in polar bears primarily spending the open-water period fasting (Stirling et al. 1977; Derocher et al. 1993; Ferguson et al. 1997). Thus, the nutritional effects documented in polar bears in Western and Southern Hudson Bay (Stirling et al. 1999; Obbard et al. 2006) associated with a longer period of open-water may not occur in the Southern Beaufort and Chukchi populations provided that the nutritional value of bowhead whale and walrus carcasses meet the energetic demands required to offset reduced foraging opportunities on seals. This suggests that in the SBS recently documented declines in body condition of bears (Regehr et al. 2006) are the result of mechanisms other than increased land use.

Though subsistence-harvested bowhead whale carcasses may be a significant anthropogenic food source for polar bears, polar bear concentrations at carcasses have the potential to increase bear–human interactions and exposure to oil spills (Perham 2005; Miller et al. 2006). Food-habituation of bears has been attributed with increased bear mortality (Herrero 2002). However, the number of polar bears sighted during fall aerial surveys was not related to the number of bears reported as harvested for subsistence ($r = 0.36$, $n = 6$ years, $P = 0.48$) or due to defense of life in local communities (i.e., Barrow, Nuiqsuit, and Kaktovik) across years ($r = 0.22$, $n = 6$ years, $P = 0.68$). This result occurred despite polar bear density on the coast varying by a factor of two during the study which is believed to reflect local hunter values of conserving polar bears with a harvest based on need versus availability. However, fall polar bear subsistence harvests, in general, are relatively low on the North Slope and are not necessarily indicative of whether bears are learning to associate villages with food and thereby increasingly coming to villages throughout the year when natural sources of food may be scarce. Total polar bear subsistence harvests and defense of life killings for the Alaskan side of the SBS were stable throughout the course of this study, but had increased from earlier periods (USFWS 2007). Several management mechanisms exist to maintain stable levels of polar bear subsistence harvest despite potential increases in bear–human interactions, including an oil-field hazing program managed by the US Fish and Wildlife Service (Perham 2005), a co-management agreement between the Inuvialuit Game Council and the Alaskan North Slope Borough signed in 1988 which sets annual harvest quotas for the SBS (Brower et al. 2002), and polar bear patrol programs conducted by Natives in the villages of Barrow and Kaktovik.

Removal of whale carcasses to minimize bear–human interactions both in villages and in relative proximity to oil and gas fields is complicated by the potential to increase nutritional stress similar to that exhibited by bears in Western Hudson Bay. Currently, the majority of bears coming to shore appear to be utilizing whale carcasses. In the absence of whale carcasses, bears are likely to continue their pattern of coming ashore in the fall in order to remain close to the continental shelf where ringed seal density is concentrated (Harwood and Stirling 1992; Frost et al. 2004) and where landfast ice formation provides earlier access to ringed seal habitat. The nutritional implications of reductions in fall sea-ice extent may therefore also now be influenced by accessibility to and availability of bowhead whale carcasses. A recent study found that bowhead whales constituted 6–18% on average of winter diets of polar bears in the Southern Beaufort Sea (Bentzen et al. 2007). Other potentially negative aspects of increased land use by polar bears during the fall open-water period include extended open-water swimming (Monnett and Gleason 2006), increased intra-and interspecific interactions, potential increase in disease transmission, and increasing bear–human interactions. We recommend that these issues be further evaluated and monitored.

Acknowledgments Funding for aerial surveys in 2000–2002 was provided by British-Petroleum (BP) Exploration Alaska Environmental Studies Group, as part of mitigation for Northstar oil production facility, and by the U.S. Fish and Wildlife Service. Chuck Monnett of the U.S. Minerals Management Service generously provided ringed seal data collected during bowhead whale surveys. Craig Perham (USFWS), Rosa Meehan (USFWS), John Haddix (former USFWS), Verena Gill (USFWS), Jonathan Snyder (USFWS), Charlie Hamilton (USFWS), Bill Streever (BP), and staff of LGL Research Associates participated as observers in aerial surveys. Special thanks to Dave Weintraub and Ralph Aiken of Commander Northwest Limited for many hours of safe flying. Surveys were coordinated with the North Slope Borough, Alaska Eskimo Whale Commission, and representatives from the villages of Barrow, Nuiqsut, and Kaktovik.

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