USING DISCRETE CHOICE MODELING TO GENERATE RESOURCE SELECTION FUNCTIONS FOR FEMALE POLAR BEARS IN THE BEAUFORT SEA

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Abstract: Polar bears (*Ursus maritimus*) depend on ice-covered seas to satisfy life history requirements. Modern threats to polar bears include oil spills in the marine environment and changes in ice composition resulting from climate change. Managers need practical models that explain the distribution of bears in order to assess the impacts of these threats. We explored the use of discrete choice models to describe habitat selection by female polar bears in the Beaufort Sea. Using stepwise procedures we generated resource selection models of habitat use. Sea ice characteristics and ocean depths at known polar bear locations were compared to the same features at randomly selected locations. Models generated for each of four seasons confirmed complexities of habitat use by polar bears and their response to numerous factors. Bears preferred shallow water areas where different ice types intersected. Variation among seasons was reflected mainly in differential selection of total ice concentration, ice stages, floe sizes, and their interactions. Distance to the nearest ice interface was a significant term in models for three seasons. Water depth was selected as a significant term in all seasons, possibly reflecting higher productivity in shallow water areas. Preliminary tests indicate seasonal models can predict polar bear distribution based on prior sea ice data.

Key words: discrete choice models, habitat selection, polar bear, resource selection function, RSF, sea ice, *Ursus maritimus*.

Polar bears (*Ursus maritimus*) occur in most ice-covered seas throughout the Arctic basin (Lentfer 1982). Their range includes the Beaufort Sea of northern Alaska and the Chukchi and Bering Seas of western Alaska. Polar bears depend on the sea ice for all of their life history requirements, including access to prey (Stirling et al. 1993), and reproduction (Stirling and Andriashek 1992, Stirling et al. 1993, Amstrup and Gardner 1994). Seasonal variation in sea ice determines polar bear distribution and habitat use (Garner et al. 1990, Amstrup et al. 2000, Ferguson et al. 2000), hence, seasonal models are necessary to adequately explain resource selection by polar bears. The association with sea ice is so strong that the distribution of polar bear sub-populations may be determined by regional characteristics of the sea ice (Ferguson et al. 1998). The welfare of polar bears is an international and local concern (Lentfer 1974, Nageak et al. 1991). Addressing this concern will necessitate a greater understanding of polar bear habitat use in order to prevent or mitigate negative consequences from environmental perturbations.

Sea ice is composed of a complex array of ever changing structure and composition (MANICE 1994). The seasonal action of currents, winds and temperatures produce a range of ice compositions from rafts of new ice only several centimeters thick to pressure ridges of first year and old ice that rise several meters above and below the sea surface. Pack ice leads form and close and floes of various sizes are created. Some ice survives the summer's melt to become thick and stable multiyear ice. In arctic seas, biological productivity is likely driven by relative proximity of the continental shelf, ice edge habitat, and waters fed by near shore polynyas (Stirling 1997). Ultimately, however, prey and predator populations are driven by the nature of the sea ice (Stirling et al. 1977, Mauritzen et al. 2003). Changes in population status and distribution of polar bears may be used to determine variation and productivity in the sea ice environment (Stirling and Derocher 1993, Stirling 1997).

Understanding the relationship between polar bears and sea ice is useful from a management perspective. Future industrial development along the northern Alaska coast is expected to extend further into polar bear habitat and will increase the potential for anthropogenic disturbances (Amstrup et al. 1986). Off-shore petroleum exploration and development, and ocean-going vessels, can alter sea-ice habitat and thus polar bear distribution (Amstrup et al. 1986, Stirling 1990). Petroleum spills can be directly fatal to polar bears or result in long-term negative health effects (Øritsland et al. 1981, St. Aubin 1990). Spilled oil will most likely accumulate in habitats frequented by seals and polar bears (Neff 1990). Evidence suggests that arctic climate patterns are changing (Vinnikov et al. 1999, Morison et al. 2000, Parkinson 2000, Drobot and Maslanik 2002). Slight increases in average temperatures may cause dramatic changes in the sea ice on which polar bears depend on. Long-term absence of sea

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ice will negatively impact polar bear populations (Stirling et al. 1999) and one effect may include local extinction within the southern periphery of their range (Stirling and Derocher 1993, Stirling et al. 1999).

We have a sound understanding of the population status and distribution of polar bears in the Beaufort Sea (Amstrup et al. 2000, Amstrup et al. 2001a, Amstrup et al. 2001b). Other agencies have developed protocols for accurate mapping of sea ice through compiling various remotely sensed and *in situ* data sources (MANICE 1994, Partington et al. 1999). Considerable gains have been made in understanding polar bear and sea ice relationships in other regions of the Arctic (Ferguson et al. 2000, Mauritzen et al. 2001, 2003) but not, however, in the Beaufort Sea. In particular, the coarse resolution of previous studies has been inadequate to explain the fine-scale aspects of sea ice habitat use (Arthur et al. 1996, Mauritzen et al. 2003). A need exists for practical models of polar bear/sea ice relationships that managers may use to assess the impacts of anthropogenic and natural changes in the Arctic. The ability to predict the response of polar bears to a changing Arctic and to reduce the potential negative effects of human-caused perturbations will increase with a better understanding of polar bear sea ice requirements.

In this study we used discrete choice models to quantify patterns of sea ice habitat use by polar bears in the Beaufort Sea. We tested the performance of our models against an independent set of real polar bear location data. The practical application of this knowledge will allow managers to predict occurrence of polar bears and create flexible management plans prior to initiation of proposed human activities.

METHODS

Our study area was the extent of the National Ice Center's (NIC, Washington, D.C.) chart of the Beaufort Sea (Fig. 1). This area includes 607,000 km^2 of seasonal and permanent ice covered waters that occur between 122 - 155° west longitude, and north of the mainland coast of Alaska and Canada to 76° north latitude. The region is typified by continuous sea ice coverage between November and May and approximately 50% ice coverage during the period of minimum ice extent in September. Ice movement is influenced by seasonal fluxes and a clockwise gyre that is centered in the Beaufort Sea (Gloersen et al. 1992).

Ice Data

We used ice charts created by the NIC and charts from the Canadian Ice Service (CIS, Environment Canada, Ottawa, Ontario). NIC and CIS produce detailed charts of sea ice conditions from a diverse source of remotely sensed data. NIC uses National Oceanic and Atmospheric Administration (NOAA) passive microwave Special Sensor Microwave Imager (SSM/I; 25 km resolution), Advanced High Resolution Radiometer (AVHRR; 1 km resolution), RADARSAT-1 synthetic aperture radar imagery (SAR; 100 – 200 m resolution), and Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS; 550 m resolution). CIS also uses AVHRR and RADARSAT, plus NOAA Geostationary Operational Environmental Satellite images (GOES; 4 – 6 km resolution), and ERS (European Space Agency) satellite data. NIC and CIS charts are geographic information system (GIS) ARC/INFO (ver. 8.0; ESRI, Redlands, CA) polygon coverages. Both NIC and CIS charts were projected as polar projections with the central meridian at 180º and the latitude of true scale at 60°. For the Beaufort Sea, NIC charts are created on average every 5.8 days (SD = 3.3, n = 265) and CIS charts every 11.1 days (SD = 8.3, n = 136). Each habitat polygon in an NIC chart represents the aerial extent (partial concentration) and stage (the thickness, or age) for the three thickest stages of ice (Table 1). Likewise, CIS charts delineate habitat polygons of the partial concentration and form (average floe size) of ice. We binned similar ice stages and similar ice forms to simplify models (Table 1). We converted NIC categorical values of partial concentration into continuous variables by simply defining concentrations as the midpoint of the concentration range defining the NIC category. Converting categorical variables into continuous variables can introduce bias into model parameter estimates. This generally is not a problem, however, when the original values are continuous in nature, and have been binned into categories after data collection (binned by NIC and CIS). We defined total concentration as the sum of partial concentrations within the respective region. Distance to the nearest polygon edge of NIC charts (ice interface) was also calculated. This category "ice interface" denotes the change of one NIC ice polygon to another adjacent ice polygon and is not

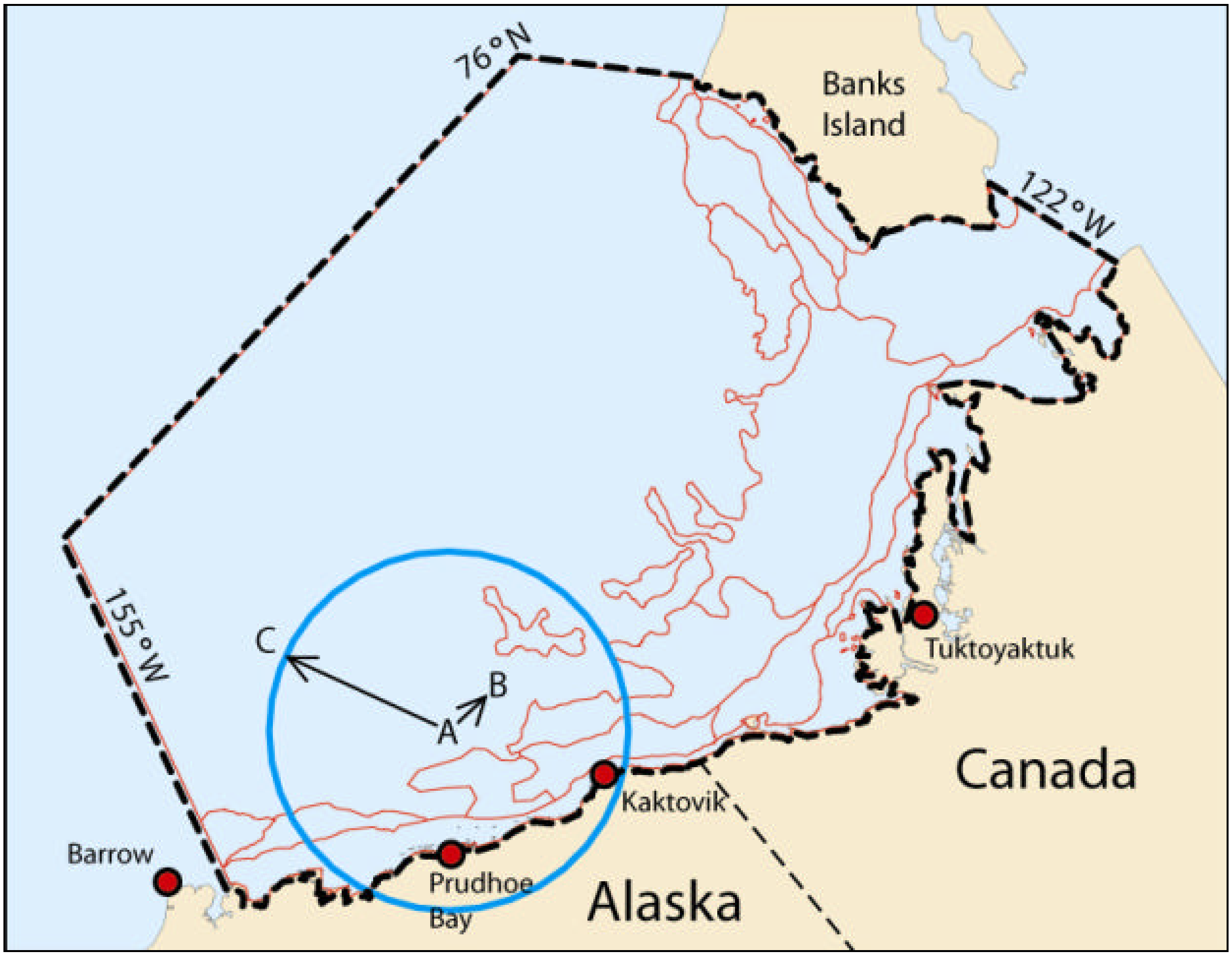

Figure 1. Extent of the National Ice Center ice chart of the Beaufort Sea region for modeling polar bear habitat use, and determination of habitat available to polar bears, 1997 – 2001. The distance from **A** (9 February 2000) to **B** (16 February 2000) represents the actual distance traveled by a bear (~ 50 km in this example). The distance from **A** to **C** (~195 km), is the distance a bear could be expected to travel given the month and the duration in time between **A** and **B**. The circle encloses the area (minus land) expected to be available to the polar bear in this example.

to be confused with "ice edge," where ice edge denotes the transition from ice to relatively open water (Ferguson et al. 2000, Mauritzen et al. 2003). Because of the many different combinations of ice polygons that would produce an ice interface, we did not attempt to categorize ice interface types.

NIC does not routinely provide ice form (the average diameter of ice floes) as an attribute in ice charts. Because ice form is an important variable in describing sea ice use by polar bears (Ferguson et al., 2000), we extracted these data from CIS ice charts (MANICE, 1994). In CIS charts, ice form is routinely provided in as many as three partial forms, each with its respective partial concentration. Because of the temporal differences between NIC and CIS charts, we used CIS charts solely as a source for ice form data, and we re-calculated the extent of CIS partial ice forms as a proportion of NIC total ice concentration.

Both NIC and CIS data offer several advantages in modeling polar bear sea ice relationships. They provide a far higher resolution ice picture than previously available over large areas (Arthur et al. 1996, Mauritzen et al. 2003). Maps are generated from diverse remotely sensed data that are interpreted to provide information on total ice concentration, as well as partial ice stages and forms. NIC and CIS charts are almost real time data. The extent of both NIC and CIS data includes the entire distribution of polar bears in the world. Thus, near real time analysis of expected polar bear distribution anyplace in the polar basin may be possible by modeling NIC and CIS data. Lastly, these data are interpreted and readily available to researchers and resource managers.

Table 1. Descriptions and codes for ice stage and form, and the number of used and random locations with that data for generating polar bear resource selection functions in the Beaufort Sea, 1997 – 2001.

National Ice Center

Ice stage	Thickness (cm)	NIC code	Our code for stage	Used records	Random records
Ice free		00	Ice free	270	23510
No stage		80	Ice free		
New		81	Ice free		
Nilas, rind	< 10	82	Ice free		
Young	10 – 30	83	Young	625	62902
Grey	10 – 15	84	Young		
Grey – white	10 – 30	85	Young		
1st year	30 – 200	86	First year	1826	170002
Thin 1st year	30 – 70	87	First year		
Thin 1st year stage 1	30 – 50	88	First year		
Thin 1st year stage 2	50 – 70	89	First year		
Medium 1st year	70 – 120	91	First year		
Thick 1st year ice	> 120	93	First year		
Old ice		95	Old	818	83056
2nd year		96	Old		
Multi-year		97	Old		

Canada Ice Service

Form description	Width (m)	CIS code	Our code for form	Used records	Random records
Pancake	< 2	0	Cake	0	0
Small cake ice	< 2	1	Cake	0	0
Ice cake	2 – 20	2	Cake	0	0
Small floe	20 – 100	3	Small floe	206	16341
Medium floe	100 – 500	4	Small floe		
Big floe	500 – 2000	5	Big floe	445	43053
Vast floe	2000 – 10,000	6	Vast floe	925	92786
Giant floe	> 10,000	7	Vast floe		
Fast ice		8	Fast ice	191	16637

Ocean Depth

We used data provided by the International Bathymetric Chart of the Arctic Ocean (IBCAO; http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html) to obtain data of ocean depth (*depth*). These data are provided as a polarstereographic projection grid with 2500 m resolution. We converted the grid into an ARC/INFO polygon coverage with the same projection as ice charts.

Creating Discrete Choice Habitats

Data derived from both the NIC and CIS charts, and the bathymetry chart, were combined to produce units of discrete habitats. We define a discrete habitat as a point on a map which is composed of several layers of habitat information including partial concentrations of up to three different stages and forms of sea ice, total ice concentration, distance to the nearest ice interface, and ocean depth.

Polar Bear Locations

We captured adult female polar bears in the Beaufort Sea and equipped many of them with satellite radio collars, or Platform Transmitter Terminals (PTTs; Telonics, Mesa, AZ, USA). Polar bears were captured by injection of zolazepam HCl and tiletamine HCl (Telazol®, Warner-Lambert Co.) through projectile darts fired from a Bell 206 helicopter (Stirling et al. 1989). Data transmitted by PTTs were received by polar orbiting NOAA satellites, which then were processed by the ARGOS Data Collection and Location System (Fancy et al. 1988).

PTTs transmitted data hourly up to six hours per day and every 1 – 7 days. Because this could generate a large amount of data we restricted our analysis to the best position per day and only when that position was estimated to have a > 68% chance of being within 1.2 km of its true location, or an area of 4.5 km^2 (ARGOS quality locations 1, 2, and 3; Fancy et al. 1988, Keating et al. 1991). This potential error is much lower than the average size of ice polygons ($\bar{x}$ = 18,964 ± 51,821 km^2 SD, n = 8417). Only 1 % of ice polygons had areas = 72 km^2. We retained all observations of bears that were not associated with maternal denning and were not located on land. We also used only those locations that were separated from the prior location by 2 – 7 days (44 – 172 hours) and fell within the temporal and spatial extent of NIC charts for the Beaufort Sea (Fig. 1). Location data were stored as an ARC/INFO point coverage.

Defining Habitat Available to Polar Bears

Habitat data (NIC, CIS and *depth*) encompassed a large region, the area of which would not be entirely available to a polar bear during any particular period of time. We modified the method of Arthur et al. (1996), who defined the habitat available to a bear at a particular location and time as the area within a circle whose center was the location of the prior observation (Fig. 1). The radius of that circle was determine by the duration of time between the prior observation and the subsequent observation and by a set distance that a bear was expected to travel during that time. Because movement rates of female polar bears in the southern Beaufort Sea varies by month (Amstrup et al. 2000), we calculated radii for each unique bear/date observation by the following equation:

radii of available habitat = $\{a + (b ? 2)\} ? c$;

where a equals the mean hourly movement rate for all bears within each month; b is the standard deviation of the movement rate; and c equals the number of hours between locations (Fig. 1). Sometimes, however, the actual straight-line distance traveled by a bear between observations exceeded the expected distance. In these cases the radius of available habitat was defined as the straight-line distance actually traveled plus 1 meter.

Generating Random Locations and Attaching Habitat Variables

We compared habitat characteristics of each bear location to a set of up to 100 random points generated with ARC/INFO tools. These had a minimum spacing of 200 m and were generated in the portion of the availability circle that fell within the NIC chart. Both bear and random locations were merged with NIC and CIS charts, and the ocean depth coverage in order to attach habitat variables. Distance between locations and the nearest NIC polygon edge (ice interface) were calculated.

Generating a Resource Selection Function

Estimation of a resource selection function (RSF) followed the methods of McCracken et al. (1998), Arthur et al. (1996) and Cooper and Millspaugh (1999). These methods fit discrete choice models for polar bear site selection and keep the availability of landscape characteristics unique to each polar bear location/date-time combination. That is, points in one polar bear's circle of available points on a particular day were not available for selection by another polar bear, unless the two circles overlapped. The discrete choice model is estimated by maximizing the multinomial logit likelihood (Manly et al. 2002). This was accomplished using the stratified Cox proportional hazards likelihood maximization routine available in the SAS procedure PROC PHREG (SAS Institute 2000). Although PROC PHREG was not designed to fit discrete choice habitat selection functions, Kuhfeld (2000) describes a method by which PROC PHREG can be "tricked" into fitting the appropriate discrete choice likelihood function.

Prior to model building, Pearson's Correlation Coefficients (r; Conover 1980) were calculated for all main effects for each season. Main effects (Table 1) were excluded from the analysis if $r = |0.6|$. Separate models were developed that included one or the other correlated main effect. That is, each member of a pair of correlated main effects was not allowed to enter the same model building procedure. From these, we selected the best model based on how well models appeared to predict the RSF of an independent sample of polar bears locations.

Stepwise model building began with developing a single-term model for each main effect. We set the critical level of covariate entry as a = 0.1 for the adjusted score $?^2$ (Klein and Moeschberger 1997). The single-term model with the largest significant score $?^2$ was selected as the start of a forward selection process for model building. We allowed each step of the forward-selection process to add one other term only when the adjusted score $?^2$ value for that term was a = 0.1. Each forward selection step was preceded by a backward removal step, where the variable with the smallest Wald $?^2$ value was dropped from the model, provided that a > 0.1. An interaction or quadratic term was not allowed in the model if the main effect involved was not already in the model. If a backward selection step identified a main effect for exclusion, and that main effect was also present in the model in an interaction with another main effect, the main effect was not dropped from the RSF model. The RSF model was considered complete when no other terms could be entered or removed under the constraint of a = 0.1.

As an evaluation of our model building procedure, we compared each model to two other commonly used methods of RSF model building. First, we compared each step in our procedure to the change in the likelihood ratio ?^{2} each time a covariate was added (Manly et al. 2002). Each coefficient in the final model was also tested to see if it was significantly different from zero. This was done by dividing the coefficient by its standard error, and then comparing the absolute value of this number (z) to a normal distribution. This is the classic Wald *t*-test, where a value of $z > 1.64$ indicates a significant difference from zero at a = 0.1 (Manly et al., 2002).

A primary focus of this work was to develop tools that would predict where polar bears may occur. Hence, we were interested in how our seasonal models would perform with real data. To do this we first created a RSF map from the average multi-year habitat values for each season. We then overlaid an independent data set of bear locations on the RSF maps and attached to each bear location its respective RSF value from the seasonal map. The distribution of RSF values assigned to bear locations was then graphically compared to the distribution of RSF values of the map in order to provide an index of the predictive abilities of our models.

RESULTS

Between 1 September 1997 and 31 December 2001, 88 PTTs were deployed on 80 polar bears in the Beaufort Sea. A total of 32,105 satellite observations from 77 bears were available for analysis. Following the imposition of temporal and spatial filters, 1780 observations from 53 bears remained for analysis. The time between bear observations ranged between 44 – 171 hours ($\bar{x}$ = 94.4 ± 45.7 SD). We subdivided data into four seasons, which were defined by major seasonal changes in ice concentration near the southern Beaufort Sea coast. Seasons included spring: 30 May – 23 July; summer: 24 July – 6 October; fall: 7 October – 15 November; and winter: 16 November – 29 May.

Seasonal models were unique in their combination of terms (Table 2). *Depth* appeared in four models and ice interface (*edge*) appeared in three models. Small changes in *depth*, and *edge* resulted in large changes in the relative probability of use (Fig. 2 – 5).

Spring

Locations of 36 polar bears entered spring model building. There were a total of 234 actual bear observations and 22,531 random observations ($\bar{x}$ = 96.3 ± 5.3 SD random observations per bear observation). High correlations were found between young ice (*youngice*) and first year ice (*firstyr*) (r = -0.74, P < 0.0001); old ice (*oldice*) and *youngice* (r = 0.74, P < 0.0001); *oldice* and *firstyr* (r = -0.92, P < 0.0001); vast floe (*vastfloe*) and fast ice (*fastice*) (r = -0.65, P < 0.0001); and *vastfloe* and big floe (*bigfloe*) (r = -0.62, P < 0.0001). Four permutations of model building resulted in two spring models. Based on the distribution of an independent sample of polar bear locations, our best spring model started with *depth* (score ?^{2} = 5.0378, P = 0.0248). The sequence for covariate entry was *vastfloe* (score ?^{2} = 5.9091, P = 0.0151) and then *totcon* (score ?^{2} = 3.4177, P = 0.0645). An additional forward step did not identify any other variable that met the a = 0.1 criteria for model entry. The final spring model included a negative coefficient for *depth*, and positive coefficients for *vastfloe* and *totcon* (Table 2). During spring, polar bears used habitats over water depths between 5 – 3659 m deep, however 50 % of all bear observations occurred in waters = 400 m deep. According to the spring model, polar bears in the Beaufort Sea select habitat in relatively shallow waters (Fig. 2a) with a high proportion of *vastfloe* (Fig. 2b), and high *totcon* (Fig. 2c).

Our stepwise approach to building a spring model by using the score ?^{2} was perfectly concordant with the change in likelihood ?^{2} (Manly et al., 2002). Also, all three coefficients in the final model were significantly different from zero (Manly et al., 2002). These results boosted our confidence in our choice of model building procedures.

Summer

Locations of 36 polar bears entered summer model building. There were a total of 256 actual bear observations and 24,531 random observations ($\bar{x}$ = 95.8 ± 6.2 SD random observations per bear observation). During summer, there was a significant correlation between *oldice* and *totcon* (r = 0.68, P < 0.0001). Model building began with *edge* (score ?^{2} = 20.4780, P < 0.0001). The sequence of covariate entry was *oldice* (score ?^{2} = 21.557, P < 0.0001), the quadratic for *oldice* (*old^2*) (score ?^{2} = 15.0429, P = 0.0001), *depth* (score ?^{2} = 11.9040, P = 0.0006), *firstyr* (score ?^{2} = 4.7995, P = 0.0285), *youngice* (score ?^{2} = 5.8774, P = 0.0153) and the interaction between *edge* and *youngice* (*edge*youngice*) (score ?^{2} = 7.1407, *P* = 0.0075). No additional covariates met our criteria for model entry.

The summer model included positive coefficients for *oldice*, *firstyr*, and *youngice* (Table 2). Negative coefficients resulted from *edge*, *old*^{2}, *depth*, and *edge*youngice*. While our summer model suggests that polar bears select habitat in shallow waters (Fig. 3a), this is relative, however, because 75 % of polar bear locations occurred in habitats where ocean depth was = 355 m. Polar bears also select habitats with a high proportion of old ice (Fig. 3b) or first year ice (Fig. 3c), or a high proportion of young ice close to an ice interface (Fig. 3d).

Table 2. Seasonal discrete choice models predicting relative probability, w(x), of an adult female polar bear selecting a point in the landscape characterized by x, in the Beaufort Sea, 1997 – 2001.

Season	Model (standard errors are in parentheses below coefficients)
Spring	**w(x) = exp{-0.0002402(*depth*) + 0.52481(*vastfloe*) + 3.99265(*totcon*)}** (0.0000826) (0.27476) (0.92598)
Summer	**w(x) = exp{-0.01085(*edge*) + 6.58263(*oldice*) - 4.93599(*oldice*^{2}) - 0.0003382(*depth*)** (0.00440) (1.29720) (1.40941) (0.0000924) **+ 1.21442(*firstyr*) + 4.52479(*youngice*) - 0.29138(*edge*youngice*)}** (0.45996) (1.35200) (0.011078)
Autumn	**w(x) = exp{-0.00152(*depth*) – 0.02968(*edge*) + 3.99265(*totcon*) + 0.000000231511(*depth*^{2})** (0.0003056) (0.00521) (1.3244) (0.000000094957) **– 2.70505(*totcon*^{2})}** (1.11305)
Winter	**w(x) = exp{-0.00170(*depth*) + 0.000000349299(*depth*^{2}) + 0.44398(*vastfloe*)** (0.0002075) (0.0000000661291) (0.11599) **+ 1.94584(*youngice*) – 0.00524(*edge*) + 0.47312(*firstyr*)}** (0.73993) (0.00244) (0.25120)

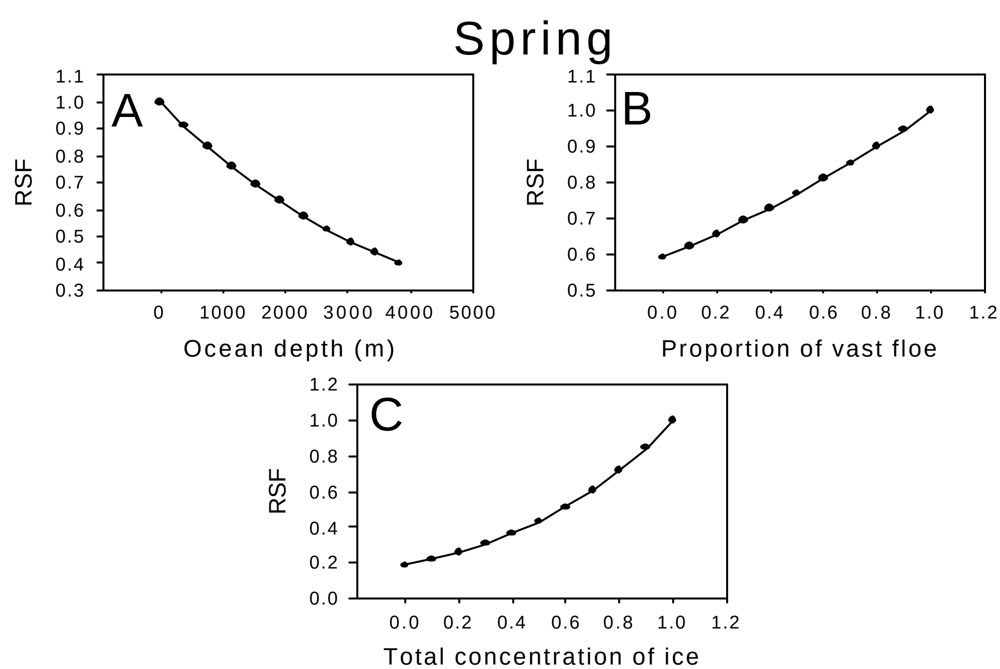

Figure 2. Relative probability of selection as a function of variables in the final polar bear sea ice RSF model for spring in the Beaufort Sea, 1999 - 2001. Variables in the final model not in a plot were held at their median values.

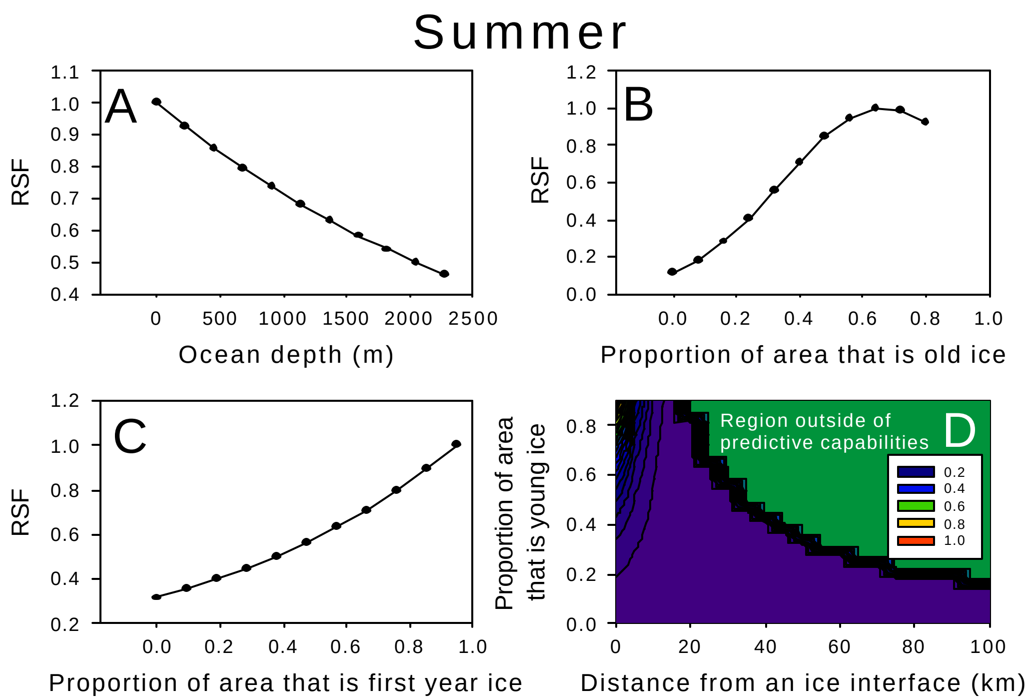

Figure 3. Relative probability of selection as a function of variables in the final polar bear sea ice RSF model for summer in the Beaufort Sea, 1999 - 2001. Variables in the final model not in a plot were held at their median values.

Autumn

Thirty-nine individual bears entered autumn model building. There were a total of 311 actual bear observations and 29,805 random observations ($\bar{x}$ = 95.8 ± 5.4 SD random observations per bear observation). During autumn, there was a significant correlation of *oldice* with *youngice* (r = -0.70, P < 0.0001). The highest score $?^2$ in a single term model resulted with *depth* (score $?^2$ = 108.8619, P < 0.0001). The sequence of covariate entry was *edge* (score $?^2$ = 41.2362, P < 0.0001), *totcon* (score $?^2$ = 7.9508, P = 0.0048), the quadratic for *depth* (*depth*^{2}) (score $?^2$ = 6.3139, P = 0.0120), and the quadratic for *totcon* (*totcon*^{2}) (score $?^2$ = 5.9884, P = 0.0144).

The autumn model (Table 2) had a positive coefficient for *totcon* and *depth*^{2},and negative coefficients for *depth*, *edge*, and *totcon*^{2}. The quadratic term for *depth* results in a curvilinear form of the RSF with increasing *depth* (Fig. 4a). This initially causes a decrease in the RSF with increasing *depth*. The RSF function, however, approaches an asymptotic pattern when *depth* was > 1000 m. During autumn, polar bear locations occurred over waters as deep as 3729 m. Of those, 75 % occurred in waters = 189 m deep and 50 % occurred in waters = 30.5 m deep. Our autumn model indicates that polar bears use habitat in relatively shallow water (Fig. 4a) close to an ice interface (Fig. 4b), and with high total ice coverage (Fig. 4c).

Winter

Locations of 47 polar bears entered winter model building. There were a total of 864 actual bear observations and 82,094 random observations included in the analysis ($\bar{x}$ = 95.0 ± 5.7 SD random observations per bear observation). Significantly large correlations were found between *firstyr* and *oldice* (r = -0.83, P < 0.0001),

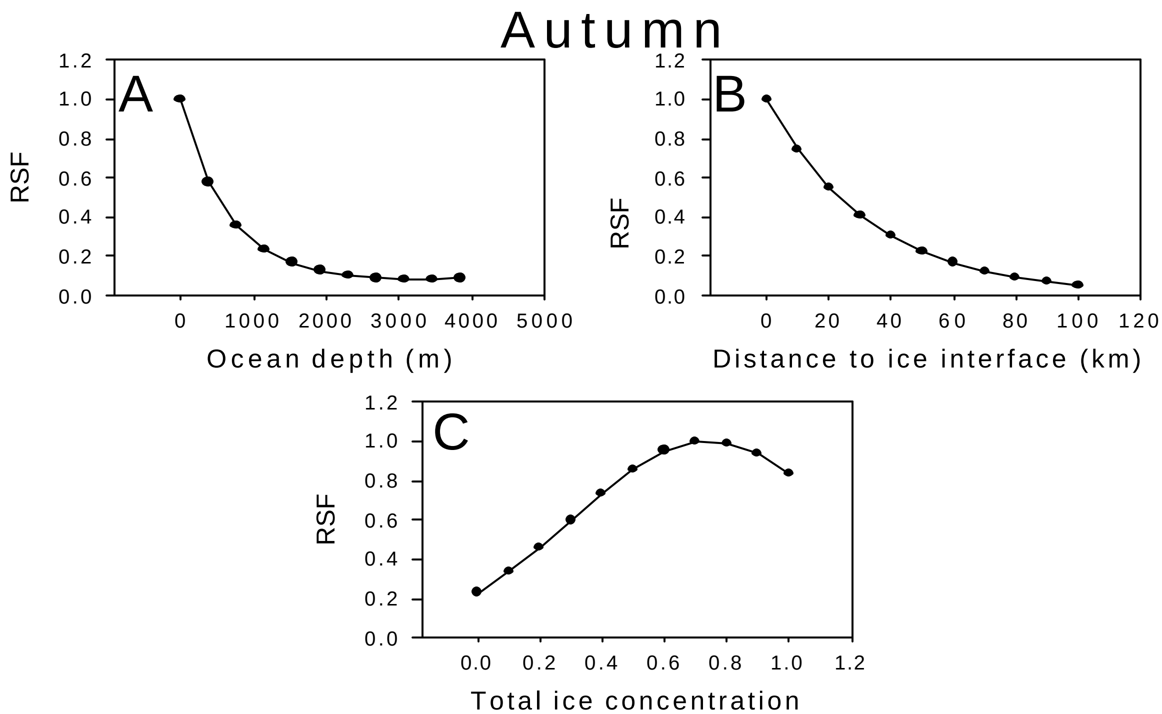

Figure 4. Relative probability of selection as a function of variables in the final polar bear sea ice RSF model for autumn in the Beaufort Sea, 1999 - 2001. Variables in the final model not in a plot were held at their median values.

and between *vastfloe* and *bigfloe* (r = -0.65, $P < 0.0001$). Our winter model began with *depth* (score ?^{2} = 179.6092, $P < 0.0001$). The sequence of covariate entry into the model was the quadratic of *depth* (*depth*^{2}) (score ?^{2} = 30.5267, $P < 0.0001$), *vastfloe* (score ?^{2} = 9.6772, $P = 0.0019$), *youngice* (score ?^{2} = 5.1145, $P = 0.0237$), *edge* (score ?^{2} = 4.4296, $P = 0.353$), and *firstyr* (score ?^{2} = 3.5582, $P = 0.0593$). Positive coefficients included the quadratic for *depth*, *vastfloe*, *youngice*, and *firstyr*. Negative coefficients were *depth*, and *edge*.

During winter polar bears select habitat over shallow water (Fig. 5a) and close to an ice edge (Fig. 5b). Polar bears also select vast floe ice (Fig. 5c) that is composed of a high proportion of first year ice (Fig. 5d) or young ice (Fig. 5e). The quadratic term for *depth* results in a curvilinear form of the RSF with increasing *depth* (Fig. 5a). This initially causes a decrease in the RSF with increasing *depth*. The RSF function, however, approaches an asymptotic pattern when *depth* was > 1000 m. During winter, polar bear locations occurred over waters as deep as 3640 m. However, 75 % of observations occurred in waters = 107 m deep and 50 % occurred in waters = 38 m deep.

Evaluation of Models

During spring, 81 % of bear locations from 2002 occurred on the highest 30 % of mapped RSF values in the study area (Fig. 6a). During summer (Fig. 6b), the predictive abilities of our model was evident, however, much less than the spring model. Fifty-eight percent of bear locations during summer 2002 occurred within 30 % of the highest mapped RSF values in the study area. Autumn showed an improvement of prediction, where 74 % of bear locations fell within the highest 30 % of mapped RSF values (Fig. 6c). Finally, winter showed the best predictive results, with 85 % of polar bear locations occurring in the highest 30 % of mapped RSF values (Fig. 6d). Mapped

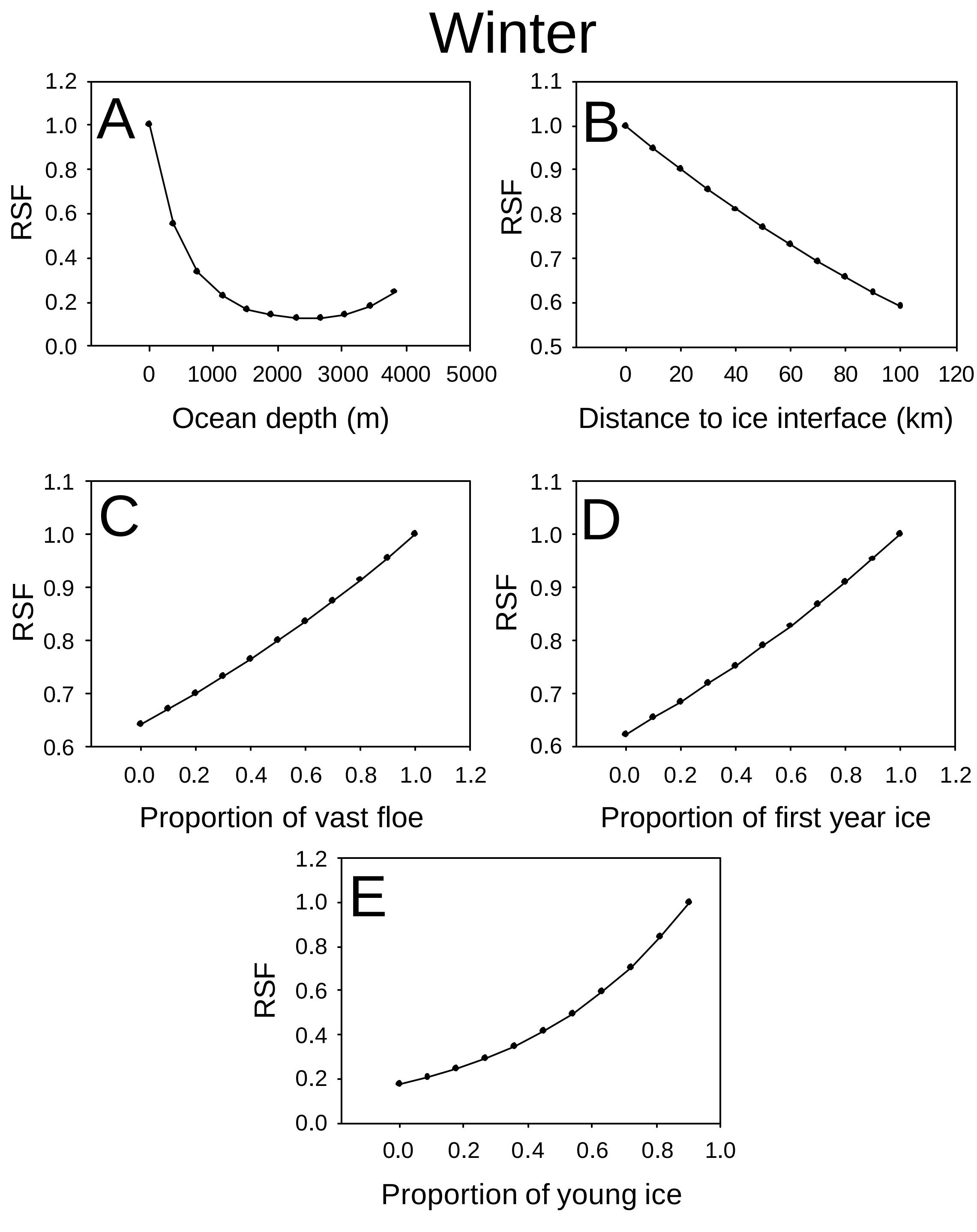

Figure 5. Relative probability of selection as a function of variables in the final polar bear sea ice RSF model for winter in the Beaufort Sea, 1999 - 2001. Variables in the final model not in a plot were held at their median values.

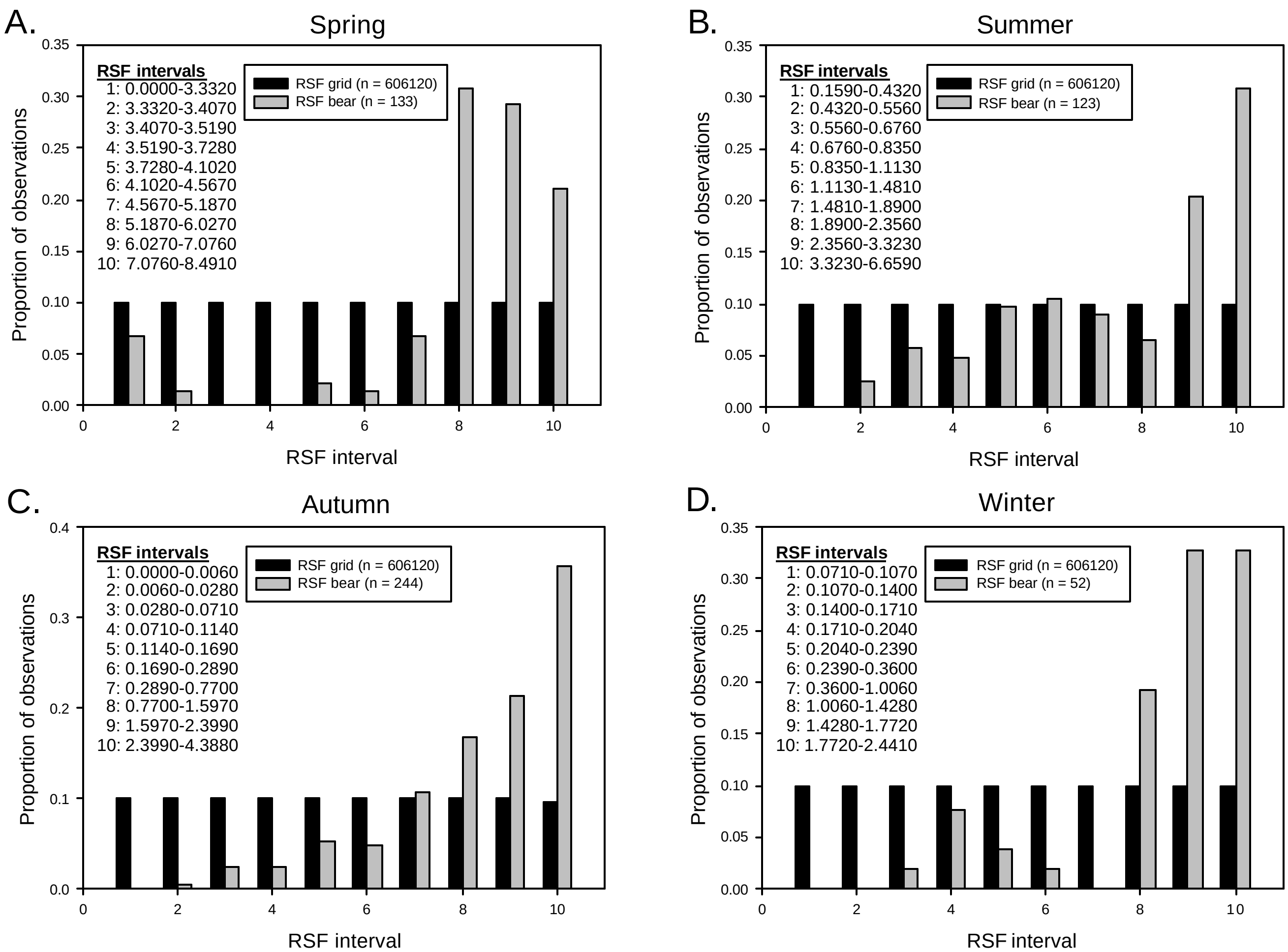

Figure 6. Comparing the seasonal distribution of RSF values in the Beaufort Sea to known polar bear locations during 2002. Grid RSF values were calculated from averaged ice data derived from NIC and CIS charts between 1997-2001.

RSF values and polar bear locations clearly demonstrate a tendency for polar bear locations to fall within areas of greatest RSF values for both spring (Fig. 7) and winter (Fig. 8).

DISCUSSION

The presence of *depth* and *edge* in most models indicates the importance of these variables to polar bears throughout the year. The extent of ice cover and the characteristics of form and stage of sea ice also were important in habitat selection by polar bears. Selection of different habitats is likely driven by the abundance and accessibility of prey and the availability of safe resting and refuge habitat. The use of floes > 2 km in spring is similar to that observed in the Canadian high Arctic (Ferguson et al. 2000) but differs from the use of open ice in the Chukchi Sea (Arthur et al. 1996). The pattern we observed may reflect adjustment in hunting strategies and an attempt to remain on stable ice during the melt season (Ferguson et al. 2000, Mauritzen et al. 2003). The melt in late spring likely resulted in many bears using habitats in waters > 400 m deep.

During summer, selection of habitats with high ice concentrations places most polar bears far from the coast. Hence 75 % of bear locations occurred in waters = 355 m deep and outside of areas of greatest prey abundance (Stirling et al. 1977, Stirling et al. 1982, Harwood and Stirling 1992, Gjertz et al. 2000). Three different ice types are used by polar bears for different reasons. The use of old ice is similar to that observed in Canada (Ferguson et al. 2000) and may reflect refuge selection (Mauritzen et al. 2003) because seals seldom use old (multi-

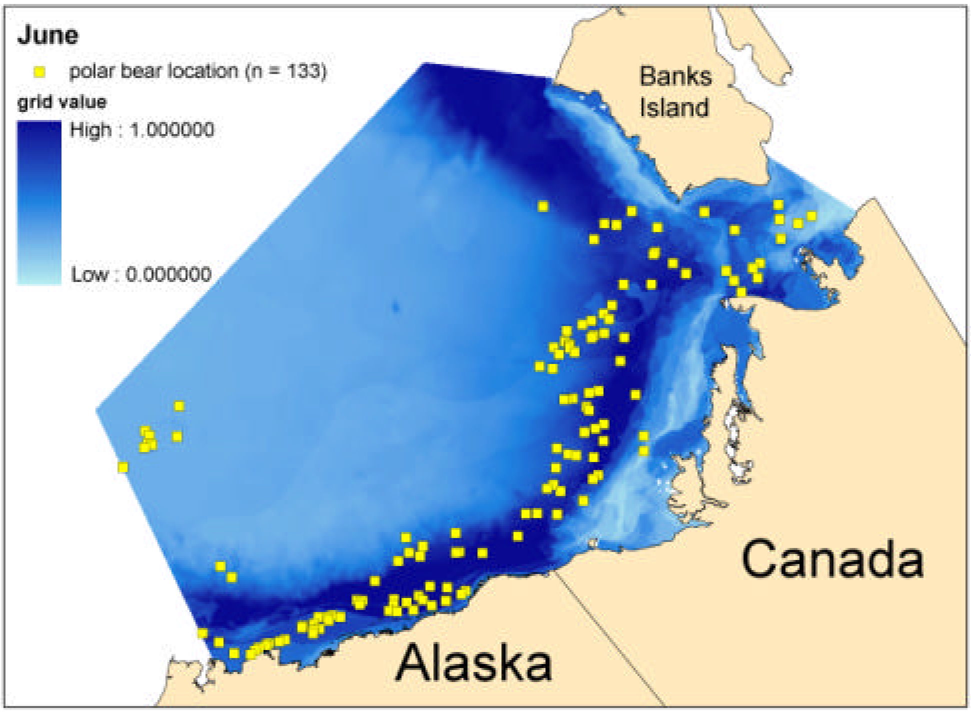

Figure 7. Distribution of the spring RSF in the Beaufort Sea, derived from average ice characteristics during June, 1999 – 2001, to the RSF distribution at known polar bear locations during June 2003 (n = 133).

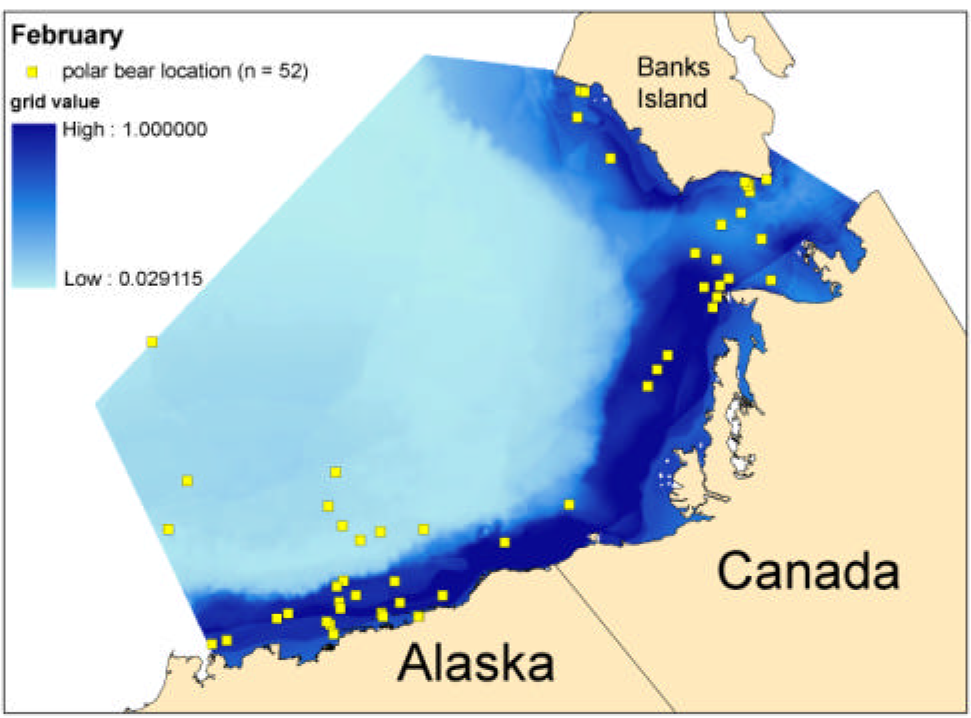

Figure 8. Distribution of the winter RSF in the Beaufort Sea, derived from average ice characteristics during February, 1999 – 2001, to the RSF distribution at known polar bear locations during February 2003 (n = 52).

year) ice (Kingsley et al. 1985). Selection of first year ice, and young ice near an ice interface, may be evidence of bears attempting to track the distribution of the few seals that may be available.

During autumn, polar bears return to areas of water depths = 189 m, with a high total concentration of ice and close to an ice interface. Selection for high ice cover was observed in two regions in Canada (Ferguson et al. 2000). Selection of habitat near an ice interface may be a response by polar bears to anticipate changes in ice conditions (Ferguson et al. 2000) in their push to get to productive near shore waters where prey abundance is greatest. During winter, formation of fast ice and consolidation of off shore ice resulted in the majority of active ice and leads at shear zones close to and parallel to coastlines (Smith and Rigby 1981). The accessibility of prey is highest there and polar bears respond by selecting active ice edges (Ferguson et al. 2001) in waters < 107 m deep. That bears focus on a relatively small area of optimal hunting habitat is consistent with a pattern of small home range size observed for polar bears during winter in the Beaufort Sea (Amstrup et al. 2000).

Our models demonstrate the utility of discrete choice models for predicting the seasonal distribution of polar bears in the Beaufort Sea. Both industrial expansion and climate change may impact the sea ice environment that polar bears depend on. Short-term forecasting of polar bear sea ice habitat may allow managers to predict effects of industry and oil spills on polar bears and take appropriate remediation. By knowing what ice conditions to expect at a proposed development site we may extrapolate how many polar bears might be affected. Long-term forecasting will allow prediction of sea ice characteristics resulting from climate change. If change can be predicted in total ice concentration, stage and form of ice, and the duration of the ice-free season then we can also predict the resulting distribution of polar bears. The methods and models that we present here are a promising tool that will allow researchers and resource managers to understand the use of sea ice by polar bears in order to make sound management decisions.

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