Aerial Surveys for Bowhead Whales in the Alaskan Beaufort Sea: BWASP Update 2000-2009 with Comparisons to Historical Data

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ABSTRACT

Broad-scale aerial surveys of the Alaskan Beaufort Sea (140°-157°W) in autumn commenced in 1979, and have continued uninterrupted to the present. These surveys are now known as the Bowhead Whale Aerial Survey Project (BWASP). BWASP represents a multi-decadal time-series of data on distribution, abundance, and habitat preferences of Arctic marine mammals, including the Bering-Chukchi-Beaufort Sea stock of bowhead whales. Here, we present an update of this aerial survey effort, summarize data for the last 10 years (2000-2009), and draw comparisons with results from historical analyses. Nearly 190,000 total km were flown in September and October, with over 93,000 km on transect. A total of 1,429 bowhead whales were seen, distributed across the study area on the inner shelf. Habitat preference between 140° and 154°W longitude was for 20-50m depths, but overwhelmingly shallower (<20m) in the westernmost part of the study area (154°-157°W longitude). Distribution was similar in 2000-2009 compared with the observed distribution from earlier years with light ice cover. Most bowheads were recorded as "swimming," heading west or northwest. Feeding and milling bowhead whales were recorded across the study area, but with highest frequency in the westernmost region (154°-157°W longitude).

KEYWORDS: ARCTIC; BOWHEAD WHALE; HABITAT; SURVEY-AERIAL; FEEDING; OCEANOGRAPHY

INTRODUCTION

The U.S. Bureau of Land Management (BLM) commenced funding of aerial surveys of endangered whales in offshore oil and gas lease areas in the Alaskan Beaufort Sea in 1979. The U.S. Minerals Management Service (MMS) assumed these responsibilities in 1982. From 1979-1987, surveys were conducted through a series of Interagency Agreements between MMS and the Naval Oceans Systems Center and various sub-contractors (Ljungblad *et al*., 1987). Starting in 1987, MMS agency personnel conducted the field work and produced the annual reports summarizing results (Monnett and Treacy, 2005). In 2007, the National Marine Mammal Laboratory (NMML) of the U.S. National Marine Fisheries Service (NMFS) assumed management of the surveys and all analysis and reporting activities via Interagency Agreement. Throughout the 30-year time span, these aerial surveys (now termed the Bowhead Whale Aerial Survey Project, or BWASP) have been conducted in September and October with remarkable consistency in objectives and field protocol. These surveys were designed to document the annual migration of bowhead whales and any significant inter-year differences in migration. They were also designed to monitor the temporal and spatial trends in the distribution, relative abundance, habitat and behaviors of bowhead whales.

The Bering-Chukchi-Beaufort Sea stock of bowhead whales undergoes an annual autumn migration from summering grounds in the Canadian Beaufort to winter habitat in the Bering Sea (Moore and Reeves, 1993). The migration passes nearshore in the Alaskan Beaufort Sea, through active offshore oil and gas leases. Climatic changes in the Arctic in the past 30 years, including (but not limited to) the reduction in summer sea ice have potentially changed the habitat available to bowhead whales. The long-term and consistent nature of the BWASP study enables investigation of multiyear trends in various aspects of bowhead ecology over three decades.

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Data from the early years of BWASP (1982-1991) were used to investigate patterns in bowhead whale distribution, relative abundance, and behavior (Moore, 2000; Moore *et al*., 2000, 1989a, 1989b; Moore and Clarke, 1991; Ljungblad *et al*., 1986b, 1987), including responses to active geophysical vessels (Ljungblad *et al.* 1988), and a study specifically on calves (Clarke *et al*., 1987). BWASP data have also been used to examine beluga distribution (Clarke *et al.*, 1993; Moore *et al*., 1993). Data from 1982-2000 were used in an analysis of the effects of ice cover on bowhead whale distribution in heavy ice years (Treacy *et al*., 2006). In addition, Givens (2009) used BWASP data through 2008 to examine the spatiotemporal distribution of bowhead relative density. Data from recent BWASP surveys have also reached the scientific community through agency reports (e.g., Monnett and Treacy, 2005) and other reports available via the MMS website (http://www.mms.gov/alaska/ref/AKPUBS.HTM).

The focus of this paper is to describe patterns in the temporal and spatial distribution of bowhead whale sightings, with feeding/milling and calf sightings as special cases, based on the most recent decade of surveys (2000-2009), which have not been comprehensively examined to date. In the context of the complete BWASP dataset, sea ice cover during the 2000-2009 surveys was relatively light. Describing patterns and variability or trends in bowhead distribution in general (or of feeding whales or calves in particular) can provide insight into a suite of ecological questions, including habitat use, foraging ecology, and response to climate change or anthropogenic activities. Our goal is to provide the scientific community with an update of the information that has recently been added to the BWASP time series with the hope that these data may be used correctly to inform future in-depth investigations into the Alaskan Arctic ecosystem, which may in turn facilitate the management of Alaskan Arctic resources.

METHODS AND RESULTS

The study area encompassed the Alaskan Beaufort Sea from 140°W to 157°W longitude and from shore north to 72°N latitude, an area totaling 112,000 km^2. The survey design was based on 12 survey blocks (Figure 1). Surveys were flown from 31 August to 20 October 2000-2009 in deHavilland Twin Otter aircraft outfitted with bubble windows to allow direct observation of the trackline. Line transect aerial surveys were flown over north/south tending transects located between randomly determined start and end points anchored to the survey block boundaries. The aircraft flew at 305 to 460 m altitude, maintaining a speed of 220 to 300 km/h. Two primary observers maintained a continuous watch for marine mammals, one on each side of the aircraft, while a third observer/data recorder entered data into a laptop computer for each sighting, whenever survey conditions changed or every five to ten minutes. The aircraft occasionally made brief (less than 10 minutes) diversions from the transect to investigate sightings to verify species, determine group size and confirm presence or absence of calves. Flightlines were considered to be "on effort" if the data were logged as on transect. In contrast, "off effort" flightlines included data collected while on search, circling, connect or deadhead. Data routinely logged when cetaceans were seen included time, altitude, position, sea state, ice cover, visibility, species, inclinometer angle (to determine distance from the trackline), number of whales, initial animal heading and behavior. Sea state was classified according to the Beaufort scale (Chapman, 1977), and ice cover estimated as a percentage of the sea surface. Additional details of survey protocol are provided elsewhere (e.g., Monnett and Treacy, 2005; National Marine Mammal Laboratory, NMFS, NOAA, 2010).

Total survey distance (km) was summed for all years from tables presented in previous annual reports (e.g., Monnett and Treacy, 2005). Total transect distance (km) per survey block and depth zone (0-20m, 20-50m, 50-200m, 200-2,000m and >2,000m) for "on effort" flightlines only was calculated by clipping the transects to polygons defined by either survey block boundaries or isobaths using R version 2.10.1 (R Development Core Team, 2009) and packages *sp* (Pebesma and Bivand, 2005), *maptools* (Lewin-Koh *et al*., 2009), *rgdal* (Keitt *et al*., 2010), *gpclib* (Peng *et al*., 2009), and *PBSmapping* (Schnute *et al*., 2008). Transect distances differ slightly among the effort-by-year, effort-by-block, and effort-by-depth analyses due to slight differences in the region within which effort was summarized. For example, the survey block polygons that were used in the effort-by-block analyses did not include areas inside barrier islands, whereas the depth polygons did. Sighting rate (WPUE=whales per unit effort) was calculated as the number of whales per transect kilometer (tr-km) surveyed for survey blocks and depth zones. Depths at sightings were derived from the International Bathymetric Chart of the Arctic Ocean (IBCAO; http://www.ngdc.noaa.gov/mgg/bathymetry/arctic/arctic.html). Differences in median depths at sightings were analyzed for various subsets of on-effort data using the nonparametric Mann-Whitney *U*-test in *Statistica* Software. One data subset encompassed the area from 154°-157°W (Block 12, Figure 1), which includes Barrow Canyon and other unique oceanographic features that differentiate it from the rest of the Alaskan Beaufort Sea (Moore *et al*., 2000; Ashjian *et al*., 2010).

In September and October 2000-2009, nearly 190,000 km of survey effort were flown (Figure 2). Fifty percent of all surveys was "on effort" (Figure 1). Transect effort per year varied from 5,700 km in 2002 to 14,100 km in 2004. Survey Blocks 1 and 12 had the highest amount of survey effort for all years combined (Table 1). Offshore Blocks 8, 9, and 10 were not regularly surveyed because historical data indicated that bowheads were rarely seen in offshore areas during the autumn migration (Moore *et al*., 1989b).

A total of 1,429 bowhead whales were seen on-effort from 2000-2009. Bowheads were seen across the study area during both months (Figure 3), with the majority of sightings on the inner shelf (<50m depth) and very few sightings offshore in the outer shelf and slope (>50m depth). On the inner shelf, distribution was fairly uniform across all areas surveyed with a few exceptions, including nearshore in Camden Bay, directly north of Prudhoe Bay, and north of Harrison Bay.

Sighting rate was higher in September (0.0173 WPUE) than October (0.0111 WPUE) for all years combined (Table 1). Sighting rate per survey block was highest in Block 12 in September (0.0568 WPUE), October (0.0273 WPUE) and all years combined (0.0443 WPUE). Sighting rates for individual years in September were highest in Block 12 for six out of 10 years (2000, 2003-06, 2008) and highest in October in Blocks 1 and 3 for six out of 10 years (2000-04, 2006). Lowest sighting rates for all years combined were in Blocks 7 and 11 for September and Blocks 2 and 7 in October.

Sighting rate for the eastern Alaskan Beaufort Sea (140-154°W) was highest in the 20-50m depth contour in both September and October (Figure 4). In September, 40% of total transect survey effort in the eastern Alaskan Beaufort Sea (22,400 Tr-km out of 56,600 total) was in water depths 20-50m, while 73% of all bowheads in September (474 whales out of 645 total) were observed at those depths. Sighting rates for the western Alaskan Beaufort Sea (154-157°W) were considerably higher than those calculated for the eastern part of the study area (Figure 4, Table 2), and were highest in September in the <20m depth zone (0.1371 WPUE).

Ice cover during the study period in all years 2000-2009 was light. Median depths at on-effort sightings in September-October 2000-2009 were compared to those from light ice years in the BWASP historical database (1982, 1986, 1987, 1989, 1990, 1993-1999). There was no difference in median depth at sightings during 2000-2009 compared to those from the historical light ice years (p=0.078). When sightings west of 154°W were analyzed separately, median depths at sightings were significantly shallower (median 24m, range 3-291m) in 2000-2009 than in light ice years prior to 2000 (median 28m, range 7-210m; Z=2.095, p=0.036).

The behavior recorded for most bowhead whales sighted on effort was swimming (72% of sightings); 57% of swimming whales were headed west or northwest (226-315°T). Sightings recorded as feeding or milling accounted for 11% of all sightings (milling is often indicative of feeding even when obvious evidence of feeding behavior is not observed). Feeding and milling were recorded more often in September (81%, 57 sightings) than in October (19%, 13 sightings); feeding/milling were recorded across the study area, but less frequently observed in the central Alaskan Beaufort compared to east of Kaktovik and west of Smith Bay (Figure 5). The sighting rate for feeding/milling whales in Block 5 east of Kaktovik was 0.0050 whales per tr-km, while the sighting rate in Block 12 was 0.0233 whales per tr-km. Most sightings of feeding/milling whales east of 154°W were at depths greater than 20m (n=35, range 11-59m, mean 32m, median 29m), while sightings of feeding/milling whales west of 154°W were seen both shoreward and seaward of the 20m depth contour (n=35, range 4-123m, mean 30m, median 21m). There was no significant difference in median depth at sighting between feeding/milling whales observed in September (n=57, range 4-123m; mean 33m; median 28 m) and those observed in October (n=13, range 11-49; mean 25m; median 22m; p=0.338). Sightings of feeding/milling whales throughout the study area were similarly distributed, based on median depth, as non-feeding whales, even when the study area was subdivided at 154°W.

Bowhead calves were observed across the Alaskan Beaufort Sea (Figure 6). Most calves observed on-effort in September (77%, n=30 calves) were in the eastern part of the study area (east of 148°W), while most calves observed on-effort in October (95%, n = 19 calves) were in the western part of the study area (west of 148°W). Bowhead calves were often undetected during the initial on-effort sighting event, and would likely have remained undetected if brief diversions off-effort (in search or circling mode) were not initiated.

DISCUSSION

Habitat selection indices for data collected from 1982-91 indicated that bowhead whales selected shallow inner-shelf waters during moderate and light ice years and deeper habitat in heavy ice years (Moore, 2000). Analysis of BWASP data collected from 2000-2009, all light ice years, shows that the overall distribution of bowhead whales in the autumn has remained similar to that of 20-30 years ago during light ice years. Based on raw sighting rates, habitat preference for most of the study area (140°-154°W) remained in the 20-50m depth zone. In the westernmost part of the study area (154°-157°W, Block 12), however, sighting rates were overwhelmingly highest in the <20m depth zone in both September and October (all years pooled), underscoring the importance of the nearshore area to bowhead whales in the autumn. While large groups of feeding and milling bowheads were documented in Block 12 in the early years of BWASP (1984, 1989, 1992), they were not documented every year (Moore and Reeves, 1993; Landino *et al*., 1994). Feeding and milling bowheads were located in Block 12 in 7 of the 10 years, 2000-2009. A number of factors may be related to this apparent change in occurrence. Wind-driven currents generate favorable conditions for energetically efficient feeding by bowhead whales in Block 12 (Ashjian *et al*., 2010). Sustained winds from the east promote upwelling of euphausiids from deeper waters onto the Beaufort shelf, whereupon the wind-driven, northwestward-flowing shelf current carries the euphausiids toward Barrow. When easterly winds weaken and turn to blow from the south, the northeastward-flowing Alaska Coastal Current moves adjacent to the southern edge of Barrow Canyon, thereby blocking the northwestward, alongshore movement of krill, and resulting in their aggregation at the western end of the Beaufort shelf near Barrow. Euphausiids are also concentrated in Elson Lagoon (west of Smith Bay) during strong easterly winds, and flow out of the lagoon when winds subside. Mean wind speeds at Barrow have increased steadily since 1972 (Wendler *et al*., 2010), particularly in September and October. The increased winds may be impacting the incidence of upwelling in Block 12 and potentially increasing the frequency with which bowhead whale prey is available and the frequency with which whales are seen there in September and October. Conversely, the incidence of feeding whales in the eastern Alaskan Beaufort Sea has decreased since the early 1980s, when feeding whales were seen each autumn, 1979-84 (Ljungblad *et al*., 1986a). Feeding/milling whales were seen east of Kaktovik in only 5 of the 10 years, 2000-2009, and sighting rates were much lower than in Block 12. Feeding behavior is likely underrepresented in the database due to the difficulty of identifying this behavior in the brief periods of time allowed during transects. Some indications of feeding can be easily observed during initial sightings on-effort, including open mouth at the surface, mud on the rostrum, and echelon swimming. But other behaviors that might be indicative of feeding, including synchronous diving, flukes-up diving and defecation, may not be apparent unless further investigation of the sighting is initiated. The practice of diverting from transect to investigate sightings is not standardized, and is dependent on other factors including weather, visibility, and remaining fuel reserves.

Bowhead whale distribution remains nearshore on the inner shelf in the Alaskan Beaufort Sea in September and October, as evident from the distribution map and the sighting rate analysis. In the nearshore survey blocks (1, 3, 4, 5, and 12), bowheads were seen wherever on-effort surveys were conducted, with three exceptions. Bowhead whales were not seen in the shallow waters of Camden Bay, directly north of Prudhoe Bay and in an area offshore of Harrison Bay. The lack of sightings in the Camden Bay area is consistent with results from other analyses. Bowhead whales were observed far less in the shallow waters (<20m) of Camden Bay during BWASP surveys and localized aerial surveys conducted by various oil companies from 1979-2000 (Miller *et al*., 2002; Wursig *et al*., 2002) than in areas farther offshore. Passive acoustic monitoring of Camden Bay detected few bowhead whale calls in this area as well (Blackwell *et al*., 2010). The "hole" that exists north of Prudhoe Bay, also discussed in Givens (2009), and the "hole" in Harrison Bay are unexpected. The lack of sightings in these two areas cannot be explained by a lack of survey effort. Causes for these distribution anomalies may have anthropogenic origins (e.g., offshore industrial activity, subsistence whaling) or natural causes (e.g., differences in circulation patterns or in the substrate that might affect bowhead feeding opportunities). Passive acoustic monitoring of this area indicates that bowhead whale calls are present in both of the "holes" (Blackwell *et al*., 2010). Givens (2009) suggested the lack of sightings in the "hole" north of Prudhoe Bay may be due to lack of whale availability to aerial surveyors because the whales were spending more time underwater or traversing the area more quickly. Circulation dynamics, benthic ecology, large and small vessel movements, aircraft overflights, and other variables in these regions need to be investigated further to determine potential causes of the unexpectedly low numbers of bowhead sightings in these areas.

Results from these analyses should be considered preliminary because they were based on raw sighting rates, uncorrected for perception or availability bias. In addition, the Mann-Whitney *U*-test does not take effort into account. Nevertheless, these results provide insight into where future efforts should be concentrated to close gaps in our understanding of bowhead whales and their role in the Alaskan Arctic ecosystem. For example, in-depth analyses (that include corrections for sighting biases and effort) could be used to investigate bowhead density in relation to sea ice characteristics, dynamic hydrographic features (such as upwelling), and mid-water and benthic prey communities, and to investigate whether the lack of bowhead sightings off Prudhoe, Harrison, and Camden Bays may be explained by natural variation in habitat. In addition, future BWASP field efforts could include aerial surveys in late summer (August), as conducted in the early 1980s (Ljungblad *et al*., 1986b; Moore *et al*., 1989a). Bowhead whales are already present in the Alaskan Beaufort Sea in September when BWASP surveys begin; therefore, the onset of the migration is not documented. Consequently, relatively little is known about bowhead behavior or habitat preferences during this period. Recent bowhead whale satellite-tagging results have indicated that some whales traverse the Alaskan Beaufort Sea more than once in the summer, traveling between the Canadian Beaufort Sea and Barrow (Quakenbush et al., 2010). The retreating summer sea ice may result both in increased presence of bowhead whales and an increase in the presence of offshore oil and gas interests. Results of surveys conducted in August from 1979-1984 indicated that bowheads tended to be distributed farther offshore during the late summer, which is also corroborated by satellite-tagging data from 2009, but the extent of use of nearshore ice-free areas in August remains largely unknown. Finally, detailed data should be collected on the full suite of anthropogenic activities that currently exist or are likely to occur with increasing frequency in Alaskan Arctic waters (*e.g.*, oil and gas activities, coastal development, fishing, commercial shipping, marine recreational activities, scientific research, military activities, subsistence hunting) to facilitate comprehensive analyses of bowhead whale ecology in light of natural and anthropogenic variability.

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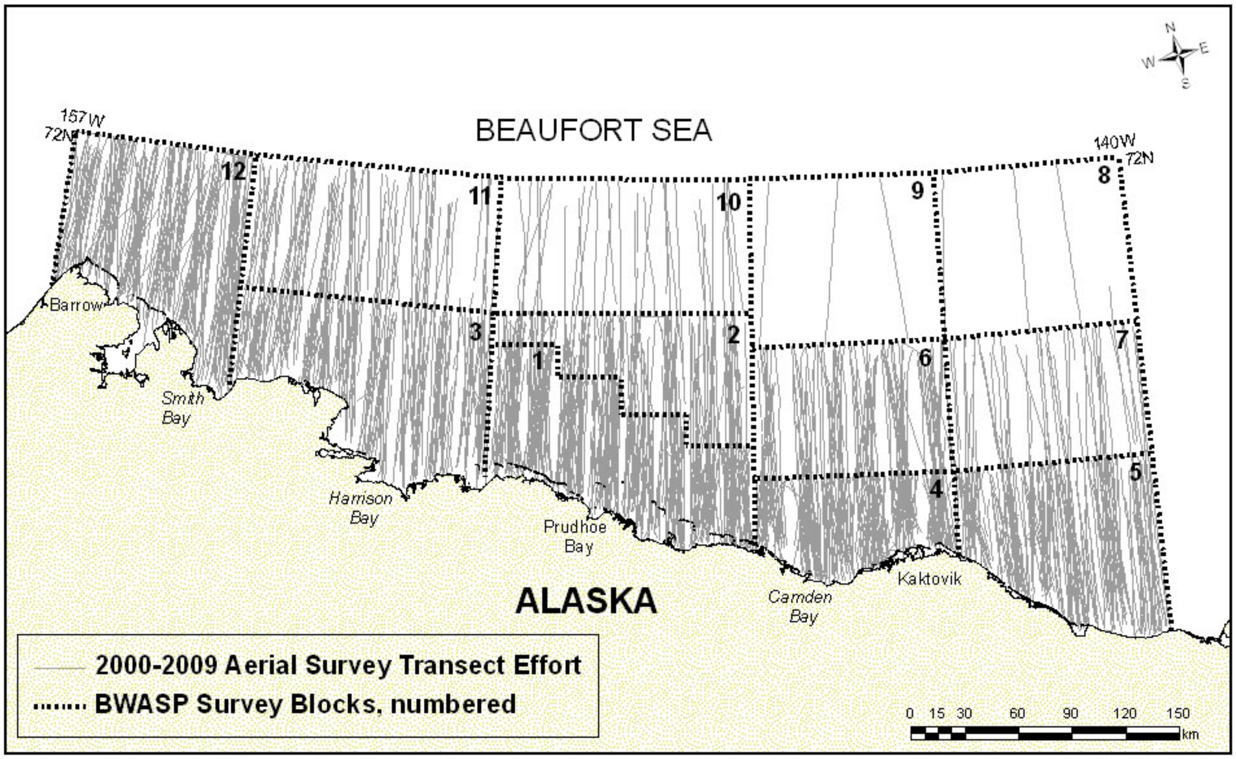

Figure 1. BWASP study area, survey blocks and effort, 2000-2009.

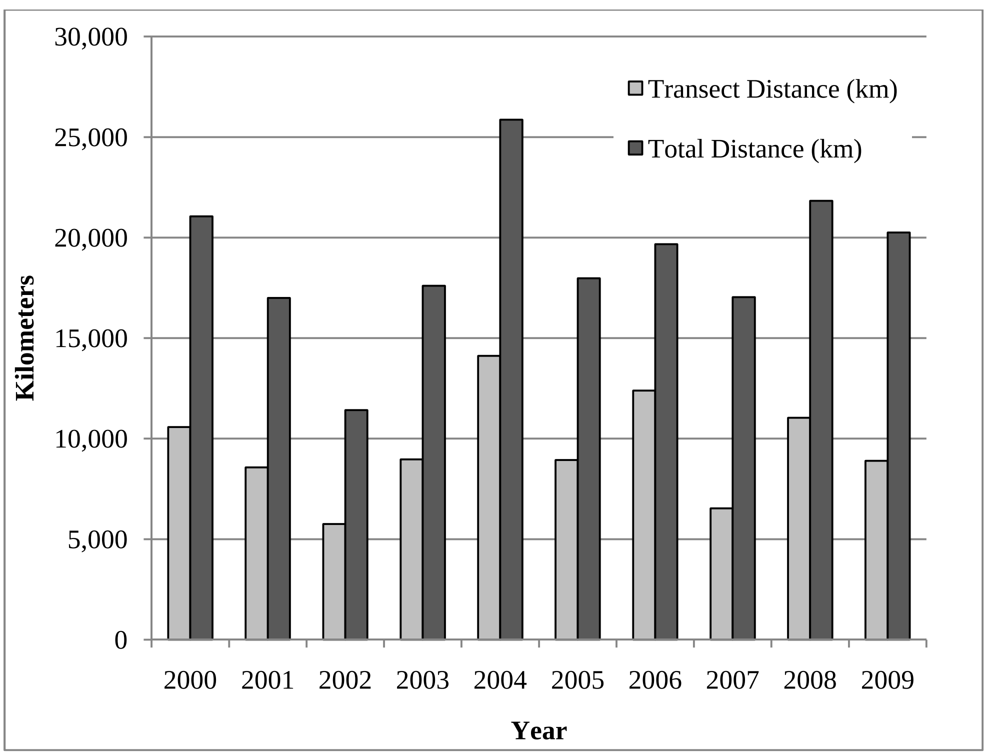

Figure 2. BWASP total and transect survey effort, per year, 2000-2009.

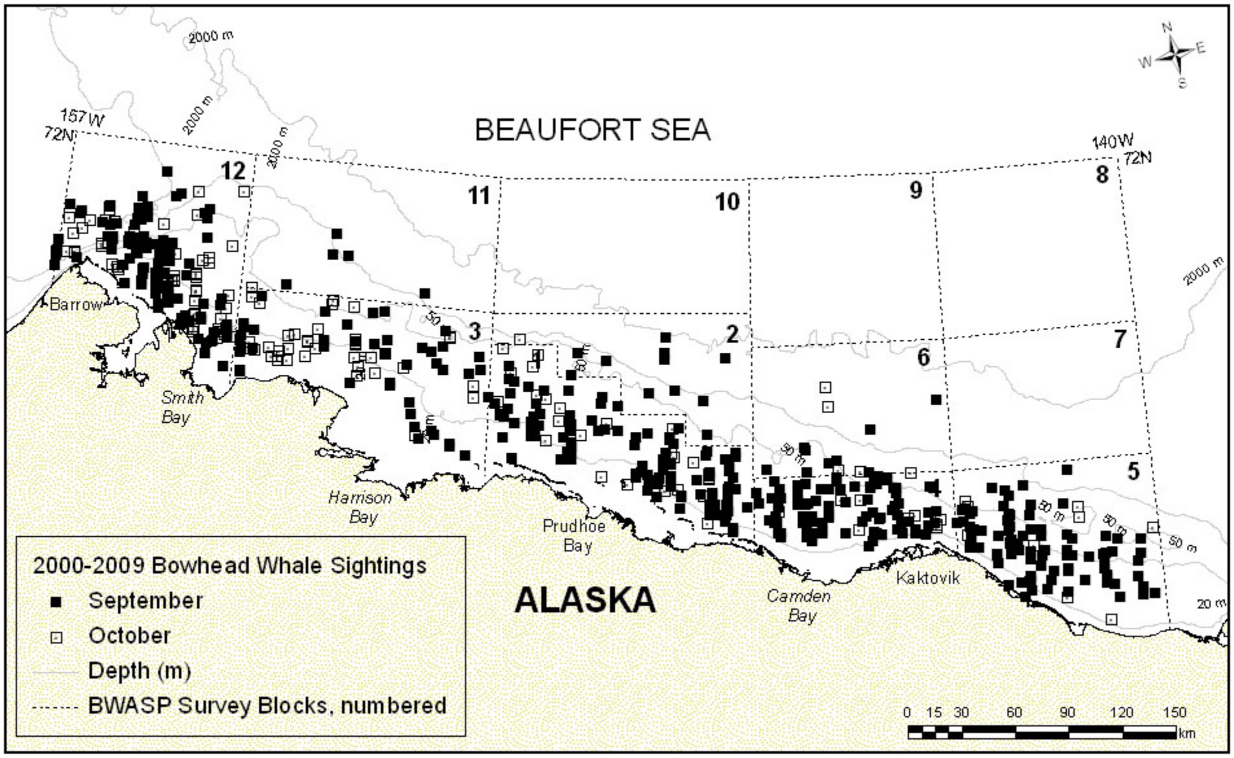

Figure 3. Bowhead whale sightings on transect, 2000-2009.

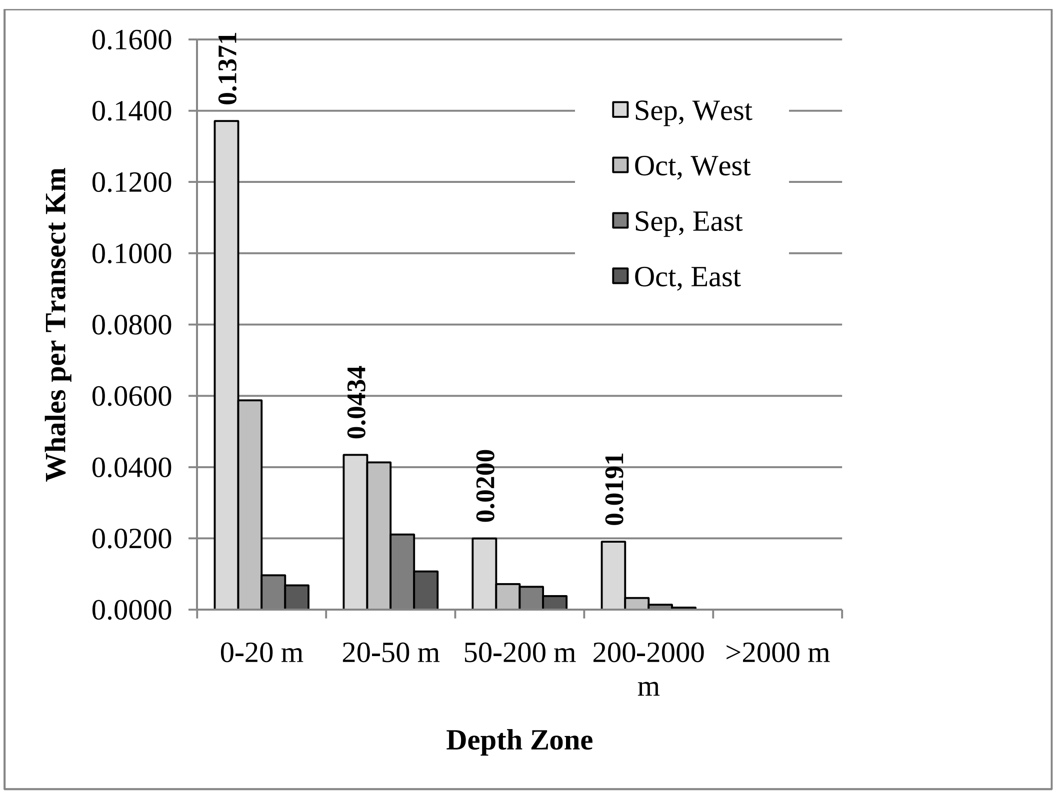

Figure 4. Sighting rates (WPUE=whales per unit effort) per depth zone for the western Alaskan Beaufort Sea (154-157°W) and the eastern Alaskan Beaufort Sea (140-154°W), 2000-2009.

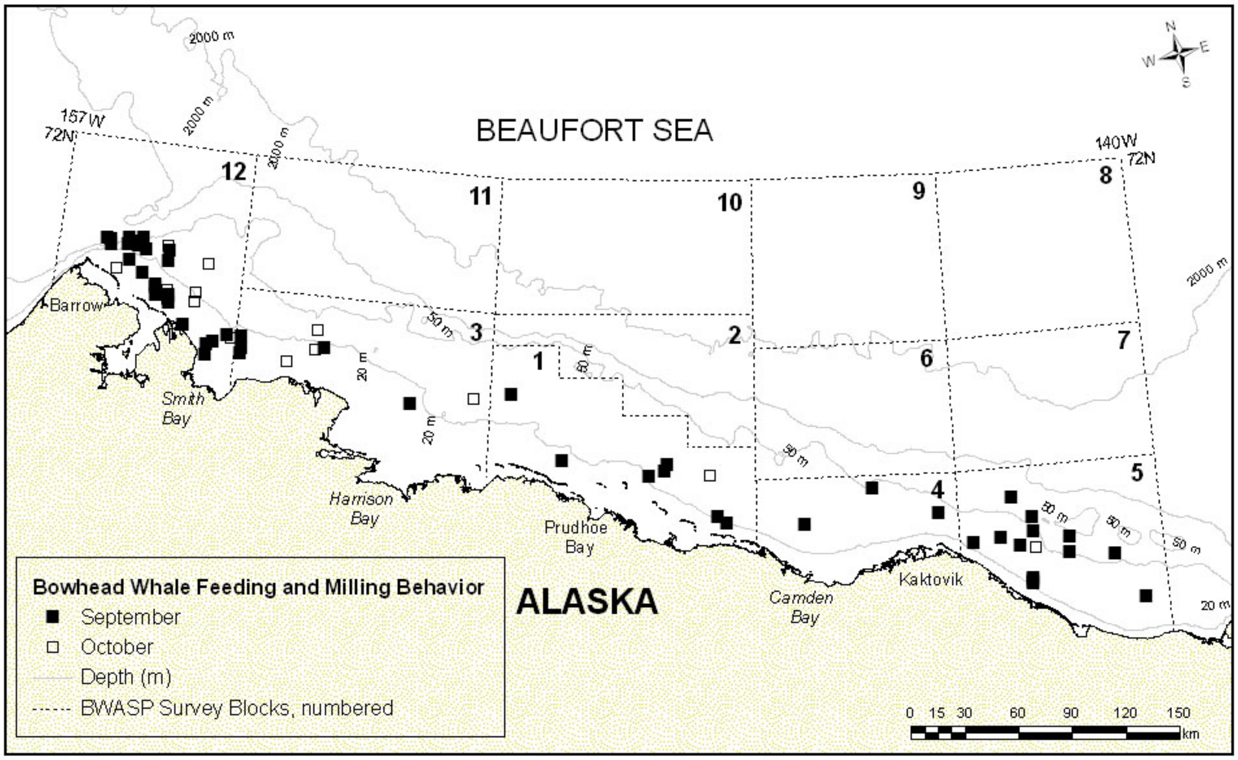

Figure 5. Feeding and milling behavior of bowhead whales sighted on transect, 2000-2009.

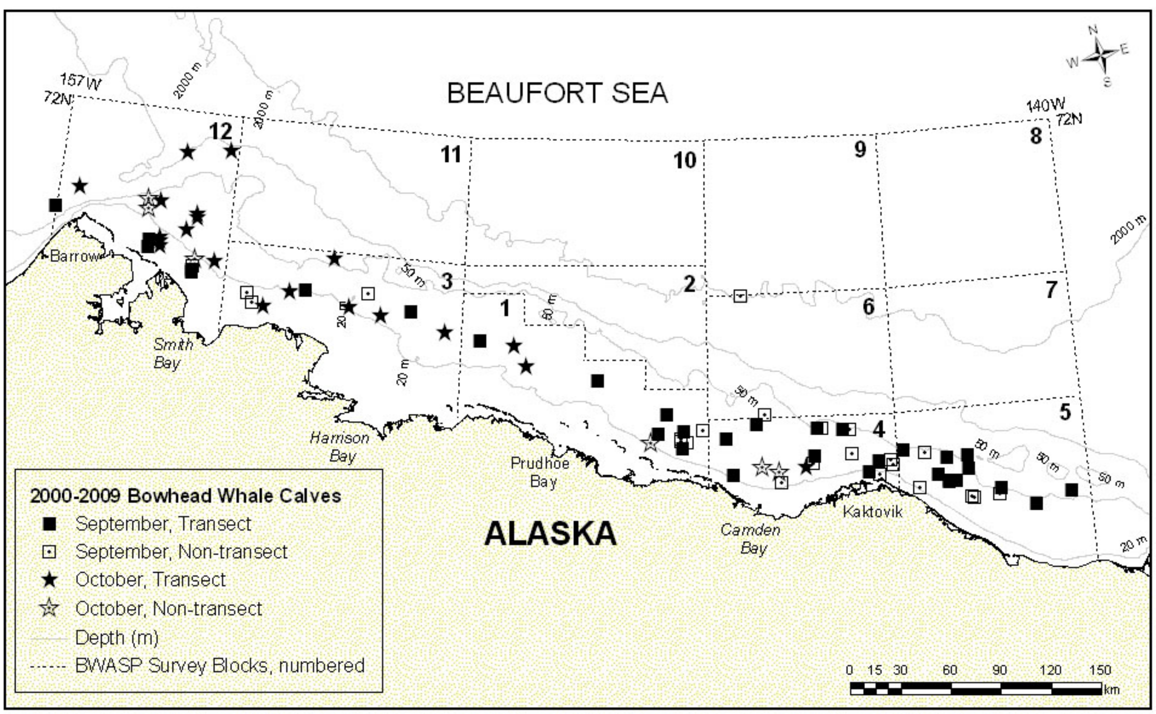

Figure 6. BWASP bowhead whale calf sightings, on and off transect, 2000-2009.

Table 1. Sighting rates (WPUE=whales per unit effort) per survey block, September-October, 2000-2009. Tr-km= kilometers on transect, Tr Bm = bowhead whales on transect. The maximum WPUE per month and for both months combined is *italicized*.

Survey	September			October			Total		
Block	Tr-km	Tr Bm	WPUE	Tr-km	Tr Bm	WPUE	Tr-km	Tr Bm	WPUE
1	11,154	239	0.0214	5,817	63	0.0108	16,970	302	0.0178
2	4,979	12	0.0024	1,738	1	0.0006	6,717	13	0.0019
3	6,978	58	0.0083	5,793	66	0.0114	12,771	124	0.0097
4	8,520	139	0.0163	2,745	13	0.0047	11,265	152	0.0135
5	9,098	176	0.0193	3,342	16	0.0048	12,441	192	0.0154
6	5,647	14	0.0025	1,738	6	0.0035	7,385	20	0.0027
7	2,470	0	0.0000	714	0	0.0000	3,184	0	0.0000
8	305	0	0.0000	3	0	0.0000	308	0	0.0000
9	291	0	0.0000	7	0	0.0000	298	0	0.0000
10	1,596	0	0.0000	598	0	0.0000	2,194	0	0.0000
11	4,359	5	0.0011	1,323	4	0.0030	5,682	9	0.0016
12	8,012	455	*0.0568*	5,931	162	*0.0273*	13,942	617	*0.0443*
Total	**63,408**	**1,098**	**0.0173**	**29,750**	**331**	**0.0111**	**93,158**	**1,429**	**0.0153**

Table 2. Sighting rates (WPUE=whales per unit effort) per depth zone for the western Alaskan Beaufort Sea (154-157°W) and the eastern Alaskan Beaufort Sea (140-154°W), September-October, 2000-2009. Tr-km= kilometers on transect, Tr Bm = bowhead whales on transect.

WEST of 154	**September**			**October**			**Total**		
	Tr-km	**Tr Bm**	**WPUE**	**Tr-km**	**Tr Bm**	**WPUE**	**Tr-km**	**Tr Bm**	**WPUE**
0 to 20m	2,159	296	0.1371	1,515	89	0.0587	3,674	385	0.1048
20 to 50m	1,681	73	0.0434	1,258	52	0.0413	2,940	125	0.0425
50 to 200m	3,501	70	0.0200	2,646	19	0.0072	6,147	89	0.0145
200 to 2000m	839	16	0.0191	608	2	0.0033	1,447	18	0.0124
>2000m	0	0	0.0000	0	0	0.0000	0	0	0.0000
Total	**8,180**	**455**	**0.0191**	**6,028**	**162**	**0.0033**	**14,208**	**617**	**0.0434**

EAST of 154	**September**			**October**			**Total**		
	Tr-km	**Tr Bm**	**WPUE**	**Tr-km**	**Tr Bm**	**WPUE**	**Tr-km**	**Tr Bm**	**WPUE**
0 to 20m	9,933	96	0.0097	6,143	42	0.0068	16,076	138	0.0086
20 to 50m	22,447	474	0.0211	10,175	109	0.0107	32,622	583	0.0179
50 to 200m	9,518	61	0.0064	3,654	14	0.0038	13,171	75	0.0057
200 to 2000m	10,009	14	0.0014	3,302	2	0.0006	13,311	16	0.0012
>2000m	4,748	0	0.0000	1,243	0	0.0000	5,992	0	0.0000
Total	**56,655**	**645**	**0.0014**	**24,516**	**167**	**0.0006**	**81,171**	**812**	**0.0100**