



Research papers

Marine mammal acoustic detections in the northeastern Chukchi Sea, September 2007–July 2011

David E. Hannay^{a,*}, Julien Delarue^b, Xavier Mouy^a, Bruce S. Martin^b, Del Leary^b, Julie N. Oswald^c, Jonathan Vallarta^b^a JASCO Applied Sciences, 2305-4464 Markham Street, Victoria, BC, Canada V8Z 7X8^b JASCO Applied Sciences, 202-32 Troop Ave., Dartmouth, NS, Canada, B3B 1Z1^c JASCO Applied Sciences, 1474 Tennis Match Way, Encinitas, CA 92024, USA

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ABSTRACT

Several cetacean and pinniped species use the northeastern Chukchi Sea as seasonal or year-round habitat. This area has experienced pronounced reduction in the extent of summer sea ice over the last decade, as well as increased anthropogenic activity, particularly in the form of oil and gas exploration. The effects of these changes on marine mammal species are presently unknown. Autonomous passive acoustic recorders were deployed over a wide area of the northeastern Chukchi Sea off the coast of Alaska from Cape Lisburne to Barrow, at distances from 8 km to 200 km from shore: up to 44 each summer and up to 8 each winter. Acoustic data were acquired at 16 kHz continuously during summer and on a duty cycle of 40 or 48 min within each 4-h period during winter. Recordings were analyzed manually and using automated detection and classification systems to identify calls.

Bowhead (*Balaena mysticetus*) and beluga (*Delphinapterus leucas*) whale calls were detected primarily from April through June and from September to December during their migrations between the Bering and Beaufort seas. Summer detections were rare and usually concentrated off Wainwright and Barrow, Alaska. Gray (*Eschrichtius robustus*) whale calls were detected between July and October, their occurrence decreasing with increasing distance from shore. Fin (*Balaenoptera physalus*), killer (*Orcinus orca*), minke (*Balaenoptera acutorostrata*), and humpback (*Megaptera novaeangliae*) whales were detected sporadically in summer and early fall. Walrus (*Odobenus rosmarus*) was the most commonly detected species between June and October, primarily occupying the southern edge of Hanna Shoal and haul-outs near coastal recording stations off Wainwright and Point Lay. Ringed (*Pusa hispida*) and bearded (*Erignathus barbatus*) seals occur year-round in the Chukchi Sea. Ringed seal acoustic detections occurred throughout the year but detection numbers were low, likely due to low vocalization rates. Bearded seal acoustic detections peaked in April and May during their breeding season, with much lower detection numbers in July and August, likely as a result of reduced calling rates after breeding season. Ribbon seals (*Histiophoca fasciata*) were only detected in the fall as they migrated south through the study area toward the Bering Sea. These results suggest a regular presence of marine mammals in the Chukchi Sea year-round, with species-dependent seasonal and spatial density variations.

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1. Introduction

All marine mammals are capable of producing sounds, and most marine mammal species use sounds extensively for communication, navigation, warning signals, keeping track of young, breeding-related or social displays, and for finding food (Edds-Walton, 1997; Tyack and Clark, 2000). The wide use of sounds by marine mammals is partly necessitated by the poor transmission of light underwater that

reduces visual effectiveness; however, the primary reason is that sound propagates extremely well underwater. Terrestrial animal communications with airborne sounds can be detected at most to a few kilometers, and more typically to just a few hundred meters. On the other hand, underwater vocalizations by mysticetes can sometimes be detected at distances of many hundreds of kilometers (Clark and Gagnon, 2004; Stafford et al., 2007b). While typical underwater sounds from marine mammals propagate to shorter distances than that, sensitive listening devices can still monitor relatively large areas of ocean to detect presence of vocalizing animals (Stafford et al., 2007a, 2007b; Nieuwkirk et al., 2012).

Passive acoustic monitoring using multiple recorders has become a feasible method for measuring temporal and spatial distributions of marine mammals over large areas (Delarue et al., 2011). Autonomous

* Corresponding author. Tel.: +1 250 483 3300x2002; fax: +1 250 483 3301.

E-mail address: David.Hannay@jasco.com (D.E. Hannay).

acoustic recorders can be deployed for long periods to listen for vocalizing marine mammals. Acoustic monitoring is effective in all weather conditions and it is well-suited for arctic work in winter when freezing temperatures, little daylight, and presence of ice complicates direct monitoring methods. Acoustic monitoring is complementary to aerial surveys, vessel surveys and satellite tag tracking methods for species distribution mapping. While acoustic monitoring is less suited than tag studies for tracking individual animals, it can sample larger fractions of populations to obtain temporal distributions of habitat use at selected locations (Mellinger et al., 2007). Unlike tagging studies, passive acoustic monitoring requires no contact with animals, thereby eliminating the effects of those interactions.

Acoustic detection of marine mammal calls requires that animals produce sounds of sufficient amplitude that they can be identified above other background noises. Thus, the results obtained from acoustic studies apply only to vocally active animals within a given distance from the recorders. The detection range of each species depends on the source level of its calls, acoustic transmission losses between the calling animal and the recorder, and background noise levels (Stafford et al., 2007b). Weather events such as storms can raise ambient noise, reducing the ability to detect calls. Anthropogenic activities such as seismic surveys can ensonify large areas and potentially mask marine mammal signals from acoustic detection (e.g., Guerra et al., 2011).

Vocalization rates can vary among individuals and over time, and may depend on behavior, age, and sex class (Parks et al., 2011). Thus, the number of calls per species does not necessarily represent the species' relative abundance. Nonetheless, acoustic call detection rates can represent the relative occurrence of animals among acoustic recording stations under the assumption that the animal calling behavior does not vary spatially between stations.

The northeastern Chukchi Sea is foraging habitat and a migration pathway for a number of marine mammal species. Bowhead (*Balaena mysticetus*), beluga (*Delphinapterus leucas*), and gray (*Eschrichtius robustus*) whales (e.g., Moore and DeMaster, 1998), spotted seals (*Phoca largha*), and walrus (*Odobenus rosmarus*) (Burns, 1970) are seasonally present and relatively abundant in this area. Killer (*Orcinus orca*) (e.g., George and Suydam, 1998), fin (*Balaenoptera physalus*) (Mizroch et al., 2009; Delarue et al., 2013a), minke (*Balaenoptera acutorostrata*) and humpback (*Megaptera novaeangliae*) whales (Ireland et al., 2009), and ribbon seals (*Histiophoca fasciata*) (Burns, 1981) are often present during open-water periods, but they are relatively rare. Ringed (*Pusa hispida*) and bearded (*Erignathus barbatus*) seals are year-round residents of the Chukchi Sea (Burns, 1970).

Beluga migrate northeast along the Alaskan coast of the Chukchi Sea in spring, but they are relatively less abundant in offshore areas of the Chukchi Sea in summer. Some beluga, however, appear to feed through the summer in the deeper waters of Barrow Canyon (Suydam et al., 2001, 2005; Delarue et al., 2011). Bowhead whales migrate through the northeastern Chukchi Sea in spring and fall and have been observed feeding just east of Point Barrow in late summer and fall (Moore et al., 2010). Walrus, gray whales, and bearded seals feed on benthic fauna (Feder et al., 1994) while in the Chukchi Sea.

The presence of sea ice and the timing of its formation and retreat affect the occurrence of marine mammals in the Chukchi Sea. Bowhead and beluga whales begin migrating north from the Bering Sea into the Chukchi Sea in the spring as soon as ice conditions allow, following leads in the ice to reach their summer feeding grounds in the Beaufort Sea (Moore and Reeves, 1993; Delarue et al., 2011). Subsistence hunters have observed that ice conditions affect the timing of bowheads' passage near Barrow in fall (Huntington and Quakenbush, 2009). In contrast, pinnipeds rely on sea ice as a platform for haul-out during their foraging trips

in summer and as substrate for birthing lairs in the winter and spring. Some bearded and ringed seals, both ice-obligate species (Moore and Huntington, 2008), are resident year-round in the Chukchi Sea whereas spotted seals, ribbon seals, and walrus appear to leave the Chukchi Sea in the fall before heavy ice forms (Burns, 1970).

Current information on the distribution and occurrence of marine mammals in the northeastern Chukchi Sea has been derived from the traditional knowledge of subsistence hunters, from aerial surveys conducted primarily between April and November since 1982 (Clarke and Ferguson, 2010) and from more recent satellite and radio tag studies, for example on walrus (Jay et al., 2012), beluga (Suydam et al., 2001), bowhead (Quakenbush et al., 2010) and ringed seals (Crawford et al., 2011). Most tag data have been acquired in summer and fall seasons. Data on the winter and spring occurrence of marine mammals in the Chukchi Sea remain scarce, particularly for areas far from shore.

This paper reports on year-round detections of marine mammal calls in the northeastern Chukchi Sea from September 2007 to July 2011 as part of a multidisciplinary study of three prospect areas in the region: Burger, Klondike and Statoil (Day et al., 2013). Acoustic detections of all species listed above, with the exception of spotted seals (whose call types are currently not well-characterized), are discussed here. The temporal and spatial distribution results presented here are relevant for evaluating possible changes in marine mammal distributions that might be influenced by noise from oil and gas exploration and production developments in this area and the effects of arctic sea ice decline (Stroeve et al., 2007). The results are presented first for cetaceans then pinnipeds, and then according to the abundance of acoustic detections for each species.

2. Materials and methods

2.1. Acoustic recording stations

Arrays of autonomous acoustic recorders were deployed in the northeastern Chukchi Sea to monitor nearly continuously from July 2007 to August 2011. Two primary deployments were conducted each year (Fig. 1, Table 1): a larger deployment of 10–44 recorders from late July to early October (summer deployments), and a smaller deployment of 5–8 recorders from early October to the following August (winter deployments). The recording

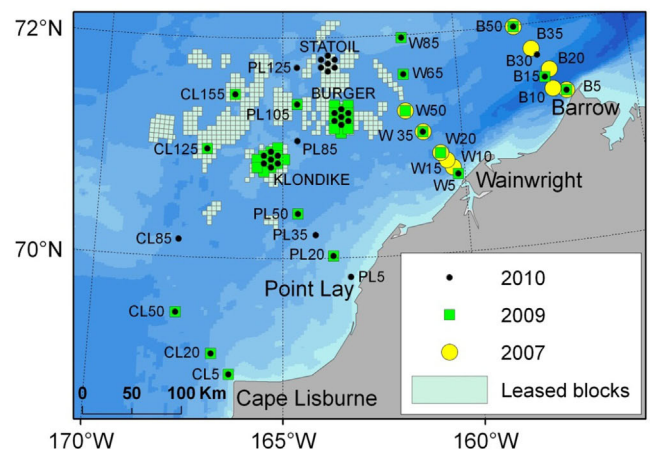


Fig. 1. Acoustic recorder locations for the 2007, 2009, and 2010 summer deployments in the northeastern Chukchi Sea. The three core study areas are Burger, Klondike, and Statoil. The numbers in the station names refer to approximate distances in statute miles from shore from the four coastal villages. Shades of blue represent water depth.

Table 1

Deployment summary for all acoustic monitoring programs between July 2007 and 2011.

Deployment	Operational recorders	Start of recording	End of recording	Recording days (range)	Average number of recording days
Summer 2007	10	10–14 Sep	19–26 Oct	37–47	41.3
Winter 2007–2008	5	21–25 Oct	20 Jul–3 Aug	272–283	277.8
Winter 2008–2009	7	12–16 Oct	13 Apr–20 Aug	179–307	259.7
Summer 2009	41	5–27 Aug	3–12 Oct	45–68	64.6
Winter 2009–2010	8	12–16 Oct	21 Mar–17 Aug	159–309	262.1
Summer 2010	43	25 Jul–17 Aug	17 Aug–16 Oct	21–81	73.0
Winter 2010–2011	7	10–16 Oct	26 Jul–6 Aug	284–294	290.6

deployment stations were aligned offshore of the four Alaskan villages: Cape Lisburne (CL), Point Lay (PL), Wainwright (W), and Barrow (B). Recording stations were named according to the village identifier and the approximate distance from shore in nautical miles. For example, Station W35 is located approximately 35 nautical miles (64 km) offshore of Wainwright, Alaska.

2.1.1. Summer recordings

Acoustic data were collected during summers of 2007, 2009, 2010 and 2011. Few data were collected in summer 2008 due to a problem with recorders and those data are not included here. The 2007 summer deployment consisted of ten Autonomous Underwater Recorders for Acoustic Listening (AURALS, Multi-Electronic, Inc., Rimouski, QC, Canada) distributed along two lines leading offshore from Wainwright and Barrow. The 2009 and 2010 summer deployments each consisted of 44 Autonomous Multi-channel Acoustic Recorders (AMAR, JASCO Applied Sciences, Halifax, NS, Canada) deployed between Cape Lisburne and Barrow. The recorders were deployed in four parallel lines of 4–7 recorders each, leading offshore of Cape Lisburne, Point Lay, Wainwright, and Barrow. Recording stations' distances from shore ranged from 8 to 210 km. These lines of recorders were supplemented by two (2009) and three (2010) clusters of recorders at selected locations within the prospects.

2.1.2. Winter recordings

AURAL recorders were deployed for winter programs in 2007–2008, 2008–2009, 2009–2010, and 2010–2011. Deployment locations were more than 65 km from shore to avoid shallow depths where winter ice keels might contact the recorders. One nearshore recorder was deployed in the deeper waters of Barrow Canyon (station B5) at 8 km off Barrow in 2009–2010 and 2010–2011 (Fig. 2; Table 1). The number of deployed recorders increased from five (2007–2008) to eight (2009–2010 and 2010–2011). Data were recorded on a duty cycle of 48 min every 4 h during 2007–2008, and 40 min every 4 h during the following years.

2.1.3. Acoustic recorders

The recorders were deployed on the seabed with their hydrophones positioned approximately 0.5 m above the seafloor in water depths of 15–100 m. All recorders were calibrated in the field using

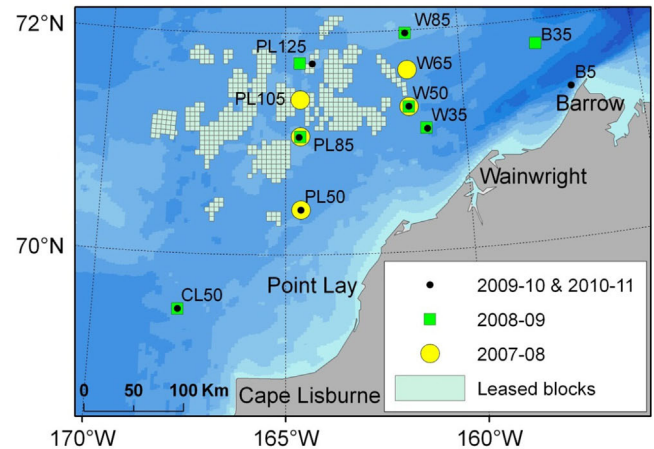


Fig. 2. Acoustic recorder locations for the 2007–2008, 2008–2009, 2009–2010, and 2010–2011 winter deployments in the northeastern Chukchi Sea. Data were not recorded at W35 in 2010–2011. Shades of blue represent water depth.

GRAS 42AA pistonphone calibrators at 250 Hz. The manufacturers provided the frequency responses of the hydrophones and recorder digitizers. AURALS were fitted with HTI-96 (High Tech Inc., Gulfport, MS, USA) hydrophones with sensitivity -164 dB re 1 V/ μ Pa. AURAL data were sampled at 16,384 Hz with 16-bit resolution using a recorder gain setting of $+22$ dB, which provided a spectral noise floor of 57 dB re 1 μ Pa²/Hz. The usable bandwidth was 10–7700 Hz. AMARs were equipped with GTI-M15B (GeoSpectrum, Dartmouth, NS, Canada) hydrophones with sensitivity -160 dB re 1 V/ μ Pa. Acoustic data were recorded at 16,000 Hz with 24-bit resolution and a gain setting of 0 dB in 2009 and $+18$ dB in 2010. The usable bandwidth was 10–7600 Hz, and the spectral noise floor was 45 dB re 1 μ Pa²/Hz in 2009 and 42 dB re 1 μ Pa²/Hz in 2010.

2.2. Analysis methods

Marine mammal vocalizations were detected and classified manually and with automated detection and classification software (Mouy et al., 2013). Three species of key interest – bowhead whale, beluga, and walrus – were targeted for closer examination than other species due to their conservation status and importance to Chukchi Sea coastal communities. Nevertheless, substantial analysis effort was applied also to measure gray whale, killer whale, bearded seal, and ringed seal acoustic detection distributions. We manually analyzed a portion of the data to determine the acoustic occurrence of all marine mammal species and to evaluate the performance of, and to calibrate, the automated detectors and classifiers described below. We applied the automated system to the entire summer datasets to produce indices of acoustic abundance for selected species at each station.

2.2.1. Call types used to classify species

Bowhead whales were identified by their moans, which typically range between 100–400 Hz and last about 1 s (Clark and Johnson, 1984). Complex notes forming the basis of songs (Delarue et al., 2009) were also present during the fall and spring migrations. Beluga whales were identified by their whistles and pulsed/ noisy calls (Chmelnitsky and Ferguson, 2012). Most calls were above 1 kHz, though some range down to the low hundreds of hertz. Gray whales were identified by their low-frequency moans, pulses and bonging sounds (Crane and Lashkari, 1996; Stafford et al., 2007a). All energy was typically below 1 kHz and always below 120 Hz for moans, the most common call type. Fin whale calls were low-frequency pulses centered around 20 Hz (Watkins

et al., 1987). Humpback whale calls were exclusively of the “wops” and “thwops” type (Dunlop et al., 2007) which were brief, low-frequency harmonic upsweeps. Minke whale detections included only boing sounds (Rankin and Barlow, 2005). Killer whale detections consisted mainly of pulsed calls (Deecke et al., 2005). Walrus were identified by their knock and bell calls (Stirling et al., 1987), along with a variety of grunts (Mouy et al., 2012). Ringed seal calls included mainly bark and yelp sequences (Stirling, 1973). Ribbon seal calls downward frequency sweeps and broadband puffing sounds (Watkins and Ray, 1977). Bearded seals were identified by their characteristic trills (Risch et al., 2007).

2.2.2. Manual detection and classification of marine mammal sounds

Up to six trained analysts manually reviewed 5% of the winter data from 2008 to 2009 (364 h analyzed), 2009–2010 (420 h analyzed), and 2010–2011 (406 h analyzed) by visual examination of spectrograms and by listening to recorded audio. The analysts were assigned datasets selected from multiple time periods from different recorders to average out inter-analyst variability effects. Two-minute data samples were selected from the middle of each of the six 40-min sound files acquired on each recorder each day. Analysts annotated all marine mammal calls in the first sample and one call per species per sample in the remaining five samples.

The 2007–2008 winter data were analyzed differently. Selected files (typically one of the six 48-min files acquired each day) were reviewed in their entirety for marine mammal calls. More files from October, November and December, during the bowhead fall migration, were reviewed than from other months. Although this yielded a monthly average of 27% (range: 7–94%) of files reviewed in their entirety at each station, resulting in a higher analysis effort overall, the analysis effort was not evenly distributed, with 1–2 days gaps between analyzed files. Therefore, despite a 100% detection probability for the files reviewed, the 2007–2008 winter results provide a coarser view of, and may underestimate, the occurrence of marine mammal calls relative to subsequent years, when samples from every file were reviewed.

Summer data from all years were acquired continuously and stored as 48 30-min files each day. Analysts manually reviewed the first 90-s sample (i.e., 5%) of each 30-min file. They identified all marine mammal vocalizations in the samples from the first file (starting between 12:00 and 12:30 a.m.) and middle file (starting between 12:00 and 12:30 p.m.) each day and one call per species per sample from the other 46 files.

2.2.3. Automated detection and classification of marine mammal sounds

Automated detectors were applied only to summer data to produce call count estimates for bowhead, walrus and bearded seals, and ultimately summer detection count isopleth maps for these species. The automated classifiers have to decide on the species responsible for a call based on features of the call chosen from time–frequency representations of the call waveforms. Decisions of the automated classifiers are then based on spectral features of the calls (Mouy et al., 2013). The bowhead detector considered time–frequency contours extracted from normalized spectrograms using a tonal detector developed by Mellinger et al. (2011). Each contour was characterized according to 46 features and these were presented to two-class random forest classifiers (i.e., bowhead vs. “other”). The random forest classification technique is based on the concept of ensemble, or committee, decisions. A collection of decision trees (Breiman et al., 1984; Breiman, 2001) comprises the forest, where each tree is grown using binary partitioning of the data based on the value of one feature at each split (or node). All features of a detected call are considered by the random forest and each tree produces a

classification vote. The final classification of the call is the species that receives the greatest number of votes.

The random forest for bowhead classification was trained using a large subset of the manually annotated calls. The walrus grunt detector worked similarly except that the detection was performed using an energy detector in the frequency band 50–600 Hz and its features were based on the frequency distribution of the energy in the normalized spectrogram (Fristrup and Watkins, 1993; Mellinger and Bradbury, 2007). Automated detection of bearded seal was accomplished as follows: adjacent time–frequency bins in the normalized spectrogram of each call were joined to create time–frequency contours using an algorithm similar to that implemented by Nosal (2008). Extracted contours were then classified as bearded seal if they met a set of defined conditions based on the contour's frequency bandwidth, minimum and maximum frequency, and duration.

We assessed the performance of the detectors/classifiers for each species by comparing automated detections to manual ones. The performance of the detectors was characterized relative to manual analyst performance according to *precision* (P) and *recall* (R) indices (Davis and Goadrich, 2006; Roch et al., 2011). The strength of this approach is that once a detector is characterized, its P and R values can be applied to adjust the detector's outputs to predict the numbers of detections that manual analysts would produce.

P and R were calculated from the numbers (N) of true positives or correct classifications (TP), false positives or incorrect classifications (FP), and false negatives or missed detections (FN):

$$P = \frac{N_{TP}}{N_{TP} + N_{FP}}, \quad R = \frac{N_{TP}}{N_{TP} + N_{FN}} \quad (1)$$

For example, a P for beluga of 0.9 means that 90% of the detections automatically classified as beluga were correct (as decided by the manual analysts), but it does not indicate the fraction of actual calls missed. An R for beluga of 0.8 means that 80% of all manually-detected beluga calls in the dataset were automatically detected and classified as beluga, but it does not indicate how many incorrect classifications occurred. Thus, a perfect detector/classifier would have $P=R=1$.

Because the detectors are imperfect, the number of automatic detections will generally not equal the actual number of calls present in the recordings that would be identified by an expert analyst. However, provided the subset of data used to characterize P and R is representative of the entire dataset, the estimated P and R can be used to correct the automated detection counts to produce an estimate of the true number of calls that would be detected by the manual analyst. The total number of detections, N_{det} , found by the automatic classifier is

$$N_{det} = N_{TP} + N_{FP}, \quad (2)$$

and the real number of calls in the data, N_{call} , is

$$N_{call} = N_{TP} + N_{FN}. \quad (3)$$

Consequently, from Eqs.(1), (2), and (3), N_{call} can also be defined as

$$N_{call} = \frac{P}{R} N_{det} \quad (4)$$

P and R were determined by comparing automated detector/classifier output to manual analysis results from the 5% of data manually analyzed. The numbers of calls identified by the automated methods on all summer data were then adjusted by multiplying by P/R to estimate the number of calls a manual analyst would have been expected to produce for that same data.

2.2.4. Marine mammal acoustic distribution presentations

Marine mammal presence and distribution results are presented first for cetacean species and then pinnipeds species. Individual species ordering within these groups is by the abundance ranking of acoustic detections.

2.2.4.1. Winter detections. The acoustic detection distributions of bowhead, beluga and gray whales, walrus, and bearded seals for winter recordings are presented in multi-year occurrence plots showing the daily number of samples with manual detections (0–6) for each station through the full recording period. The 2007–2008 results are presented in a similar format but show only daily presence. Ringed seal acoustic occurrence plots are presented only for the 2009–2010 and 2010–2011 winter data. Detection results for less-commonly detected species, including minke whales, fin whales and ribbon seals are discussed, but occurrence plots are not given. Ice-concentration measurements from the [Ocean and Sea Ice Satellite Application Facility](http://www.osi-saf.org) (<http://www.osi-saf.org>) (Eastwood, 2011) are overlain on the occurrence and presence results.

2.2.4.2. Summer. Acoustic detections of bowhead, walrus, and bearded seals are presented as spatially-interpolated call-count isopleth plots for each of the three summer datasets. These plots were generated by summing the adjusted automated call counts for each recording station over its entire deployment period. Spatial interpolation of call count sums was performed using the radial basis interpolation method in the *griddata* function of IDL version 8.2.0 (Exelis Visual Information Solutions, Boulder, CO, USA). The anisotropy ratio was set to 1.29:1 in east–west to north–south directions, and the smoothing value was 21,893, which is the average east–west recorder separation in meters from all deployments. The anisotropical scaling applied here elongates interpolated features in the east–west direction relative to the north–south direction. Recorder spacing in the east–west direction was up to 130 km and uncertainties in call count interpolations are likely large at locations distant from real recorder locations.

Other species were sporadically detected both temporally and spatially. Call detection results for gray whales and killer whales are presented in bubble maps, showing the total number of sound files per deployment containing their calls at each recorder location.

3. Results

3.1. Performance of automated detectors

The performance of the automatic detectors varied between species, but precision was generally high and recall quite low. Bowhead, Walrus and Bearded Seal had precisions of 84%, 52%, and 65%,

respectively, but with corresponding recall of only 22%, 26% and 17%, respectively. The automated detector performance was lower than that of the manual analysts. This appears to be due to the analysts' ability to detect more calls with lower signal-to-noise ratios (between 0 and 5 dB) than the automatic detectors. Nevertheless, the automatic detectors provided adequate results for presence and distribution analysis.

3.2. Cetacean acoustic detections

3.2.1. Bowhead

Bowhead were acoustically detected in the Chukchi Sea from April until January, with peaks in occurrence from April to June and September to December coinciding with the spring and fall migrations, respectively. Acoustic detections were rare in late July and August of the study years, with two notable exceptions: bowhead calls were present on 9 August 2009 in the Klondike lease area, 140 km off Point Lay, and on 27 July 2010, 290 km north of Cape Lisburne. Bowhead calls were also detected between 8 and 36 km off Wainwright on 14, 30, and 31 August 2009 (Fig. 3).

Detections increased in late summer with the onset of the fall migrations. Detections started off Barrow, first offshore (> 55 km from shore) then inshore (< 36 km from shore), and subsequently occurred at stations further west. The detections occurred in pulses (Fig. 3), and although the timing of the first detections varied between years, the detection pulses showed some interannual consistency (Fig. 5). The first fall detections in 2007 occurred at the offshore Barrow stations on 23 September (Fig. 3). This first wave of detections lasted only 5 days before spreading inshore around 30 September. Sustained bowhead detections at the inshore stations started on 6 October and lasted until the recorders' retrievals on 19–26 October. Similarly, detections off Wainwright started offshore on 1 October, becoming consistent inshore on 7 October. The relative abundance and distribution of calls in 2007 suggest that most vocalizing fall-migrating bowhead followed the coast between Barrow and Wainwright (Fig. 4A). In 2009, bowhead detections started 10 September off Wainwright and Barrow. Two pulses of migrating bowhead were observed later on stations further west, off Cape Lisburne and Point Lay. The first pulse occurred between 23 and 26 September; the second started approximately 16 October (Fig. 3) and continued until the recorders' retrievals that ended 16 October (Fig. 3). In 2010 bowhead detections started earlier, around 20 August at the two offshore Barrow recording stations B35 and B50, but not until 6 September at the two inshore stations B5 and B15. Bowhead calls were detected off Wainwright on 13 September. The first migration pulse across the study area was observed 22–24 September. It was followed by two stronger pulses centered on 1 and 8 October (Fig. 3). The relative abundance and distribution of calls for the entire study area in 2009 (Fig. 4B) and 2010 (Fig. 4C)

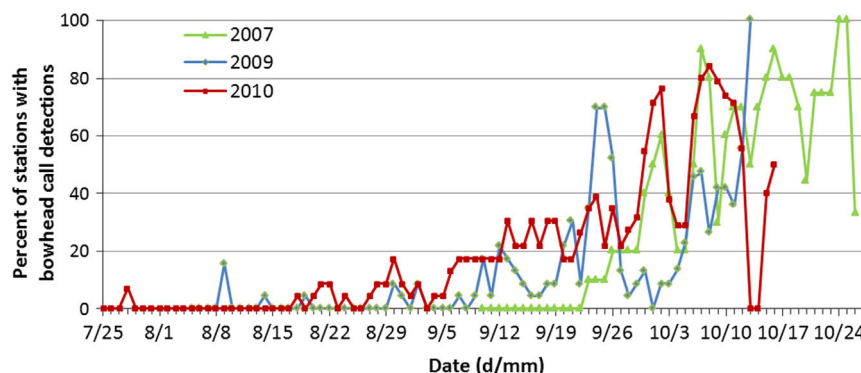


Fig. 3. Daily percentage of stations with bowhead whale call detections during the 2007, 2009, and 2010 summer deployments. The numbers of recorders with analyzed data were 10 in 2007, 23 in 2009, and 24 in 2010.

indicate that fall migrating bowhead left Barrow and headed in a west–southwest direction, thereby traveling roughly between 71 and 71.5°N.

Bowhead detections during the winter deployment recordings included calls from both the fall and spring migrations (Fig. 5). In fall 2008, 2009, and 2010, bowhead were typically first detected within 5 days of the deployments (mean deployment date: 13 October; Table 1) at all stations except CL50 and PL50, where the first detections occurred between late October and early November. The fall detections of bowhead on winter recorders in 2007 were comparatively delayed; these started between 7 and 9 November at all stations except PL50, where bowhead were detected immediately upon deployment, on 22 October.

Fall detections of bowhead ended first off Barrow, generally by the end of the first week of November, with the exception of B35 in 2008 (Fig. 5). In the central part of the study area (Wainwright and Point Lay stations, except PL50), the last detections occurred primarily during late November in 2008 and 2009 and in mid-December in 2007 and 2010 (Fig. 5). Bowhead calls were detected last at stations near the southwestern edge of the study area in all years; however, the last day of detection varied considerably. Bowhead calls were detected, on average, 29 days per station (range: 11–62) during their fall migration.

The first fall detections at most stations occurred in ice-free conditions. At some locations, increases in detections occurred synchronously with increases in ice concentration, with the last detection peaks coincident with the rapid approach of the ice edge. In 2007 and 2010, bowhead detections at some stations continued while ice concentrations approached 100% (Fig. 5).

Spring-migrating bowhead at offshore stations (all except B5) were typically first detected in the southwestern part of the study area with detections spreading progressively to stations further northeast. Although the first detections usually occurred in ice concentrations greater than 95%, the majority of detections coincided with lower concentrations. Bowhead calls were consistently detected between 13 April and 31 May, after which detections were more scattered and their occurrence decreased from June through July, although there was a resurgence of detections in the last two weeks of July 2011 north of Point Lay.

The addition of a winter recorder at station B5 in October 2009 provided improved measurement of the timing of the spring migration of the Beaufort–Chukchi–Bering (BCB) bowhead stock (Fig. 5). Because of the local lead configuration, a significant portion of the population is believed to pass through this area to enter the Beaufort Sea (Zeh et al., 1993). The earliest spring migration detections occurred in the final days of March in 2010

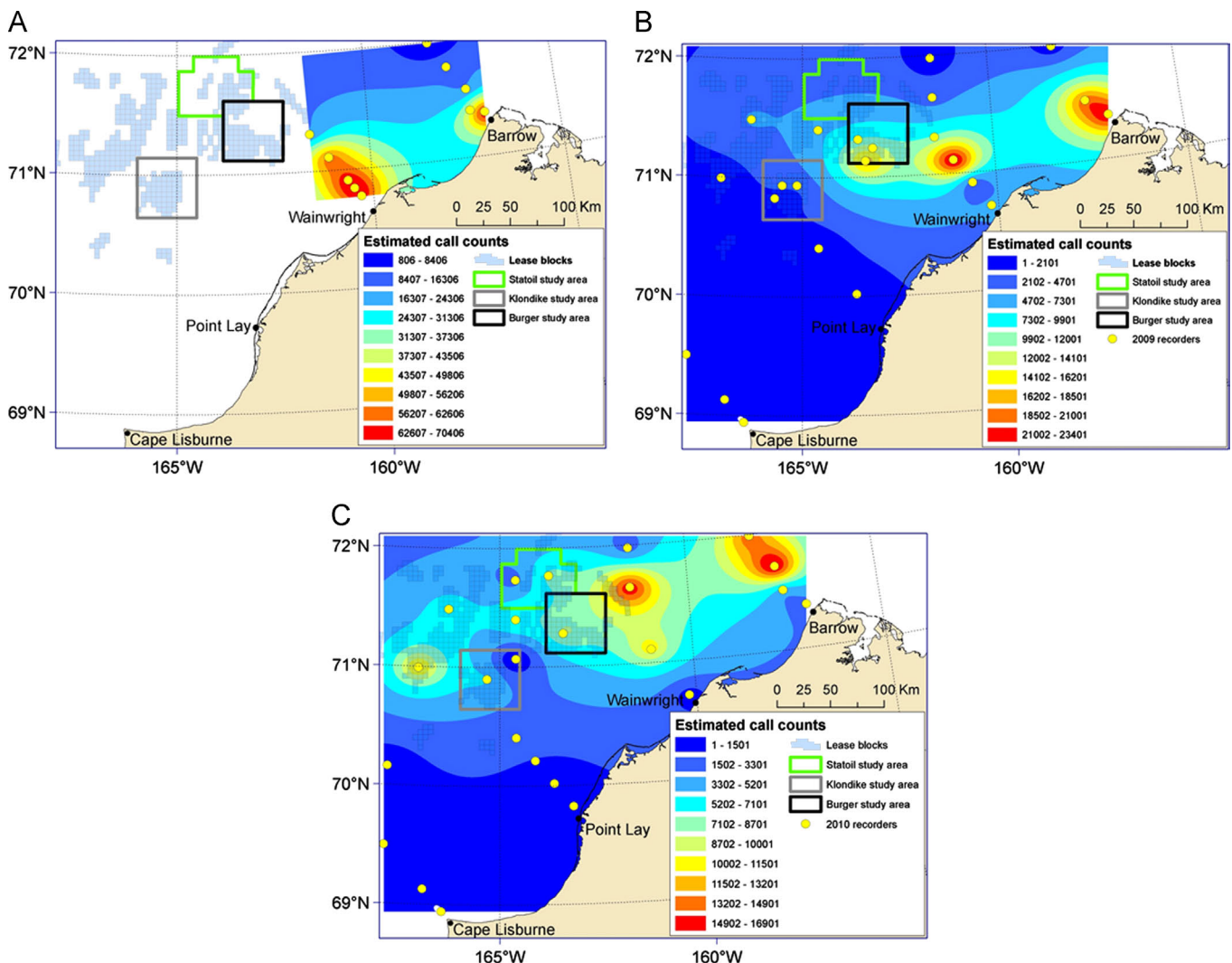


Fig. 4. Bowhead whale call-count isopleths from 10 September to 26 October 2007 (A), 5 August to 12 October 2009 (B) and 25 July to 12 October 2010 (C). Calls were automatically detected, with counts corrected using performance indices of the detector.

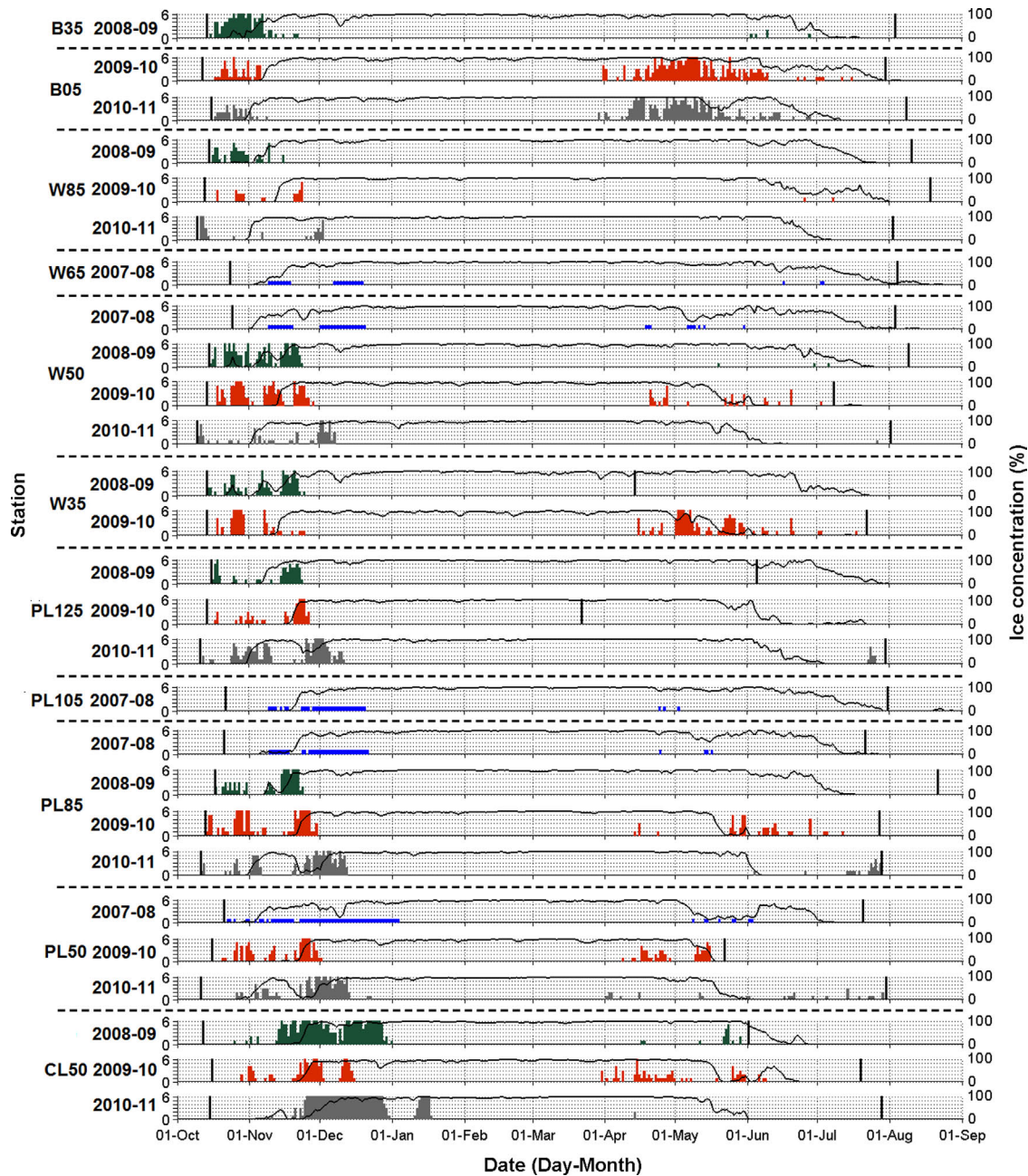


Fig. 5. Bowhead whale daily call presence per station during the 2007–2008 (blue), 2008–2009 (green), 2009–2010 (red), and 2010–2011 (gray) winter deployments. Recorder start and stop times are indicated by vertical black lines. Presence level is indicated by the number of manually reviewed 4-h sound file segments (up to 6 per day) containing bowhead calls (colored bars). Ice concentration is shown by the solid black lines. The 2007–2008 analysis did not follow the systematic approach applied afterwards.

and 2011 (Fig. 5). Most of the spring detections at B5 (65% in 2010, 74% in 2011) were concentrated between 13 April and 16 May, but calls were recorded almost daily until the second week of June and only three more detections occurred after 14 June in 2011. In 2010, bowhead calls were detected sporadically on eight occasions between 9 June and 15 July (Fig. 5).

In addition to the variation in timing, the number of spring migration detection days varied between years; there were 8 detection days at CL50 in 2009 and 36 in 2010; 0 in 2009 at PL85 and 22 in 2010. The number of detection days at B5 was consistently high, while those at the two stations farthest from shore (PL125 and W85) were consistently low or null. The number of detection days per station in the spring was negatively correlated with their distance from shore ($p < 0.001$). Spring-migrating

bowhead whales were detected, on average, 10 days per station in the study area (range: 0–41), excluding the Barrow stations B5 and B35, which had 67 and 61 detections days in 2010 and 2011, respectively.

3.2.2. Beluga

Beluga detections corresponded mainly with the spring and fall migrations events and were rare in summer deployment recordings (Fig. 6). During the 2007 summer deployment, beluga calls were detected on 6 days within 18 km of Barrow and on 6 days 27 and 65 km off Wainwright from 8 to 25 October. Beluga were detected at only three 2009 summer stations, two of them located off Barrow, between 14 September and 15 October. Beluga were detected three

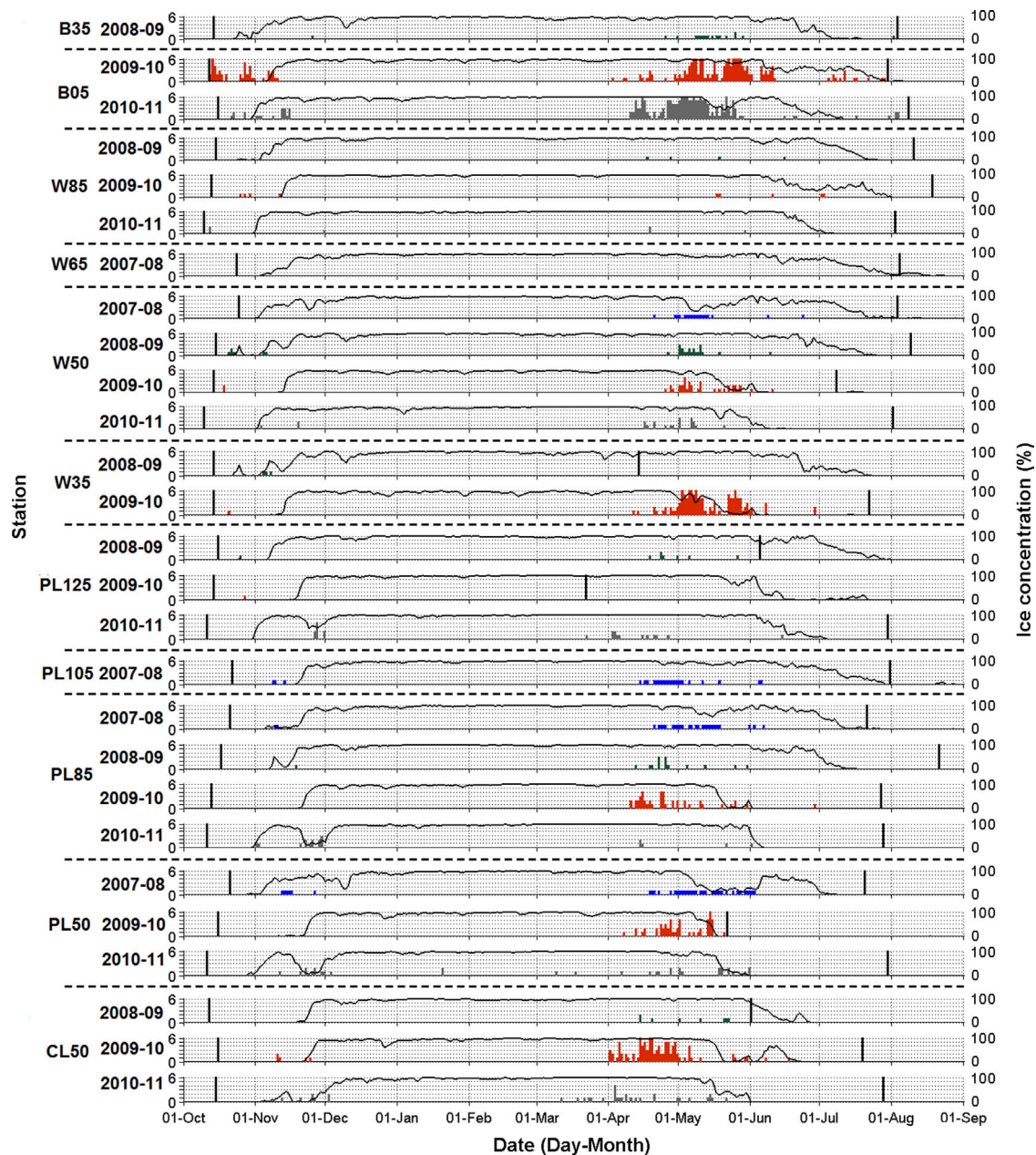


Fig. 6. Beluga whale daily call presence per station during the 2007–2008 (blue), 2008–2009 (green), 2009–2010 (red), and 2010–2011 (gray) winter deployments. Presence level is indicated by the number of manually reviewed 4-h sound file segments (up to 6 per day) containing beluga calls (colored bars). Recorder start and stop times are indicated by vertical black lines. Ice concentration is shown by the solid black lines. The 2007–2008 analysis did not follow the systematic approach applied afterwards.

times at Station W5 and on 10 different days between off Barrow in August 2010. A single isolated detection occurred near Barrow on 8 October 2010.

Fall detections in the winter recordings occurred as early as 12 October off Barrow and as late as 3 December 90 km off Point Lay (Fig. 6). Detections were usually isolated, occurring in short bouts of one or two days, but lasting up to five consecutive days. The fall 2009 detections off Barrow differed with three distinct detection peaks occurring between 12 October and 10 November, each lasting seven days and separated by 3–5 days. The 2010 detections off Barrow were less consistent than in 2009 but still were more concentrated than at other stations. Four of the twenty recorders deployed in total over the last three winter deployments did not detect beluga calls using our sampling protocol. The mean number of detection days in fall was 4.5 (range: 1–20) and 3.4 excluding the Barrow recorders (range: 1–8) at stations where beluga were detected.

No obvious relationship was apparent between acoustic detections and sea ice concentrations in the fall. Like bowhead, the first beluga detections usually occurred in ice-free conditions. The last detections sometimes coincided with, or occurred a few days prior to, rapid increases in sea ice associated with the progression of the ice edge (Fig. 6). Nevertheless, beluga calls were detected on 20 January 2011, 90 km off Point Lay, long after the area became ice-covered. The ice concentration at that time was above 95%.

Spring detections of beluga were far more numerous than fall detections. The mean number of spring detection days was 19 (range: 0–59). Only one station (W65 in 2008) did not record beluga calls in the spring. Calls were generally detected first in the southwest in early March and then progressively later at more northeast stations. Detections occurred regularly until the end of May at most stations, while most beluga detections afterwards were isolated events, with the exception of B5, at which more

persistent detections occurred. There were only seven beluga detections after 1 June 2011, occurring between 16 June and 3 August (Fig. 6). As for bowhead, the number of detection days of beluga was negatively correlated with distance from shore ($p < 0.001$). All spring detections started in ice with concentration over 95%. Detections continued as the ice receded but typically ended before ice completely disappeared (Fig. 6).

3.2.3. Gray whale

Summer detections of gray whales were sporadic but somewhat constrained in time and space (Fig. 7). Gray whales were not detected during the 2007 summer deployment. In 2009, detections occurred between 11 August and 10 October. Gray whales were detected on ten different days at five stations within 100 km of shore, but W05 alone accounted for seven of those detection days; the remainder of calls were detected on single days at the other four stations. Gray whale detections in summer 2010 were more constrained in time than in other years, occurring between 26 July and 31 August. However, 91% of the sound files containing gray whale calls occurred before 2 August, with 80% of these files from stations PL5–35, while the majority of detections in August occurred at stations CL50 and PL35.

Gray whale detections were rare in the winter deployment recordings. Gray whales were detected at W50 on three consecutive days in late July 2009, then once at PL50 and on four days at CL50 between mid-October and late November 2009.

3.2.4. Killer whale

Killer whale calls were detected during each summer deployment, with higher detection counts in the southwestern region of the study area (Fig. 8). Detections off Cape Lisburne, Point Lay and Wainwright represented 38%, 37%, and 25% of all detections, respectively. The 2007 summer deployment stations off Barrow had only four detection days, all in early October. Ten stations of the summer 2009 deployment had detections of killer whale calls on more than 5 days, with the Klondike area having the most detections, those occurring between 17 August and 2 October (Fig. 8). Killer whale calls were detected between 27 July and 25 September 2010 at 13 stations during the summer 2010 deployment. Several the stations within 100 km of shore (PL20, PL50, CL20, CL50, and W35) each had 4–6 detection days with calls present in approximately one-third of the recording files on those days. All the operating Cape Lisburne and Wainwright recorders had at least one killer whale detection in 2010, whereas only Point Lay recorders between 37 and 92 km from shore detected calls

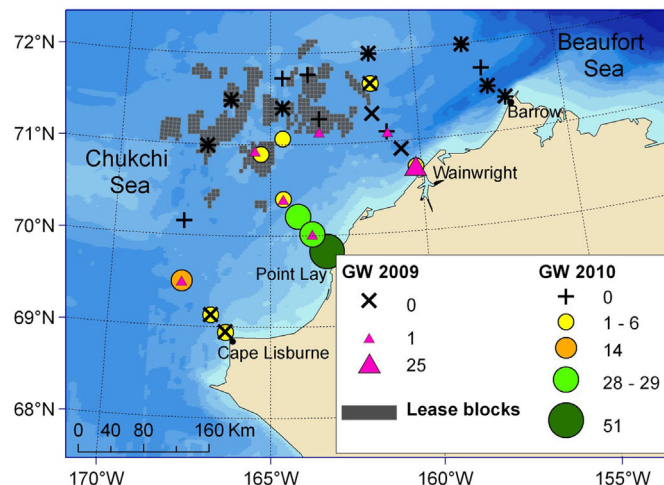


Fig. 7. Number of sound files with gray whale detections at all stations of the 2009 and 2010 summer deployments that were manually analyzed.

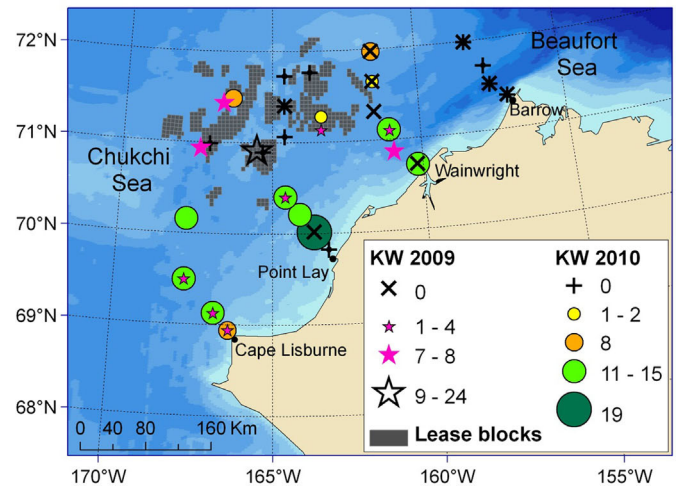


Fig. 8. Number of sound files with killer whale detections at all stations of the 2009 and 2010 summer deployments that were manually analyzed.

(Fig. 8). Most detection days in 2009 and 2010 occurred in September.

Killer whales were not detected in any of the winter deployment recordings.

3.2.5. Fin whale

Acoustic detections of fin whales in both 2009 and 2010 summer recordings were restricted to southwest stations CL50, CL125, and PL50. Detections occurred between 20 August and 5 September on 2–7 days per station in 2009. Detections occurred between 7 August and 3 October over 2–5 days per station in 2010. CL50 had the most detection days in both years.

Fin whales were not detected in any of the winter deployment recordings.

3.2.6. Humpback whale

Humpback whale calls were detected at CL50 on 7 and 17 August 2010. These were the first and only humpback acoustic detections during the summer and winter study periods discussed here.

3.2.7. Minke whale

Minke whale calls were detected on 31 October and 1 November 2009 at station CL50. These were the only minke whale acoustic detections during the summer and winter study periods discussed here.

3.3. Pinniped acoustic detections

3.3.1. Walrus

Walrus were the most abundant mammal species detected acoustically in July, August, and September in all study years. Stations averaged 28 detection days (range: 21–37; mean deployment duration: 41 d) in 2007, 33 detection days (range: 14–56; mean deployment duration: 65) in 2009, and 32 detection days in 2010 (range: 14–66; mean deployment duration: 73). In both 2009 and 2010, walrus were most widely distributed in the study area from mid-August to mid-September (Fig. 9). The fraction of stations with detections was typically lower outside of that period with the exception of a few detections in late September and early October. In 2007, detections continued off Barrow and Wainwright until 17 October.

Despite their broad distribution in the northeastern Chukchi Sea, large and consistent differences in walrus call detection counts

between stations suggest that walrus are not uniformly distributed in the study area. Walrus appear to show a strong affinity for the southern edge of Hanna Shoal and along a coastal band between Wainwright and Cape Lisburne (Fig. 10). Despite limited recorder coverage and relatively later recorder deployments in 2007 than in other years, the area south of Hanna Shoal also measured the highest 2007 call counts (Fig. 10A). In 2010, station PL05 recorded the most calls despite being second to W65 in terms of the number of detection days ($n=59$ vs. 66 respectively). Station PL05 was not

recovered in 2009, but PL20 (27 km away) also had many detection days that year ($n=43$). Station CL5, despite being farthest from walrus' prime foraging grounds on southern Hanna Shoal, had high detection-days in both 2009 and 2010 suggesting that large numbers of walrus migrate close to the shore of Cape Lisburne. The Klondike study area had consistently low call counts relative to the Burger study area which appeared to be at the edge (2009) or within (2010) the area favored by walrus.

Walrus acoustic detections over the entire study area decreased after mid-September in all study years.

The earliest spring detection of walrus calls occurred at station PL85 on 14 May 2011, but walrus typically were first detected in the second and third weeks of June, with the exception of the Barrow stations where detections were not made until the first half of July. Walrus were consistently detected at all stations after their arrivals. A steady migration of walrus toward the northeast and the Wainwright stations was apparent, with detections stopping first on the Cape Lisburne line and then on the Point Lay line. Walrus call detections continued on Wainwright stations through the end of the winter deployment recording periods, as late as mid-August (Figs. 11 and 12). While the first bowhead and beluga call detections occurred before ice concentrations decreased from their winter maxima, the first walrus detections consistently occurred when ice concentrations had started to decrease. Based

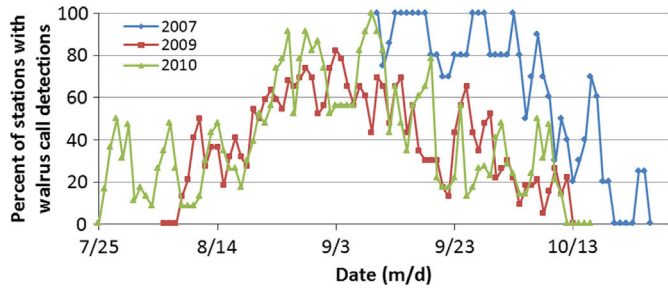


Fig. 9. Daily percentage of stations with walrus call detections during the 2007, 2009, and 2010 summer deployments. The number of recorders with analyzed data was 10 in 2007, 23 in 2009, and 24 in 2010.

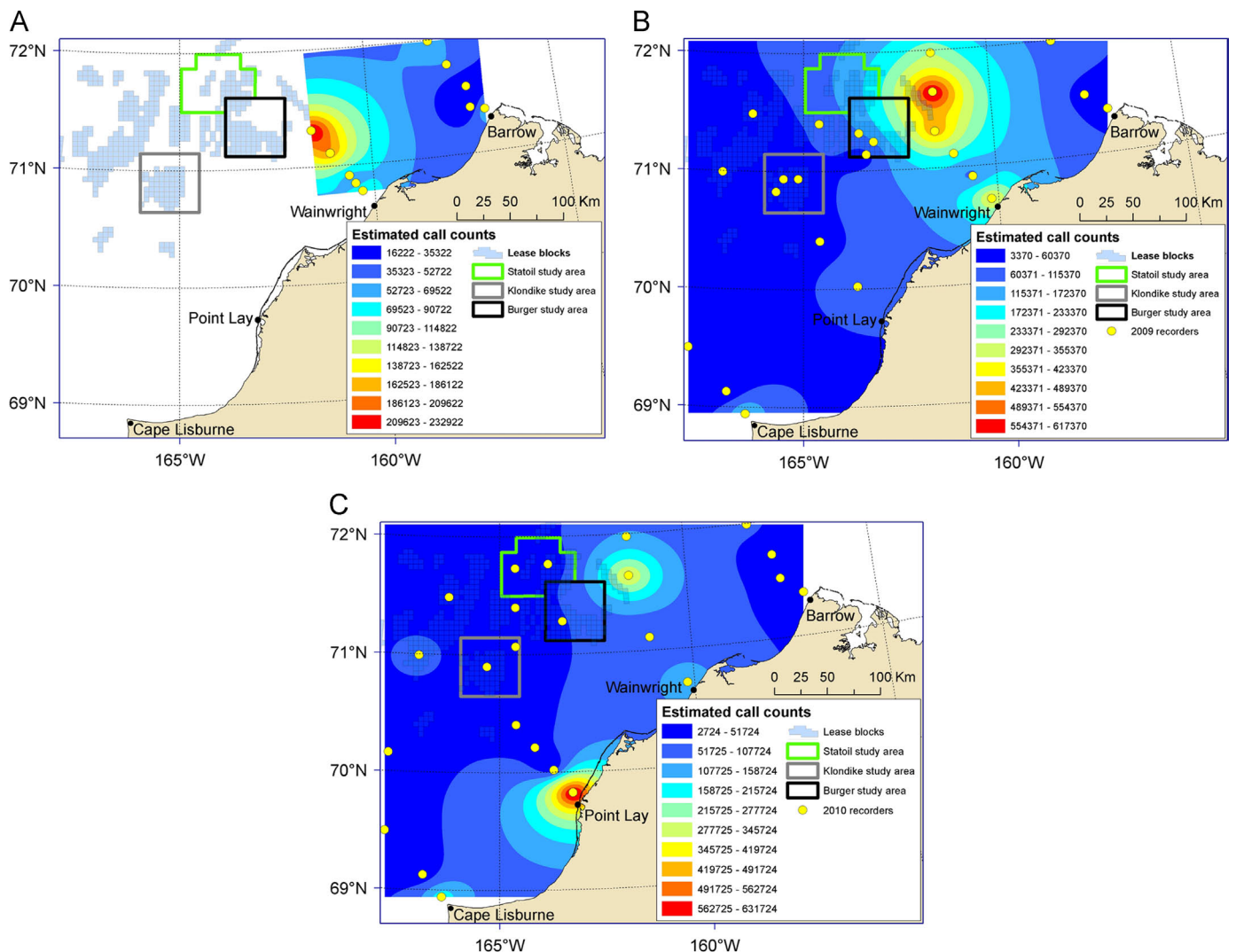


Fig. 10. Walrus call-count isopleths from 10 September to 26 October 2007 (A), 5 August to 12 October 2009 (B) and 25 July to 12 October 2010 (C). Calls were automatically detected, with counts corrected using performance indices of the detector.

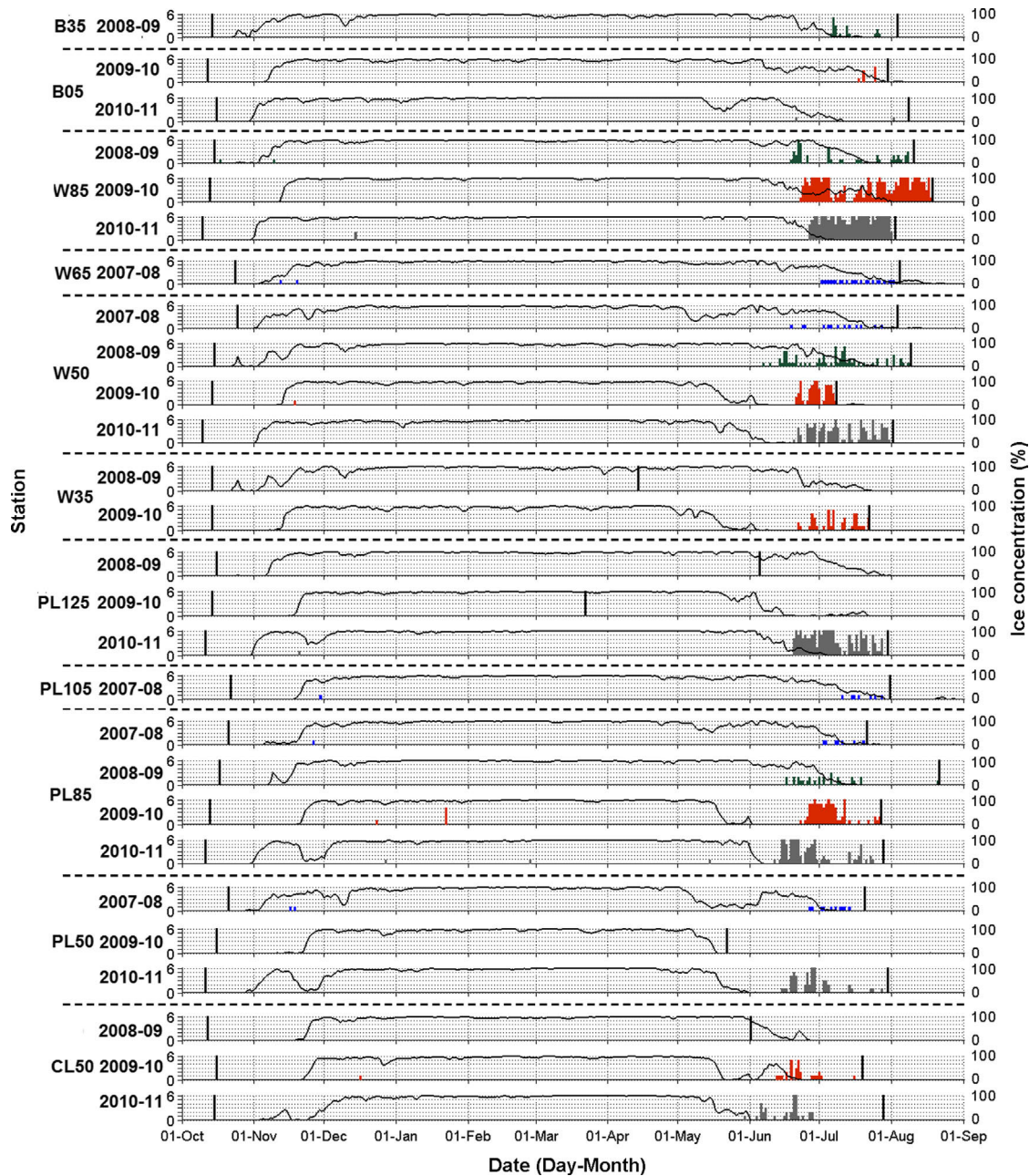


Fig. 11. Walrus daily call presence per station during the 2007–2008 (blue), 2008–2009 (green), 2009–2010 (red), and 2010–2011 (gray) winter deployments. Presence level is indicated by the number of manually reviewed 4-h sound file segments (up to 6 per day) containing walrus calls (colored bars). Recorder start and stop times are indicated by vertical black lines. Ice concentration is shown by the solid black lines. The 2007–2008 analysis did not follow the systematic approach applied afterwards.

on these call detection results, the main period of walrus presence in the northeastern Chukchi Sea is from mid-June to the end of September.

3.3.2. Bearded seal

Summer bearded seal detection timing was characterized by a phase of sporadic call detections from the recorder deployments (late July–early August) through early September. These detections represented 6.4% and 10.8% of all summer detections in 2009 and 2010, respectively. In 2009, these early detections were concentrated off Wainwright, but in 2010 they were more dispersed. The second phase started mid-September and was characterized by a gradual increase in call detection rates (Fig. 13). The 2007 increase was relatively delayed, starting the first week of October. In 2009

and 2010, the second phase of bearded seal detections started in the northeastern part of the study area and spread southwest. The call-count isopleths indicate that vocalizing bearded seal presence varied between study years but highest counts occurred at stations on the Wainwright and Barrow in 2007, with fewer detections further offshore that year (Fig. 14A). The call count maximum in 2009 occurred at station W5 just 8 km off Wainwright (Fig. 14B) whereas the highest call counts in 2010 occurred at stations more than 30 km offshore (Fig. 14C).

Temporal variations of bearded seal acoustic detections between different years at the same stations were for the most part small (Fig. 15). Detections were somewhat sporadic in October and November at all winter deployment stations. Call detection rates increased in December and calls were detected regularly

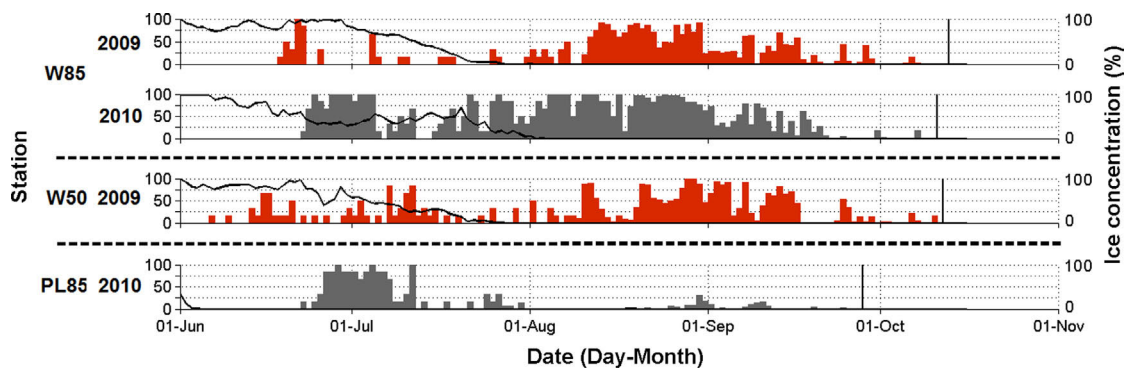


Fig. 12. Walrus daily call presence per station during summer 2009 (red) and 2010 (gray) at W85, W50, and PL85 as indicated by the percent of manually reviewed file segments per day containing walrus calls. Recorder stop times are indicated by vertical black lines. These stations had uninterrupted monitoring throughout the spring and summer 2009 and 2010. Ice in percentage concentration is shown by the solid black lines.

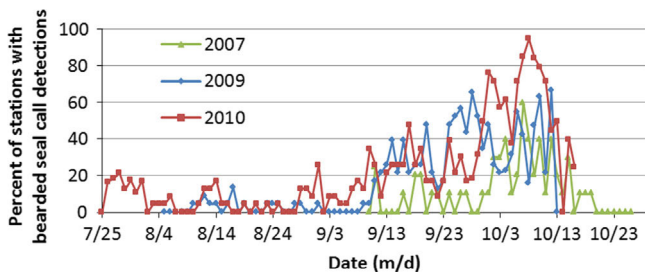


Fig. 13. Daily percentage of stations with bearded seal call detections during the 2007, 2009, and 2010 summer deployments. The numbers of recorders with analyzed data were 10 in 2007, 23 in 2009, and 24 in 2010.

from early January through February. The 2008–2009 and 2010–2011 detection results at station CL50 differed from the other stations, as regular detections there did not start until early March in 2008–2009 and early February 2009–2010. Bearded seal calls were detected in every acoustic file of all recording stations starting in late April or early May. This period of high vocal activity ended abruptly, with call detection rates diminishing from maximum to near-zero over approximately one week, starting on dates between 22 June and 6 July, except at station CL50 in 2011 where the reduction started on June 16. Only a few isolated calls were detected thereafter (Fig. 15).

The end of the detection period occurred later at the north-eastern stations. Ice presence did not appear to influence the timing of the end of the period of high vocal activity. In several instances, calling continued even when ice concentrations had decreased below 10%.

3.3.3. Ringed seal

Ringed seal call detection analysis was performed on data collected in the 2009–2010 winter, 2010 summer, and 2010–2011 winter datasets. Ringed seals were detected at eight stations (out of 24 analyzed) during summer 2010. The number of detection-days at each station was low (1–4), with the highest number at station B30. Detections occurred from 27 July to 8 October 2010 and detection rates, though very low, were uniform over the deployment period.

During the 2009–2010 winter deployment, ringed seal calls were detected intermittently at all stations and through most of that recording period, although detections decreased considerably in June and were absent in July (Fig. 16). The first detection occurred on 31 October 2009 at station PL50 and the last occurred on 9 June 2010 at station W85. The maximum number of detection days was 25 at station CL50. No obvious peak in calling rates was

apparent. Ringed seal call detections were substantially lower in winter 2010–2011 than in winter 2009–2010. Detections occurred at least once at each station and were concentrated between November 2010 and early February 2011. There were only three detections between mid-February 2011 and the end of the deployment (26 July–6 August, 2011).

3.3.4. Ribbon seal

Ribbon seal call detections in summer were extremely rare. Only three summer detections occurred: on 29 September 2009 at W50, on 12 October 2009 at B5, and on 11 October 2010 at CL155. Ribbon seal detections in winter deployment recordings were constrained to a short period between October and November. In 2008, calls were detected at six of seven stations between 19 October and 10 November for 2–10 days per station. In 2009, ribbon seals were detected on four days between 28 October and 16 November at CL50. They were not detected in fall 2007 or fall 2010.

4. Discussion

4.1. Cetaceans

4.1.1. Bowhead

Bowhead calls were detected regularly from September until December during their fall migration, and from April until June during their spring migration, consistent with known migration periods for this species (Braham et al., 1980; Quakenbush et al., 2010; Citta et al., 2012). The low numbers of detections in July and August is likely representative of reduced presence, but may also be due to bowhead's low calling rate in those months (e.g. Würsig and Clark, 1993). Higher noise from anthropogenic noise from oil and gas exploration activities may also produce localized reductions in call detections as it obscures calls in the acoustic recordings (Guerra et al., 2011). However, we would expect the effects of exploration noise on bowhead detections to be limited to regions near the activities, while bowhead call detections in July and August were generally low throughout the study area. Low acoustic presence contrasts with historical records of numerous whaling takes in the Chukchi Sea in July and August (e.g. Dahlheim et al., 1980). The small number of acoustic detections nonetheless is consistent with low numbers of recent visual sightings in these months (Miller et al., 1986; Clarke and Ferguson, 2010; Ireland et al., 2009; Aerts et al., 2013).

There were several notable summer detections, including the ones that occurred on 28 July 2010 at CL155. A satellite-tagged bowhead was tracked as it traveled from the Beaufort Sea to the Chukotka coast between 19 July and 2 August 2010. This whale passed approximately 20 km away from CL155 on 24 July (J. Citta,

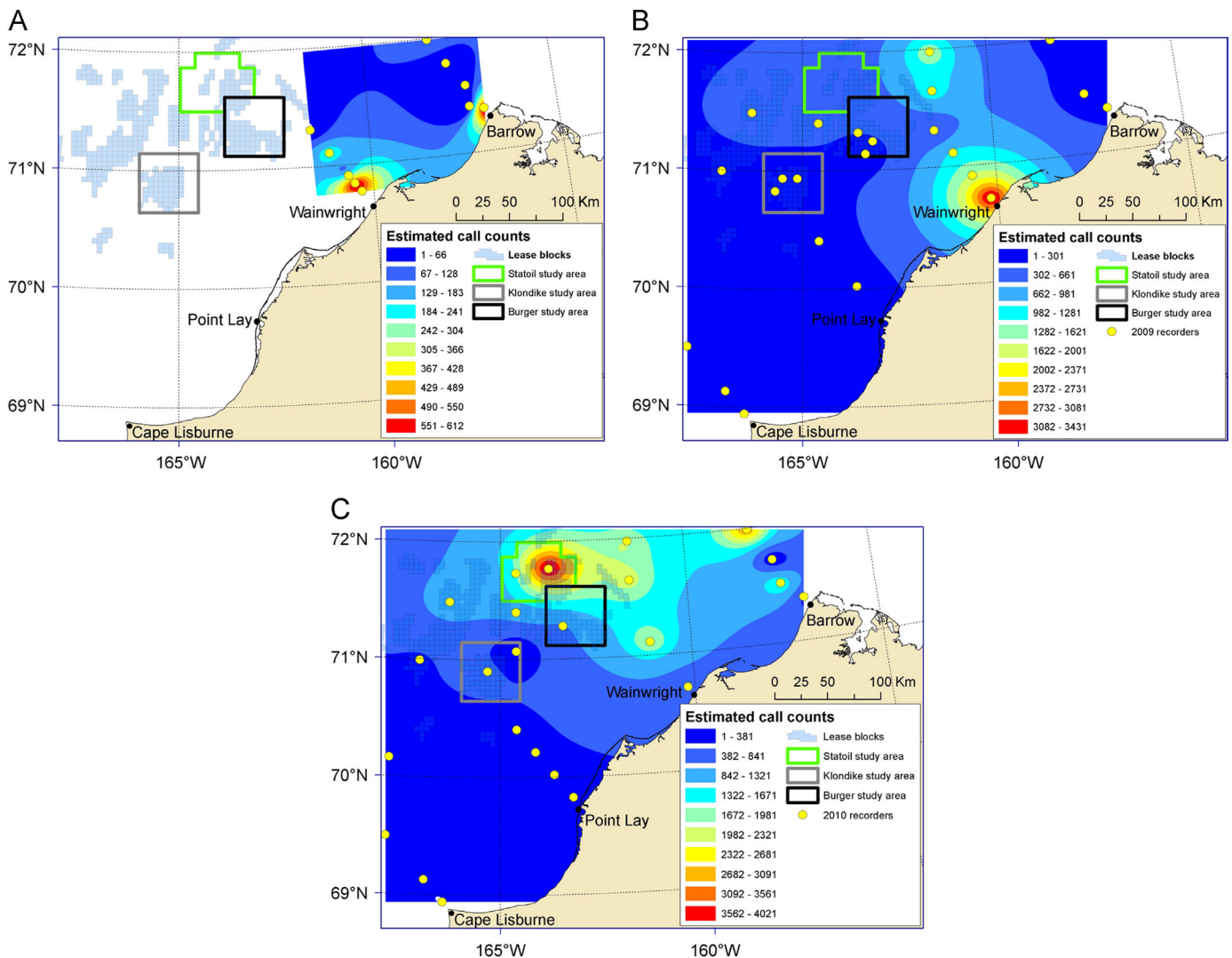


Fig. 14. Bearded seal call-count isopleths from 10 September to 26 October 2007 (A), 5 August to 12 October 2009 (B) and 25 July to 12 October 2010 (C). Calls were automatically detected, with counts corrected using performance indices of the detector.

Alaska Department of Fish and Game, Fairbanks, AK, pers. comm.). While there were no acoustic detections during the day of that whale's passage near CL155, several bowhead calls were detected at that station on 28 July 2010. The close spatial and temporal presence of the tagged whale and the acoustically-detected whales in late July, far from the normal summer feeding areas in the Beaufort Sea, could suggest multiple animals returned west well in advance of the normal fall migration. The isolated detections on 8 August 2009 in the Klondike study area may have been produced by whales migrating west ahead of the typical fall schedule, possibly suggesting that this could be a recurring pattern for a portion of the Beaufort–Chukchi–Bering (BCB) bowhead stock. In contrast, the recurring detections at station PL85 (35 km from the Klondike study area), through late July in 2011 and until 8 August in 2012, suggest bowhead may have been foraging in that part of the study area. This might be, consistent with the notion of a growing population (George et al., 2004), expanding back into historical habitat (Burns, 1993).

Winter deployment detections also indicate bowhead presence after the normal spring migration period, but detections after the end of June in these data were limited; only four winter recorder detections occurred after 7 July 2011, including two off Barrow. The late June and early July detections in the winter data likely represent late spring migrants, a hypothesis supported by sporadic

detections continuing off Barrow until 15 July. However, these detections may also be from whales returning from the Beaufort to forage in the Chukchi Sea. Recent satellite tracking of a bowhead showed it returned to the Chukchi Sea from the eastern Beaufort in late June 2012 (J. Citta, pers. comm.).

Bowhead were repeatedly detected 55–90 km north of Barrow after 18 August 2010 but no other stations detected bowhead until 7 September. These detections may represent offshore feeding whales, such as those observed in Barrow Canyon in late August and early September 2005 and 2006 (Moore et al., 2010). They are also consistent with the paths of migrating bowhead equipped with satellite tags during the early part of the fall migration (J. Citta, pers. comm.). Overall, these detections confirm the importance of the Barrow area for bowhead whales in August and September (Quakenbush et al., 2010).

Detections increased in the study area in September with the onset of the fall migration in all three summer periods. The first detections usually occurred at the offshore Barrow stations 1–2 weeks earlier than at the inshore Barrow station. Detections then progressed westward throughout the rest of the study area starting in late September or early October. Pronounced interannual variations were observed in the onset of bowhead acoustic detections associated with the fall migration. The first 2007 fall detections occurred a month later than the first detections in 2009

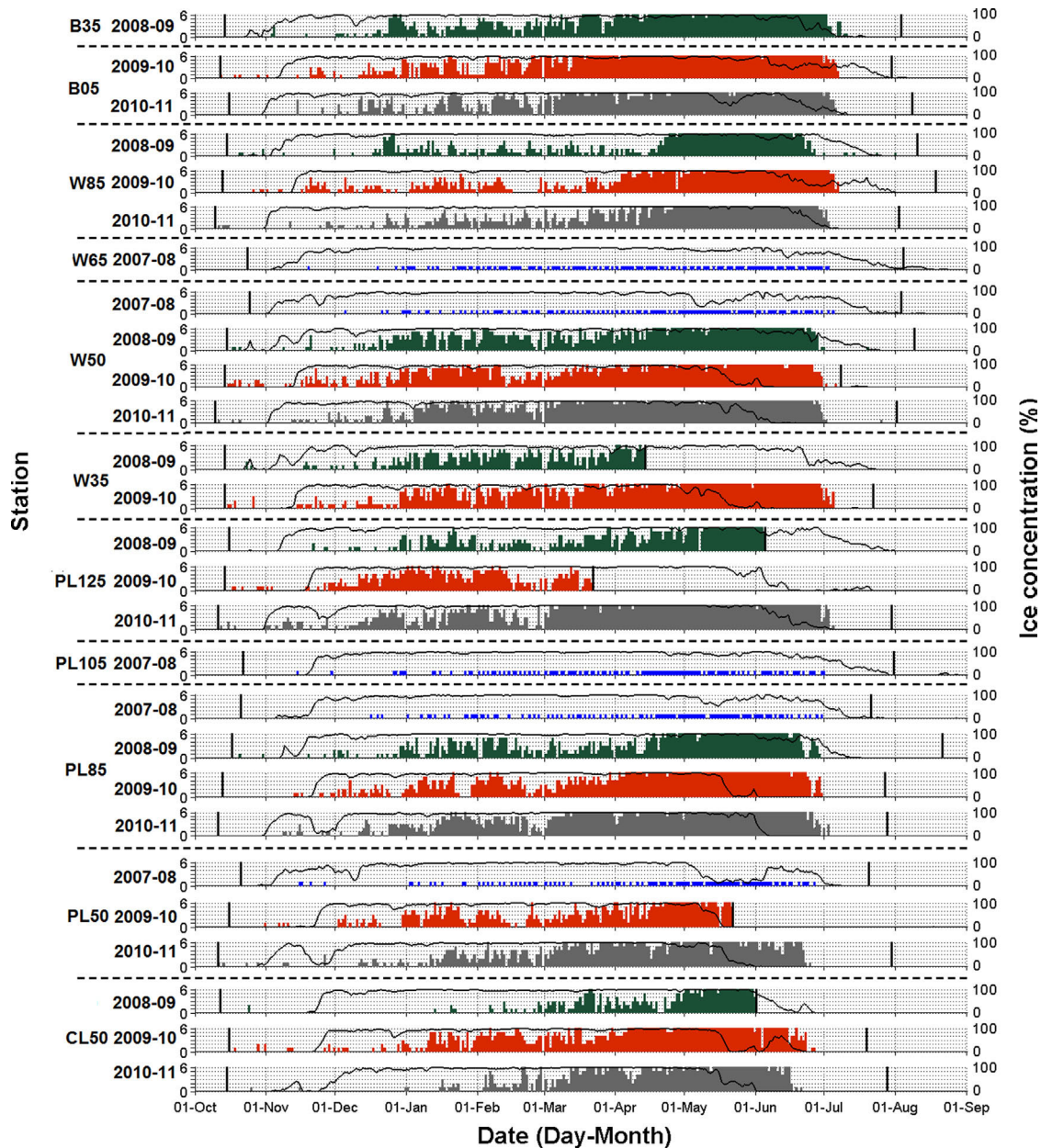


Fig. 15. Bearded seal call presence per station during the 2007–2008, 2008–2009, 2009–2010, and 2010–2011 winter deployments. Presence level is indicated by number of manually reviewed 4-hour sound file segments (up to 6 per day) containing bearded seal calls (colored bars). Recorder start and stop times are indicated by vertical black lines. Ice concentration is shown by the solid black lines. The 2007–2008 analysis did not follow the systematic approach applied afterwards.

and 2010. The summer of 2007 was characterized by record low ice conditions in the Arctic (Stroeve et al., 2008) and late return of sea ice may have delayed the onset of the migration. Whalers from Barrow report that “the migration tends to occur later in years with little or no ice than in years with heavy ice” (Huntington and Quakenbush, 2009).

The fall 2007 data (winter deployment) differed from other study years. Call detections at stations PL85, PL105, W50, and W65 in the central part of the study area started 9 November, at least three weeks later than in 2009 and 2010 at PL85 and W50. This was not the case at PL50 where detections started between 20 and 26 October in 2007, 2009, and 2010. The lack of detections in the central part of the study area coincided with a seismic survey conducted in the Burger study area between stations W50 and PL105 from 21 October to 4 November 2007. Blackwell et al. (2007, 2013) showed bowhead acoustic reactions to airgun sounds during the fall migration in the Beaufort Sea. A statistically significant

decrease in acoustic detections of bowhead calls occurred when airgun sound exposure level (SEL) in a 10 min period reached ~ 126 dB re $1 \mu\text{Pa}^2 \text{s}$ (Blackwell S., Greeneridge Sciences Inc., Goleta, CA, USA, pers. comm.). Calling behavior changes, physical displacement, or potential masking by airgun sounds (Guerra et al., 2011) could explain the lack of detections by the four recorders (PL85, PL105, W50, and W65) in 2007.

Acoustic detections revealed the presence of bowhead whales in the northeastern Chukchi later in fall and winter than previously believed. Bowhead were present off Cape Lisburne and Point Lay until the end of December in three of four study years and until mid-January in 2011. The spatial distribution of call detections indicates that the fall migration corridor passes through the oil and gas lease areas, as also shown by Quakenbush et al. (2010). The Klondike study area lies on the southern edge of the corridor whereas the Burger study area appeared to be near its axis. The northern edge of the corridor is not well defined, but it

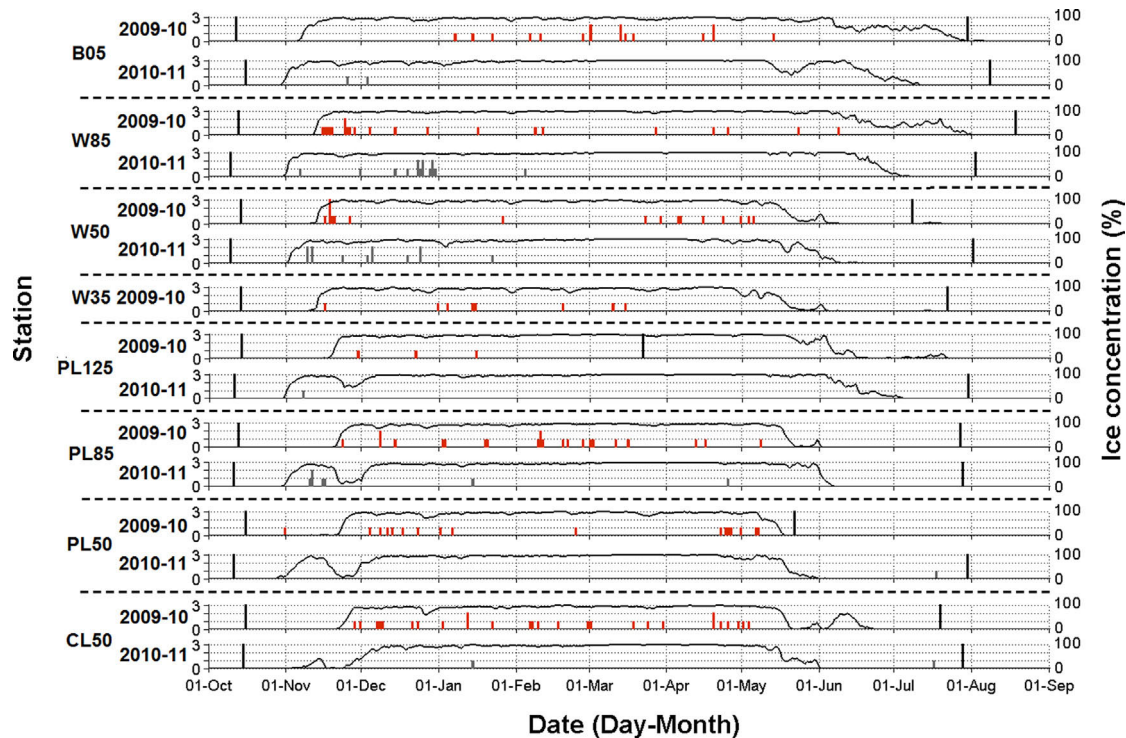


Fig. 16. Ringed seal daily call presence per station during the 2009–2010 (red) and 2010–2011 (gray) winter deployments. Presence level is indicated by the number of manually reviewed 4-h sound file segments (up to 6 per day possible but maximum observed was 3) containing ringed seal calls. Recorder start and stop times are indicated by vertical black lines. Ice concentration in percent is shown by the solid black lines.

extends to at least 72°N and includes the Statoil survey area. Bowhead calls were detected in the lease areas until at least late November and in some years to mid-December.

Two fall migration routes have been proposed for the BCB stock, based on aerial survey sightings: a northern route across the Chukchi Sea toward Herald and Wrangle Islands, and a southwesterly route by which bowhead transit toward Herald Shoal and the northern Chukotka coast (Moore and Reeves, 1993). The latter corresponds to the migration corridor identified in this study, whose acoustic core appears to vary annually. The importance of the northern route and the proportion of BCB bowhead using it remain unknown at this time. The northern route has been identified by tracks of bowhead equipped with satellite tags between 2006 and 2008 (Quakenbush et al., 2010), but that route is outside the present acoustic study area. The addition of six new acoustic recording stations on the northern side of Hanna Shoal between August 2011 and August 2012 should allow an assessment of the relative proportion of whales migrating north of the main corridor. The earliest spring acoustic detection on 29 March at station B5 matches the earliest Barrow sighting reported (Braham et al., 1980). Barrow whalers have described three distinct pulses of whales (Huntington and Quakenbush, 2009), but this was not obvious in the acoustic detection record. Many calls were recorded at 185 km from shore on station PL125 indicating that not all of the population within the nearshore leads that form every spring between Cape Lisburne and Barrow (Moore and DeMaster, 1998; Braham et al., 1980; Moore and Reeves, 1993).

4.1.2. Beluga

Beluga were detected acoustically from mid-July until the end of August 2007 almost exclusively off Barrow, and primarily within Barrow Canyon. This is consistent with satellite tagging data showing that eastern Chukchi Sea (ECS) beluga typically transit through Barrow Canyon and sometimes forage therein after leaving Kasegaluk

Lagoon, where they aggregate from mid-June to mid-July (Suydam et al., 2001, 2005).

The large difference in the number of detection days between fall and spring is attributed to differences in the migratory routes of the two beluga stocks known to transit through the Chukchi Sea. Eastern Beaufort Sea (EBS) beluga do not appear to migrate in large numbers through the study area during fall migration; instead, they seem to travel further offshore along the shelf edge bordering northern Alaska toward Wrangel Island (Richard et al., 2001). The almost complete absence of detections in September, when EBS migration is expected, suggests that migration does not pass through the study area. The acoustic detections from October to late November coincide with the migration schedule of ECS beluga (Suydam et al., 2001, 2005). Thus, only the smaller of the two stocks ($n_{min}=3710$; Small and DeMaster, 1995) may transit through the central northeastern Chukchi Sea in fall, and this could explain the smaller number of fall detections than spring detections.

Another possible explanation for relatively low beluga call detections in fall is that the migration occurs inshore of the acoustic stations. Most winter recorders were deployed more than 90 km from shore to avoid damage from ice in shallower waters closer to shore; station B5 at 8 km from shore in deeper water is the only exception. On 5 October 2011, a group of approximately 1000 beluga was sighted off Wainwright traveling south along the shore (J. Burns, pers. comm.). Although this appears to be an unusual event, it does indicate that migration can occur well inshore of the acoustic stations, and such animals would not be acoustically detected.

A final possible explanation for low beluga call detection counts in fall is that they may have reduced vocalization rates at that time of year relative to springtime and summer. Reduced vocalizations may be a mechanism to avoid detection by killer whales, a known predator of beluga (e.g. George and Suydam, 1998).

Beluga detections were much more common in the spring. Large differences in the number of detection days between years are attributed to variations in migration routes due to differing ice conditions. Spring migrating beluga are commonly observed with bowhead in nearshore leads that form in the spring between Cape Lisburne and Point Barrow (Moore and DeMaster, 1998), a pattern that is consistent with the generally lower beluga detection-days for recorders more distant from shore. Ice conditions influence beluga migration routes and timing (Richard et al., 2001). In 2011, beluga were first detected four weeks earlier than in previous years, at the southern end of the study area and at station PL125, 185 km from shore. The early detections may have been due to the early ice retreat in 2011.

Whether the ECS and EBS beluga have different spring migration timing remains unclear. The main detection period at station B5, in April and May 2010, was followed by a 22-day gap in detections from 11 June to 4 July before continuing to 28 July. The end of the detections on 11 June may have marked the end of the passage of EBS beluga. These animals continue east toward the Eastern Beaufort Sea and the Mackenzie River estuary where they start aggregating in late June (Norton and Harwood, 1986). The detections starting on 4 July could be ECS animals traveling toward Barrow Canyon or farther north after leaving Kasegaluk Lagoon (Suydam et al., 2001, 2005).

4.1.3. Gray whale

Gray whale acoustic detections occurred between late July and late October. However, acoustic detections were low considering the high relative abundance of gray whales in the northeastern Chukchi Sea. Gray whales are indeed the most commonly sighted cetacean species there in summer (Clarke and Ferguson, 2010; Ireland et al., 2009; Aerts et al., 2013). The trend of decreasing acoustic detections with increasing distance from shore is consistent with the visual sightings distribution (Clarke and Ferguson, 2010; Aerts et al., 2013). Peard Bay, southwest of Barrow, was not sampled by the current acoustic programs but it is an important area for gray whales (Clarke and Ferguson, 2010). The waters surrounding Hanna Shoal also had numerous visual sightings in the 1980s, but not in 2008 or 2009 (Clarke and Ferguson, 2010). Gray whale acoustic detections were low in that area relative to the historic sightings, but were consistent with the more recent sighting data. Gray whale acoustic detections were low in the lease areas.

The discrepancy between the paucity of gray whale acoustic detections and the substantial number of sightings is puzzling, but may be reflective of low calling rates combined with the masking of very low-frequency gray whale moans by ambient noise and recorder self-noise. In 2011, a lowering of the noise floor of the recorders used for the monitoring program made the detection of the most common call type (low-frequency moan; Crane and Lashkari, 1996) easier. The pattern of gray whale detections in 2011 (i.e., widely distributed but most abundant inshore between Icy Cape and Barrow, with higher-than-average detections on the southern edge of Hanna Shoal) more closely coincides with the latest information on gray whale distribution based on aerial surveys (Clarke and Ferguson, 2010). Nevertheless, the results presented in this study likely underestimate the occurrence of gray whales in the northeastern Chukchi Sea.

4.1.4. Killer whale

Killer whales were detected sporadically in the northeastern Chukchi Sea every summer of this study between late July and October, mainly off Cape Lisburne and Point Lay. Other authors have noted killer whales' occasional presence in the Chukchi Sea (George and Suydam, 1998). The small number of acoustic detections is likely

due to low vocalization rates. The calls detected here are from transient killer whales (Delarue et al., 2010). Transient killer whales produce significantly fewer calls than resident killer whales, so as not to alert potential prey of their presence, although calling rates increase notably after a kill (Deecke et al., 2005).

Based on satellite telemetry studies, it appears that at least some of the killer whales recorded in the study area travel from as far south as the Aleutian Islands (C. Matkin, North Gulf Oceanic Society, Homer, AK, pers. comm.). The transient killer whale population in western Alaska and the eastern Aleutian Islands area has been estimated at 251 individuals (95% CI: 81–488; Zerbini et al., 2007). Killer whale abundance in the northeastern Chukchi Sea is presumably only a fraction of that number. The low number of killer whales in the Chukchi is consistent with the absence of sightings from several aerial surveys conducted between 1981 and 1991 and in 2008 and 2009 (Clarke and Ferguson, 2010), and the small numbers of sightings during vessel surveys conducted during 2006–2010 (Ireland et al., 2009; Brueggeman 2009; Aerts et al., 2013).

4.1.5. Fin whale

Fin whale acoustic detections occurred in the summers of 2007, 2009, and 2010 (Delarue et al., 2013a). The spatial distribution of fin whale detections in the 2007 acoustic data was similar to the 2009 and 2010 distributions, but the number of detections was more than an order of magnitude higher. The unusually high numbers in 2007 could be attributed to very early ice retreat and increased prey availability that year. Fin whale detections occurred almost exclusively at stations off Cape Lisburne with the remaining detections at station PL50. Infrequent detections in 2009 and 2010 are consistent with the overall scarcity of sightings in the study area in those years. After the resumption of regular boat and aerial surveys in 2006, fin whales have been sighted only three times, all in 2008 (Clarke and Ferguson, 2010; Ireland et al., 2009); however, most of the boat surveys since 2008 were conducted outside the areas where the acoustic detections occurred (Aerts et al., 2013).

4.1.6. Humpback whale

Only two acoustic detections of humpback whales occurred during this study. Three sightings were made in 2007, one in 2008 (Ireland et al., 2009), one in 2009 (Clarke and Ferguson, 2010), and three in 2010 (Aerts et al., 2013), suggesting that humpback are quite rare but recurring annual visitors to the northeastern Chukchi Sea. Low density and low calling rate may both contribute to the paucity of acoustic detections.

4.1.7. Minke whale

A single acoustic detection of multiple minke whales occurred in fall 2009 (Delarue et al., 2013b). There were only three summer detections, all in 2011. Several vessel-based visual observations occurred during the same period (Ireland et al., 2009; Aerts et al., 2013). Like humpbacks, the scarcity of acoustic detections is likely due to low calling rates combined with low densities (Delarue et al., 2013b). Since only a fraction of the data were manually analyzed, there were likely more calls present but missed.

4.2. Pinnipeds

4.2.1. Walrus

The acoustic detection results for walrus are thought to accurately represent walrus occurrence in the northeastern Chukchi Sea because of the high rates of vocal activity of this species. The consensus between walrus distributions derived from tagging data (Jay et al., 2012) and our acoustic detections, suggests it is

reasonable to assume that call counts can be used as an index for relative walrus abundance.

Acoustic detections of walrus generally started in mid-June as walrus followed retreating ice out of the Bering Sea and into the northeastern Chukchi Sea (Jay et al., 2012). The initial call detection distribution in June and July is evenly spread over the southwestern and central parts of the study area. Detections become more focused on the south side of Hanna Shoal toward the end of July, and a large fraction of the acoustic detections in August occur there. Walrus appear to use this area as their main foraging site in August as ice generally persists longer over the shoal than elsewhere; the ice is used by walrus as a haul-out platform from which they can feed efficiently (Jay et al., 2012). High numbers of acoustic detections persist for a few days even after ice retreats away from the shoal, generally in the last week of August. A group of walrus ($n=143$) was observed south of Hanna Shoal during a 24 h period on 24 August 2007 when ice was approximately 100 km away (Reiser et al., 2009).

The timing of walrus departures from Hanna Shoal, and their destinations after leaving, appear to depend on the timing of ice retreat. Walrus initially spread out widely upon leaving the shoal. In early ice-retreat years, such as 2007, 2010, and 2011, large numbers of walrus have moved to on-shore haul-outs that formed in early September along a coastal band between Wainwright and Cape Lisburne (Jay et al., 2012). Large haul-outs formed near Point Lay in September 2010 and September 2011 of 10,000–50,000 individuals (Garlich-Miller et al., 2011). The very high 2010 call detection counts at station PL5 – just 8 km away – are attributed to animals associated with that haul-out.

Large on-shore haul-outs have not been observed in years when ice persists on Hanna Shoal through the end of August, such as in 2008 and 2009. The 2009 acoustic detections became dispersed through much of the southwestern study area in early September at the same time that detections on the south Hanna Shoal stations decreased. These animals likely then continued their migration directly into the Bering Sea without going to major on-shore haul-outs.

The relatively high number of walrus acoustic detections at Station CL5 may be associated with the presence of a nearby haul-out and by walrus simply migrating out of the Chukchi Sea in the fall (Garlich-Miller et al., 2011; Jay et al., 2012). Consistent detections at that station starting approximately 22 August in 2009 and 2010 suggest that some walrus may be leaving the northeastern Chukchi Sea earlier than in the past, possibly as a result of earlier sea ice retreat.

Overall walrus detections decreased by mid-September even though some calling individuals were detected well into October. Later detections were sporadic and typically ended in November. Four isolated winter detections (all at PL85) occurred on 23 December 2009, 22 January 2010, 27 December 2010, and 28 February 2011.

Walrus were present throughout the Lease Sale 193 areas, but distributions of call detections showed highest density to the east of the lease sale area. Their core habitat between Wainwright and Hanna Shoal overlaps with some leased blocks. The walrus call-count isopleths indicate that walrus occur at relatively high levels within the active lease blocks of the Burger and Statoil study areas, but are comparatively rare in the Klondike study area. This finding is consistent with visual observations (Aerts et al., 2013).

4.2.2. Bearded seal

It is unclear from visual observations how the abundance of bearded seals varies in the northeastern Chukchi Sea throughout the year. Although, bearded seals were detected in the study area year-round, the number of acoustic detections followed a

consistent annual pattern of increasing numbers from October until April. The highest call detection rates occurred in May and June. This is attributed to increases in calling rate and loudness associated with vocal displays during breeding season (Van Parijs et al., 2001). Burns (1967, 1981) also reported that many of the seals that winter in the Bering Sea move to the Chukchi Sea from late April to June, which might lead to increased calls from larger numbers of animals present. This period was followed by an abrupt decrease followed by no, or very few, acoustic detections from the end of June through August. Although some individuals presumably follow the receding ice edge, leading to decreased abundance in summer in the study area (Burns, 1981), others are known to remain in open water. As bearded seals were regularly sighted in the study area during this time period (Aerts et al., 2013), the paucity of call detections in July and August reflects a lack of calling rather than an absence of animals. The increase in detections in September and October could be attributed to transiting animals returning to their Bering Sea winter grounds.

In fall 2007 and summer 2009, bearded seal acoustic detections were concentrated near Wainwright, but in 2010 the largest call counts occurred at the north and northeast parts of the study area. These interannual variations may be related to variability in ice conditions and prey availability. Bearded seal detections in 2009 were more common over the Burger and Statoil study areas than at the Klondike study area, which is consistent with visual observations (Aerts et al., 2013). This same pattern was observed in 2010, but with smaller differences between areas.

4.2.3. Ringed seal

Ringed seals were detected in all months of the year, confirming they are present year-round in the northeastern Chukchi Sea. The few detections in summer months (June–October) may be related to the close association of ringed seals with sea ice (Burns, 1970), and the low ice concentration in the study area after the mid-August. The increase in detections from November through May might be related to higher calling rates associated with the breeding season, as has been observed for bearded seals (Van Parijs et al., 2001). Detection rates decreased again in January and then remained relatively stable until April.

4.2.4. Ribbon seal

Little is known about ribbon seals in the Chukchi Sea. Ribbon seals range widely in summer; some individuals have been tracked from the Bering Sea into the Chukchi Sea (Boveng et al., 2008), which is consistent with the detection of calls during the open water season in 2008 north of Barrow (Jones et al., 2011). However, the scarcity of sightings, along with the virtual absence of acoustic detections in our study area during summer, suggests that ribbon seals are rare in the northeastern Chukchi Sea. The detections in October and November might correspond to migrating animals returning to the Bering Sea where the species is known to winter (Burns, 1970, 1981).

5. Conclusions

5.1. Relationships to sea ice

Spring bowhead detections start in March and April, while ice concentrations remain near 100% at the corresponding stations. A large fraction of acoustic detections associated with the bowhead whale fall migration occurs just in advance of the northeast-to-southwest progression of ice formation. This suggests that the timing of their migration through the southern Chukchi Sea is influenced by the advance of the ice edge. Later ice formation may therefore delay bowhead migration out of the Chukchi during fall.

Spring migrations of beluga occur with bowhead when ice conditions are still close to 100%, so it is not clear that an earlier ice retreat would affect the spring migration unless it occurred very early in the season. Few beluga call detections are made in the fall, presumably because beluga migrations pass either north or south of the instrumented area, or perhaps because beluga call rates are just lower in fall. In any case, the lack of fall detections precludes consideration of ice influence on migration timing.

There does not appear to be a clear relationship between ice concentration and the time of first walrus acoustic detections. There does, however, appear to be a relationship between the timing of departure of ice from Hanna Shoal and the formation of on-shore walrus haul-outs. The acoustic detections continued at Hanna Shoal for several weeks even after the on-shore haul-outs formed in 2007, 2010, and 2011. Walrus have been shown to move between shore haul-outs and Hanna Shoal (Jay et al., 2012). The implication for walrus of earlier ice retreat is that many, but perhaps not all, animals will move off their preferred on-ice haul-outs to on-shore haul-outs in August. Most walrus migrate back to the Bering Sea in late September or early October with acoustic detections decreasing accordingly. This is well in advance of winter ice formation and consequently delayed ice formation is unlikely to have substantial influence on walrus fall migration in the northeastern Chukchi Sea.

Bearded seal acoustic detections show little association with ice presence. Call detections off Wainwright and Barrow decreased abruptly within a few days of 1 July in all years regardless of the ice conditions. Likewise, no clear correlation was apparent between the increase in bearded seal call detections in December–January and time of ice formation.

Ringed seal acoustic detections were sparse, but nearly all detections occurred during periods of more than 90% ice presence. A small number of detections continued through the summer, indicating these animals did not entirely vacate the Chukchi Sea. Reduced summer detections suggest that ringed seals either vocalized less in summer or that a large fraction of them left the monitored area when ice concentrations decreased.

5.2. Potential interaction with oil and gas activities

Some recent exploration activity has occurred in the northeastern Chukchi Sea since 2006 associated with the 2007 Lease Sale 193. Further exploration in these areas is likely with consequent increased levels of anthropogenic noise. This study has provided distribution data useful for characterizing the present marine mammal distributions that might be influenced by future changes. The distribution measurements can also be used more directly to investigate potential interactions with ongoing oil and gas exploration activities.

This study detected few vocalizing bowhead in Lease Sale 193 blocks from late June through mid-September (Figs. 3 and 4C). Therefore, exploration activities performed within this time window would minimize interactions with this species. Bowhead acoustic presence increased quickly in late September each year and remained high through November. Exploration activities in October and November will encounter higher numbers of bowhead in the Chukchi Sea.

Beluga acoustic presence was low except during spring migration: early April to mid-June (Fig. 6). Beluga were also detected through the summer at Station B5 near Barrow in the deeper waters of Barrow Canyon. These results suggest that oil and gas exploration on the Chukchi shelf would largely avoid close interactions with beluga as long as the work is performed after the spring migration period. While some beluga appear to have been present in this area during summer, we cannot distinguish

between low abundances or lower vocalization rates during this period.

Gray whales were detected in August and September, with acoustic presence decreasing with increasing distance from shore (Fig. 7), and relatively few detections occurring beyond 50 km from shore. Most oil and gas exploration is currently planned further offshore where fewer interactions with gray whales would be expected, although some detections occur directly in the exploration lease areas.

Killer whale detections occurred but were relatively low in August and September at stations within 50 km from shore, except off Barrow where no calls were detected (Fig. 8). Many fewer calls were detected on recording stations beyond 80 km from shore, with some site-specific exceptions. These findings suggest that there would generally be few killer whale interactions with oil and gas exploration activities carried out more than 100 km offshore.

Fin, humpback and minke whale acoustic detections are substantially lower than from the other cetacean species discussed here. The Chukchi Sea is believed to be at the northern limit of the habitat range of these species. Most of their detections have occurred directly north of Cape Lisburne and Point Lay, to the west of most of the oil and gas lease blocks. Still, there is potential for some limited interactions with these species, especially for exploration activities on the western lease blocks.

Walrus was the most commonly detected species in the central northeastern Chukchi Sea in summer. Large numbers of acoustic detections of walrus were made from mid-June through September at most recording stations. While walrus detections were consistently highest on the south side of Hanna Shoal, all stations registered detections throughout this period (Figs. 9 and 11). It will be difficult for oil and gas exploration activities before late September to avoid interactions with walrus.

Bearded seal calls were detected year-round at most stations, but substantial seasonal differences in detection rates were observed. The changes in detection rates are attributed to varying calling rates of this species (see Section 4.2.2). Call detection rates are low from mid-June through August, but detections were highest on the Wainwright stations (Fig. 10). The distribution variations with time are not clear from these acoustic measurements because the increase in detections starting in September may be due to increased calling rates rather than from higher animal spatial densities.

Ringed seal acoustic detections were much lower during open water periods than when ice was present. This observation may also be related to variable calling rates, but it is likely due largely to this species' association with sea ice. Low numbers of acoustic detections throughout the summer at most stations indicates that some ringed seals were present near oil and gas exploration areas, but their numbers were probably relatively low.

6. Summary

The Chukchi Sea is an important habitat for several marine mammal species. It has generally experienced relatively low levels of anthropogenic activity and man-made noise. Some recent exploration activity has occurred in the northeastern Chukchi Sea since 2006 associated with the 2007 Lease Sale 193 prospects. Further exploration in these areas is likely with consequent increased levels of anthropogenic noise. At the same time, climate change appears to be reducing the extent of summer ice in the arctic, and particularly its duration in the Chukchi Sea.

This passive acoustic monitoring study has provided direct measurements of temporal and spatial distributions of vocalizing bowhead, beluga, humpback, fin, minke, gray and killer whales, and walrus, bearded seals, ringed seals, and ribbon seals. This approach

is allowing us to study the effects of increased anthropogenic noise and changes in sea ice presence on marine mammals at high temporal resolution, and over broad spatial scales, that cannot be matched by observer-based approaches.

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