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Acoustic Detections of Beluga Whales in the Northeastern Chukchi Sea, July 2007 to July 2008

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ABSTRACT. Beluga calls were detected during two consecutive deployments of autonomous acoustic recorders in the northeastern Chukchi Sea. During the first deployment, calls were recorded between July and October 2007, primarily near the Barrow Canyon in July and August. During the second deployment, calls were detected in November 2007 off Point Lay and again between mid-April and June 2008 in a broad area 90–150 km off Point Lay and Wainwright, Alaska. The summer and fall 2007 detections were consistent with movement and residency patterns identified through satellite tagging studies. In the following spring, detections were recorded by four out of five monitoring stations for 19 to 37 consecutive days (depending on the station) between 13 April and 21 June 2008. These acoustic detections provide additional information about the timing and distribution of beluga migrations in the Chukchi Sea in spring.

Key words: beluga whale, *Delphinapterus leucas*, Chukchi Sea, distribution, migration, sea ice, acoustic detection

RÉSUMÉ. Des sons provenant de bélugas ont été détectés sur deux réseaux d'enregistreurs déployés successivement dans le nord-est de la mer des Tchouktches. Lors du premier déploiement, des sons de bélugas ont été détectés entre juillet et octobre 2007, principalement près du canyon de Barrow en juillet et en août. Lors du second déploiement, des sons de bélugas ont également été détectés en novembre 2007 au large de Point Lay et entre la mi-avril et le mois de juin 2008 dans une large zone située entre 90 et 150 kilomètres au large de Point Lay et Wainwright, en Alaska. Les détections de l'été et de l'automne 2007 confirment les modèles de mouvement et de résidence mis en évidence grâce à la télémétrie satellite. Au cours du printemps suivant, des sons de bélugas ont été enregistrés entre le 13 avril et le 21 juin 2008 pendant 19 à 37 jours consécutifs dépendamment des enregistreurs, à quatre des cinq stations de surveillance. Ces détections acoustiques fournissent de nouvelles informations sur la distribution spatiale et temporelle des migrations de bélugas en mer des Tchouktches au printemps.

Mots clés : bélugas, *Delphinapterus leucas*, mer des Tchouktches, distribution, migration, glace, détection acoustique

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INTRODUCTION

Beluga whales (*Delphinapterus leucas*) occur throughout Arctic and Subarctic waters along the northern coasts of Canada, Alaska, Russia, Norway, and Greenland (Gurevich, 1980). Different populations have been distinguished by their summer distributions (Frost and Lowry, 1990) and, for some, by variations in mitochondrial DNA (e.g., O'Corry-Crowe et al., 1997) or nuclear DNA microsatellites (Brown Gladden et al., 1999). In western and northern Alaska, genetic studies have identified four stocks: the eastern Chukchi Sea, eastern Beaufort Sea, eastern Bering Sea, and Bristol Bay stocks (O'Corry-Crowe et al., 1997, 2002).

The distribution patterns of these stocks are not well understood except for their predictable summer occurrence in specific lagoons and estuaries (Frost and Lowry, 1990; Richard et al., 2001; Suydam et al., 2001). Although the exact purpose of these coastal aggregations remains unknown, in some areas they appear to be synchronized with the molting season, and belugas may take advantage of warmer, fresher water conditions to speed up the breakdown and sloughing of old epithelium and the growth of new skin (Finley, 1982; St. Aubin et al., 1990; Frost et al., 1993). The main summer aggregations in the eastern Chukchi Sea occur in Kotzebue Sound and along the 170 km long Kasegaluk Lagoon (Fig. 1). In the Kasegaluk Lagoon area, belugas are known to arrive from mid-June to early July, and they leave by mid-July (Frost et al., 1993; Suydam et al., 2001). Tagging experiments have recently described movement patterns of belugas after they leave Kasegaluk Lagoon. The general movement is first to the northeast towards Barrow, Alaska, and then into the western Beaufort and northern Chukchi seas. Belugas were found throughout the summer either near the shelf break off northern Alaska or in offshore, ice-covered waters of the Arctic Ocean (Suydam et al., 2001, 2005). Moore et al. (2000) also observed

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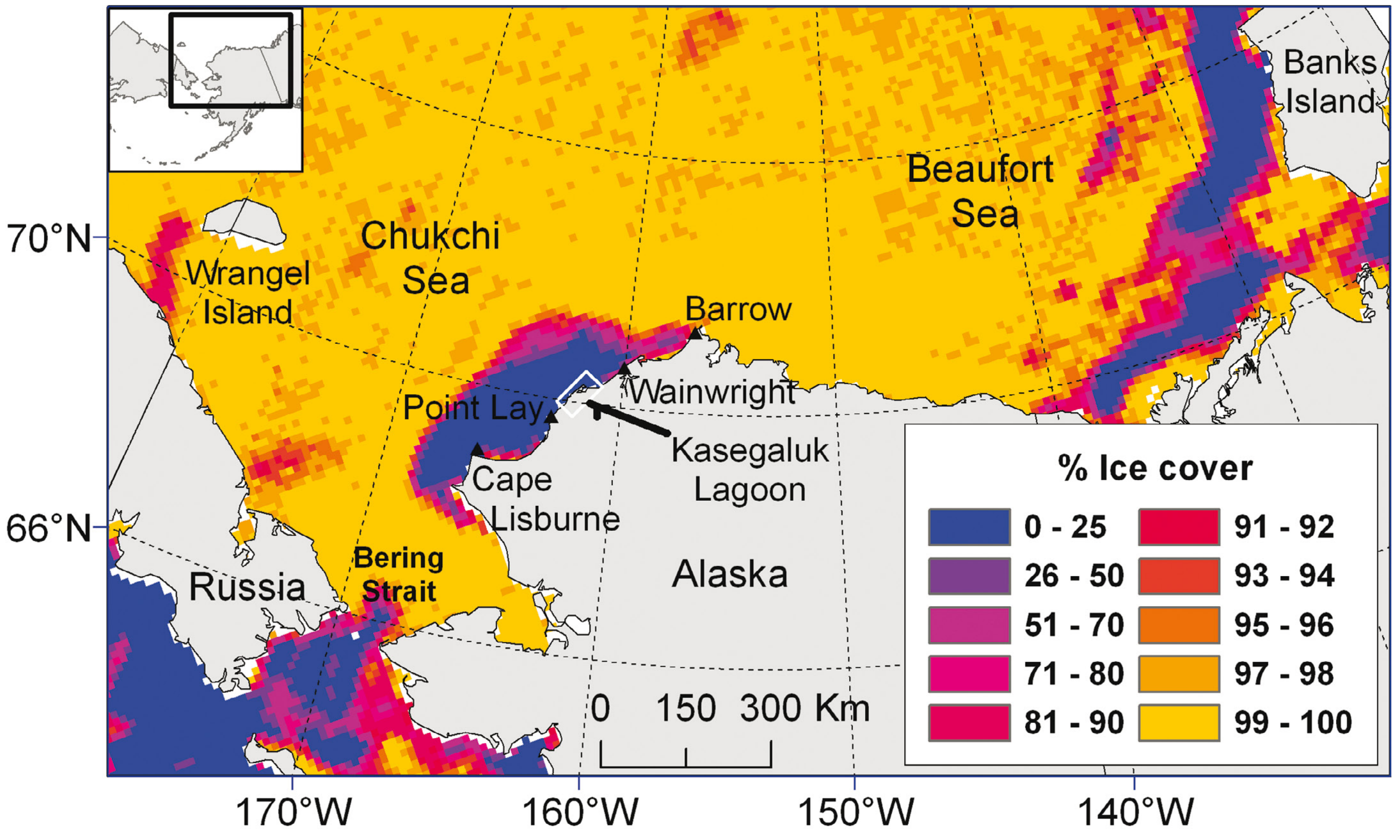

FIG. 1. Area used by eastern Chukchi Sea and eastern Beaufort Sea belugas in spring, summer, and autumn. The ice cover data are for 15 May 2008.

higher numbers of belugas along the continental slope of the Beaufort and Chukchi seas in summer and fall.

In fall, Alaskan belugas migrate from their summering areas in the Chukchi and Beaufort seas to the Bering Sea, where they are believed to spend the winter (Hazard, 1988). Eastern Beaufort Sea belugas start migrating west towards the Chukchi Sea between late August and early September (Richard et al., 2001), while eastern Chukchi Sea animals may remain in the Chukchi Sea as late as November (Suydam et al., 2005). Active satellite tags have indicated that animals from both stocks entered the Bering Sea in late November or early December (Richard et al., 2001; Suydam et al., 2005).

There are few published data regarding the distribution of belugas in winter. They presumably occupy offshore areas of shifting pack ice or remain along the ice edge in the Bering Sea (Hazard, 1988). Owing to the location of their summer areas, belugas from the eastern Chukchi and eastern Beaufort Sea stocks have to pass through the Chukchi Sea in spring and early summer. Fraker et al. (1978) suggested that they leave the Bering Sea in late March–early April. Aerial surveys designed for bowhead whales (*Balaena mysticetus*) also sighted belugas in the Chukchi Sea between Cape Lisburne and Point Barrow from April to June in 1980–84, but because of the survey design, these sightings were primarily restricted to nearshore waters (Moore et al., 1993). In the spring, at least some belugas appear to follow the same path as bowheads, which migrate en route to the Beaufort Sea primarily along an open-water lead that forms near the Alaskan coast between Cape Lisburne and Point Barrow (Fig. 1) (Moore and DeMaster, 1998). However, it remains unclear whether this route is used by all individuals or whether alternative routes exist, and the exact timing of the spring migration in the Chukchi Sea is also unknown.

Belugas are highly vocal animals and produce typical high-frequency calls (Sjare and Smith, 1986; Karlsen et al., 2002; Belikov and Bel'kovich, 2006, 2008). In this study, we report on acoustic detections of beluga calls during a year-long study in the Chukchi Sea. The spatiotemporal patterns of these detections are compared to published distribution data derived from visual surveys (Frost et al., 1993; Moore et al., 1993) and satellite tracking (Suydam et al., 2001, 2005), and new information on the spring distribution of belugas is presented.

MATERIALS AND METHODS

Acoustic Arrays

Between July 2007 and July 2008, two large-scale, bottom-mounted acoustic arrays were deployed consecutively off northwest Alaska in order to monitor ambient sound levels, marine mammals, and anthropogenic activities. The first array extended from Cape Lisburne to Point Barrow, Alaska. It was composed of independent, continuously recording units divided into four

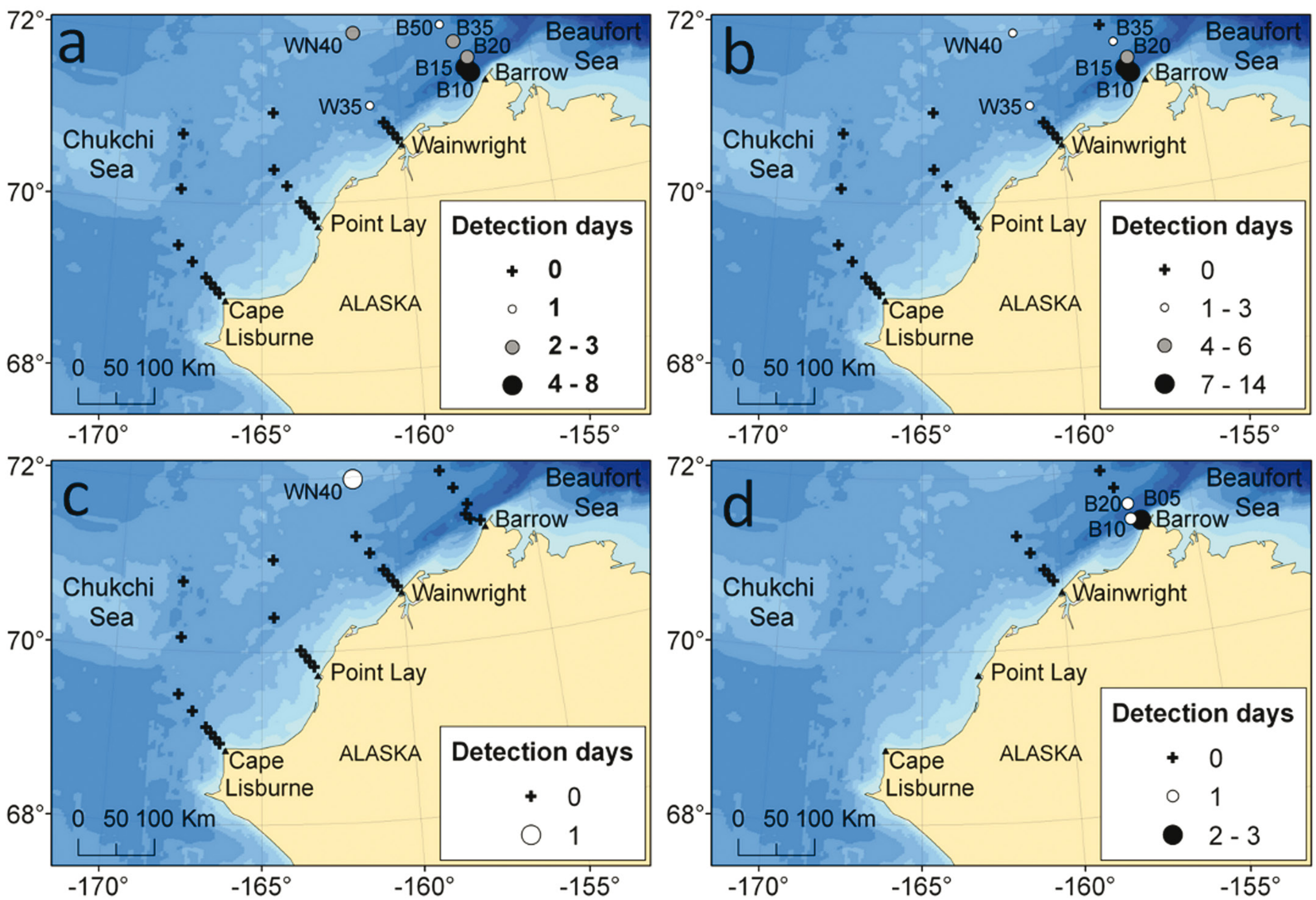

FIG. 2. Locations of beluga call detections and number of detection days (colored dots) a) from 16 to 31 July 2007; b) in August 2007; c) in September 2007; d) from 1 to 26 October 2007. Black crosses display active recording stations with no detections. Shades of blue represent bathymetry. No ice was present near the recorders. All the recorders shown in Figure 2c were recovered by 15 September 2007. From 15 September until 26 October 2007, only those stations shown in Figure 2d were redeployed and active.

parallel sub-arrays, each comprising six to eight recorder stations and extending from 8 km to between 90 and 210 km from shore. The deployment occurred in two phases. During the first phase, 26 recorders were deployed between 16 and 20 July 2007 and recorded until 10 September, when they were recovered (Fig. 2a–c). During the second phase, (10 September to 26 October), 11 stations of the Wainwright and Barrow sub-arrays were re-instrumented (see Fig. 2d for active stations). Stations B05 and W50 were deployed only during this second phase.

The second array consisted of five stations moored off Point Lay and Wainwright, Alaska, between 21 October 2007 and 3 August 2008 (Fig. 3). These stations were deployed at least 90 km from shore to avoid the risk of interaction with ice in shallower inshore areas. During this overwinter deployment, acoustic data were collected on a duty cycle of 48 minutes every four hours. Table 1 shows the deployment location and duration of all recording units. All acoustic data were obtained using Autonomous Underwater Recorders for Acoustic Listening (AURAL, Multi-Electronique, Inc.) recorders. The recorders incorporated a HT196 hydrophone (1 to 10 000 Hz; -164 dB re 1µPa), a hard drive, and batteries packaged in pressurized fiberglass tubes mounted on a stainless steel frame, and they sampled data at a rate of 16 384 Hz with 16-bit resolution and an AURAL recorder gain setting of +22 dB. The recording units were floating about 1 m above the seafloor.

Data Processing

The recording schedule generated close to 6 TB of data. To speed up the data analysis process, each sound file was scanned using a purpose-built computer program to search for peaks of acoustic energy in specific frequency bands. Two bands were expected to contain most beluga vocalizations: 1440–3500 Hz and 2900–7000 Hz. The automatic detection of acoustic events was a multi-step process. First, the spectrogram of the recordings was computed using a short time Fourier transform on 4096-sample windows zero-padded to 8192 points and overlapped at 50% (time resolution: 125 ms, frequency resolution: 2 Hz). Then, the spectrogram was normalized using a split-window normalizer. For each frequency bin, the energy value at each time step was divided by the average of the energy calculated

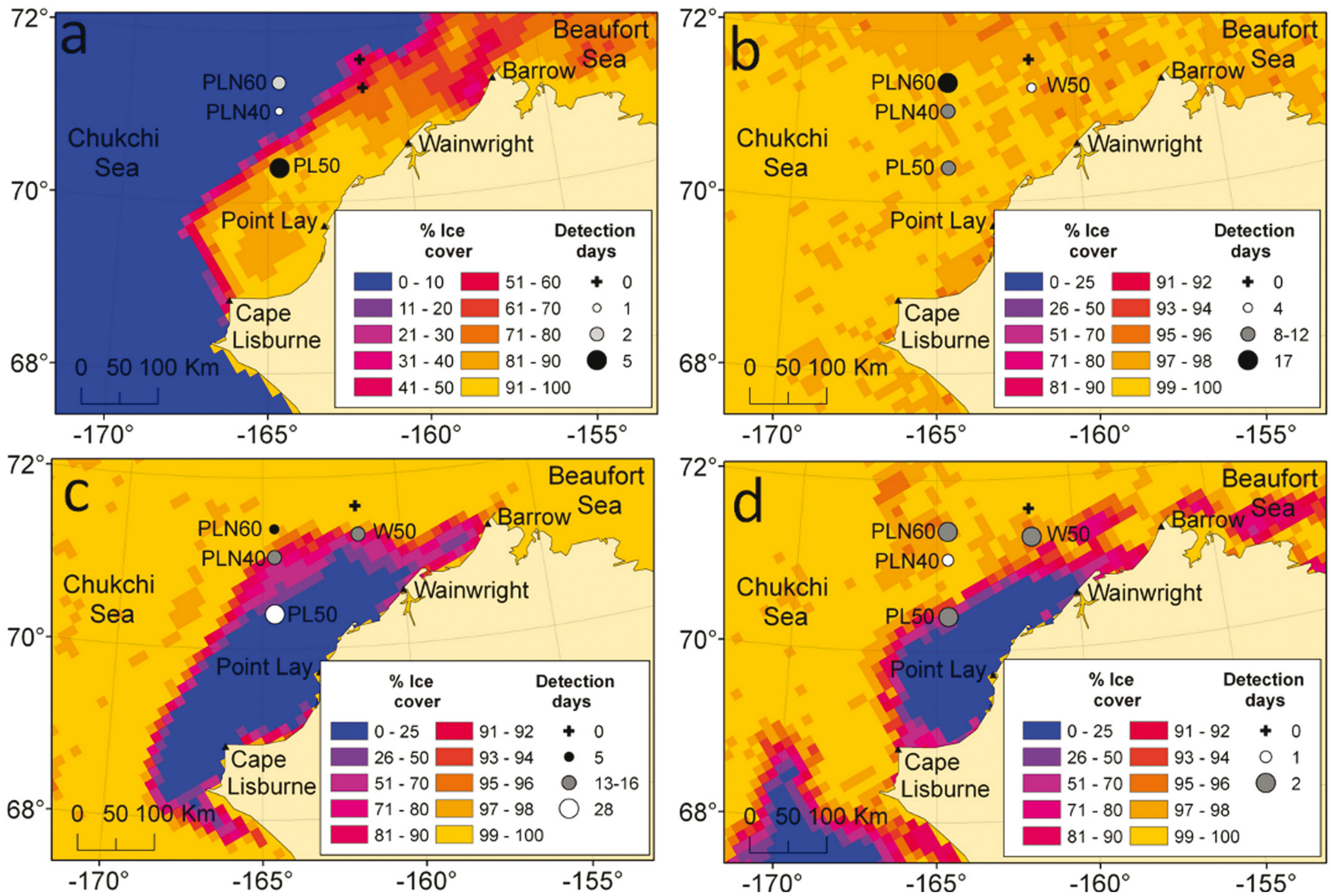

FIG. 3. Locations of beluga call detections and number of detection days (colored dots) in a) November 2007; b) April 2008; c) May 2008; and d) June 2008. Ice coverage data shown represent conditions on 10 November 2007, 15 April, 15 May, and 4 June 2008. Note that the % ice cover scale is different for each panel: in panels b, c, and d, the scale emphasizes heavy ice conditions. Black crosses display active recording stations with no detections.

for 110 bins before and 110 bins after the points, excluding the 30 closest bins on each side. Finally, all the energy values of the normalized spectrogram that exceeded a predefined threshold were considered an acoustic event that may have been a marine mammal call or part of one. Contiguous detected bins on the spectrograms were grouped together to define time-frequency contours of acoustic events.

Beluga calls were identified in two different ways. For the summer 2007 dataset, we designed an automatic classifier based on the frequency and time evolution of the call contour extracted during the detection stage. Each extracted contour was represented by a set of attributes including duration, center frequency, and variance around the center frequency. Call types known to be produced by marine mammals present in the Chukchi Sea during the open-water season were then described, using published values for the same attributes. This step was justified by the potential presence of other species with call types similar to beluga calls in the study area, leading to an increased risk of misclassification if these calls were not described. Finally, the contours detected were identified by matching their attributes with the ones from the created dictionary of vocalizations, using a set of thresholds.

The targeted beluga calls were high-frequency (1400–7000 Hz), frequency-modulated, tonal signals (i.e., whistles). Published descriptions of these calls exist for the White Sea (Belikov and Bel'kovich, 2006, 2008), Svalbard, Norway (Karlsen et al., 2002), and Cunningham Inlet, Northwest Territories (Sjare and Smith, 1986). Although not described for the Chukchi Sea, whistles are found in different populations and can be reasonably expected to be produced by belugas in this area.

Calls of two other species could have been misclassified as beluga calls. Narwhals (*Monodon monoceros*) produce similar whistles and pulsed signals (Shapiro, 2006) but are extremely rare in the Chukchi Sea (Heide-Jørgensen, 2008). Killer whales (*Orcinus orca*) also produce whistles and pulsed calls (e.g., Ford, 1989) that share some spectro-temporal characteristics with beluga calls. Killer whales are occasionally seen in the Chukchi Sea (George and Suydam, 1998), and a recent analysis of the same dataset described here showed that some were present in the Chukchi Sea in the summer of 2007 (Delarue et al., 2010). Despite the documented beluga prevalence in the Chukchi Sea, we manually verified a large proportion (~50%) of the summer 2007 acoustic files with at least one automatic classification

TABLE 1. Deployment information and number of beluga detection days for all recorders used in this study, listed from northernmost to southernmost, in both summer 2007 and overwinter 2007–08 arrays. The name of each station contains a geographical reference to its linear array (B = Barrow, CL = Cape Lisburne, PL = Point Lay, and W = Wainwright) followed by a number indicating its distance from the coast. For the CL, PL, and W arrays, which extend perpendicular to the coast out to 50 nautical miles before branching to the north, a number preceded by "N" represents the distance of the station from that 50-mile turning point.

Station	Geographical reference	Depth (m)	First record	First detection	Last detection	Last record	Detection days
Summer 2007 Array:							
B50	Barrow	59	20 July 07	30 July 07	30 July 07	26 October 07	1
WN40	Wainwright	31	20 July 07	29 July 07	5 September 07	14 September 07	6
B35	Barrow	60	20 July 07	21 July 07	22 August 07	26 October 07	5
B20	Barrow	79	20 July 07	28 July 07	13 October 07	20 October 07	9
B15	Barrow	119	20 July 07	21 July 07	28 August 07	11 September 07	22
B10	Barrow	123	20 July 07	21 July 07	8 October 07	20 October 07	20
B05	Barrow	60	11 September 07	8 October 07	18 October 07	20 October 07	3
W50	Wainwright	49	13 September 07	–	–	25 October 07	0
W35	Wainwright	53	19 July 07	29 July 07	3 August 07	26 October 07	3
PLN40	Point Lay	38	18 July 07	–	–	15 September 07	0
W20	Wainwright	53	19 July 07	–	–	20 October 07	0
W15	Wainwright	49	19 July 07	–	–	20 October 07	0
CLN80	Cape Lisburne	55	18 July 07	–	–	14 September 07	0
W10	Wainwright	42	19 July 07	–	–	19 October 07	0
W05	Wainwright	22	19 July 07	–	–	12 September 07	0
PL50	Point Lay	42	18 July 07	–	–	15 September 07	0
PL35	Point Lay	35	18 July 07	–	–	26 August 07	0
CLN40	Cape Lisburne	48	17 July 07	–	–	14 September 07	0
PL20	Point Lay	26	19 July 07	–	–	15 September 07	0
PL15	Point Lay	24	19 July 07	–	–	15 September 07	0
PL10	Point Lay	20	19 July 07	–	–	15 September 07	0
PL05	Point Lay	13	19 July 07	–	–	15 September 07	0
CL50	Cape Lisburne	46	17 July 07	–	–	13 September 07	0
CL35	Cape Lisburne	46	17 July 07	–	–	13 September 07	0
CL20	Cape Lisburne	40	17 July 07	–	–	13 September 07	0
CL15	Cape Lisburne	37	17 July 07	–	–	13 September 07	0
CL10	Cape Lisburne	33	17 July 07	–	–	13 September 07	0
CL05	Cape Lisburne	29	17 July 07	–	–	13 September 07	0
Overwinter 2007–08 Array:							
WN20	Wainwright	47	25 October 07	–	–	3 August 08	0
PLN60	Point Lay	44	22 October 07	7 November 07	4 June 08	30 July 08	26
W50	Wainwright	49	25 October 07	19 April 08	21 June 08	2 August 08	19
PLN40	Point Lay	40	21 October 07	8 November 07	5 June 08	20 July 08	30
PL50	Point Lay	42	21 October 07	11 November 07	2 June 08	20 July 08	43

(Table 2) to eliminate potential false positives and assess the performance of the detector. Files containing detections usually occurred in clusters; a sample of each cluster was reviewed for presence of beluga calls. We reviewed not only files with a high number of automatic classifications, but also those with average or lower numbers.

For the overwinter dataset, the classifier did not provide accurate results primarily because ice noise, which was frequently detected and overlapped in frequency with beluga calls, triggered many false classifications. We therefore verified manually any sound files showing a large number of acoustic detections in the upper frequency bands (1440 Hz and above) for the presence of beluga calls. Since the energy detector is by design very efficient at finding transient sounds such as beluga calls, we did not investigate files with no or few detections in the upper frequency bands. Between 20% and 35% of all files with more than 10 detections above 1440 Hz (Table 3) were examined at each station. Belugas were considered present on a day if at least one file on that day contained calls. We did not make any assumptions as to the content of unchecked files.

Manual verification revealed that the number of automatic beluga call classifications for the summer 2007 dataset did not accurately reflect the number of calls per file. This discrepancy was partly explained by the proportion of detections characterized by high calling rates: with several belugas calling simultaneously, the contour extractor could not isolate individual calls from a group of overlapping calls. Thus, although there is some evidence currently for a correlation between calling activity and the number of belugas vocalizing or present in an area (Simard et al., 2010), we did not attempt to estimate the number of calls per file, but rather focused on the spatio-temporal distribution of beluga detections on both arrays. Days containing beluga calls were compiled for all stations to produce detection time series and monthly distribution maps using ArcView 9.2 (ESRI, 2006). Ice concentration data at a resolution of 12.5 × 12.5 km derived from passive microwave telemetry were obtained from the National Snow and Ice Data Center (Cavalieri et al., 2004) and added to some maps to illustrate ice conditions at the time of detections.

TABLE 2. Number of sound files per station, automatic classifier output summary, and number of files with confirmed beluga classifications for the summer 2007 arrays.

Station	Number of acoustic files	Number of files with at least one automatic beluga classification	Number of files with confirmed beluga classifications
B50	4191	108	11
WN40	2368	635	134
B35	4187	54	12
B20	3817	66	38
B15	2270	158	145
B10	4153	195	140
B05	1651	31	12
W50	1794	14	0
W35	4244	199	16
PLN40	2497	53	0
W20	3952	118	0
W15	3941	81	0
CLN80	2497	27	0
W10	3927	117	0
W05	2336	170	0
PL50	2497	32	0
PL35	1656	38	0
CLN40	2497	64	0
PL20	2497	41	0
PL15	2497	47	0
PL10	2497	252	0
PL05	2497	250	0
CL50	2497	127	0
CL35	2497	106	0
CL20	2497	108	0
CL15	2497	56	0
CL10	2497	73	0
CL05	2493	143	0

RESULTS

Summer 2007 Deployment

During the summer 2007 deployment, detections were concentrated on the Barrow sub-array and at the offshore stations (W35 and WN40) of the Wainwright sub-array (Figs. 2 and 4). Beluga calls were first detected at stations B10, B15, and B35 on 21 July 2007, only one day after deployment. Between 26 July and 12 August, belugas were recorded consistently at B10, B15, and B20, which were located within the Barrow canyon. This underwater canyon lies 20 km off Barrow on a northeast-southwest heading and drops from the Chukchi Sea continental shelf into the deep Arctic basin. Calls were recorded almost daily at B15 during that period. Between 15 and 28 August, detections were typically separated by two to three days, and detections stopped at B15 on 28 August. The last detections at B10 and B20 occurred on 8 and 13 October, respectively. Detections at B35 and B50 were more sporadic: calls were detected on only five days at B35 between 21 July and 22 August and only one day at B50 (30 July). Calls were recorded at B05 (deployed on 11 September) on 8, 15, and 18 October, the latter being the last detection of the summer 2007 array. Detections at W35 and WN40 started on 29 July and continued intermittently until 7 August. Isolated call clusters were later recorded on 22 August and 5 September at WN40.

Manual verification of the automatic classifier's output identified the presence of a number of false positives. Confounding sounds included the high-frequency portion of walrus knock sounds (Stirling et al., 1987), as well as high-frequency, non-biological noises such as mechanical noise from the recorders' mooring. Stations with the highest number of false classifications were usually stations where walrus were most often detected (e.g., WN40, PL05; Table 2). Killer whale vocalizations were also typically misclassified because of overlap in time and frequency characteristics with beluga calls, but the vast majority of high-frequency calls detected were produced by belugas. Killer whales were easily identified thanks to their typical stereotyped calls (Ford, 1989), which were often produced repeatedly. Despite the number of false positives, the classifier significantly reduced the analysis time by identifying files containing sounds that shared characteristics with beluga calls, which could then be verified manually.

Overwinter Deployment

Throughout the 2007–08 overwinter deployment, two distinct periods contained beluga calls, namely the autumn of 2007 and the spring of 2008 (Figs. 3 and 5). Beluga calls were first detected at PLN60 on 7 November 2007. They were then successively recorded at PLN40 on 8 November and at PL50 on 11 November. Except for an additional detection day on 11 November at PLN60, all subsequent fall detections occurred at PL50, the last one being on 25 November. The sequence of these detections suggests a southward movement of belugas in the Chukchi Sea in the autumn.

In spring 2008, beluga calls were first detected on 13 April 2008 at PLN60. Detections started simultaneously on 18 April at PL50 and PLN40 and one day later at W50.

TABLE 3. Number of sound files per station and number of files manually checked.

Station	Total number of files	Number of files with more than 10 detections above 1440 Hz	Number of files checked	Number of files with more than 10 detections above 1440 Hz checked	Percentage of files with more than 10 detections above 1440 Hz checked
W50	1694	1194	401	260	21.8
WN20	1695	1062	375	210	19.8
PL50	1595	975	495	345	35.4
PLN40	1695	920	410	213	23.2
PLN60	1638	1088	412	218	20.0

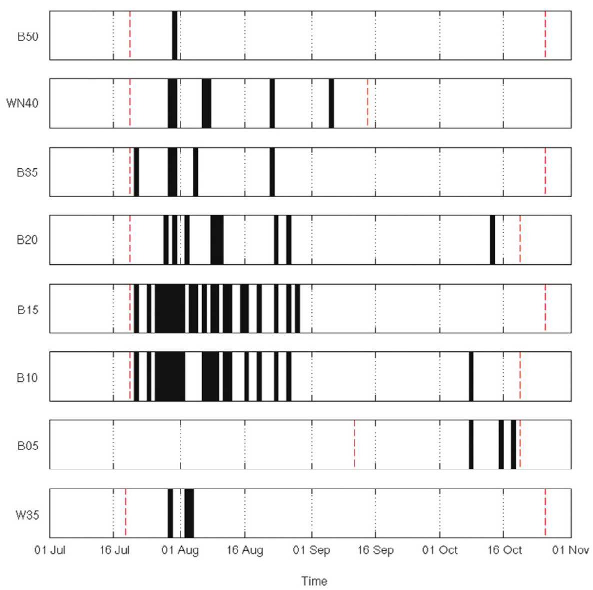

FIG. 4. Temporal distribution of beluga call detections during the summer 2007 deployment (19 July – 26 October 2007). The red dashed lines indicate the deployment and recovery dates for each station.

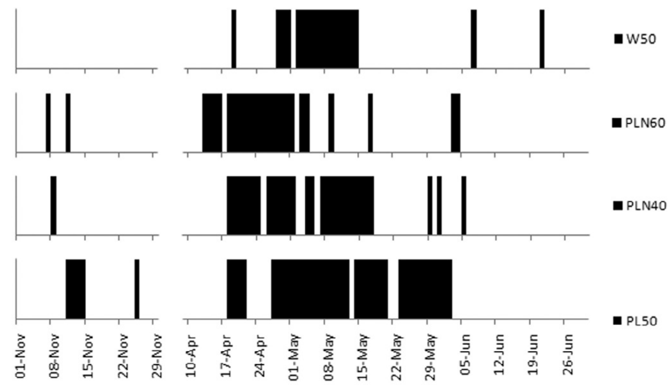

FIG. 5. Temporal distribution of beluga call detections during the overwinter deployment (21 October 2007 – 2 August 2008). The interruption along the x-axis between 29 November 2007 and 10 April 2008 represents the period when no detections were made.

Belugas were recorded almost continuously at PLN60 until 4 May, after which calls were detected on only three occasions, the last one being 4 June. Recordings at PLN40 showed a similar pattern, with a continuous detection period ending on 17 May and three more isolated detections ending on 5 June. At PL50, belugas were detected continuously, except for three days, between 27 April and 2 June. At W50, calls were recorded continuously between 28 April and 14 May. Two subsequent detections occurred on 7 and 21 June; the latter was also the last detection of the overwinter deployment, although sampling continued until 2 August. Overall, the length of the detection period in the Chukchi Sea in spring was substantial, since belugas were present for 37, 30, 22, and 17 consecutive days (including a few gaps less than two days long with no detections) at PL50, PLN40, PLN60, and W50, respectively.

DISCUSSION

Spatiotemporal Detection Patterns and Implications

During summer 2007, calls were concentrated on the Barrow sub-array, most frequently at two stations moored near the head of Barrow Canyon, B10 (along the canyon's slope) and B15 (at the canyon's floor). Detections also occurred at stations bordering the Canyon (B35 and B50) but less consistently, which indicates that belugas were present in the area but preferentially used the deeper water over Barrow Canyon. Suydam et al. (2005) showed that Barrow Canyon was used extensively by belugas throughout the summer. In particular, an immature female tagged in 1999 spent the entire summer near Barrow Canyon, although most tagged whales summered in the northern Chukchi and Beaufort seas (Suydam et al., 2005).

The belugas detected in mid-October at stations B05, B10, and B20 may have been individuals returning from the Beaufort Sea. Suydam et al. (2005) found that eastern Chukchi Sea belugas start migrating towards the Bering Sea in October and November. Eastern Beaufort Sea belugas start migrating west between late August and mid-September and some moved west across the Chukchi Sea to Wrangel Island between 20 August and 18 October (Richard et al., 2001). Thus, our detections were most likely from eastern Chukchi Sea animals returning after spending the summer in the Beaufort Sea or northern Chukchi Sea.

Most belugas tagged by Suydam et al. (2005) headed toward Barrow after being tagged in the Kasegaluk Lagoon area. There were a few exceptions, however: in 2002, tagged belugas first headed west into the Chukchi Sea before heading north. This movement pattern could explain the sporadic detections at W35 and WN40 in late July and early August. During the autumn migration, tagged belugas from the eastern Beaufort Sea continued west past Point Barrow, sometimes reaching Wrangel Island (Richard et al., 2001) before heading south toward the Bering Strait. Similar tracks could bring animals into the vicinity of station WN40, which recorded calls on 22 August and 5 September 2007.

The lack of detections at the inshore stations of the Wainwright sub-array in late July and early August was unexpected, as these stations lay on the path of belugas heading toward Barrow. However, belugas generally leave Kasegaluk Lagoon by mid-July (Frost et al., 1993; Suydam et al., 2001), and most animals may have already passed the locations of these stations before the recorders were deployed on 19 July 2007. The fact that belugas were detected at some of the Barrow recorders on 21 July, one day after their deployment, also suggests that the Wainwright recorders may have been deployed too late to detect belugas on their way to Barrow. The deployment of recorders near Point Lay slightly south of the Kasegaluk Lagoon summer aggregations and the fact that beluga whales swim predominantly towards the northeast upon leaving this area could explain the absence of detections on that sub-array. However, it is also likely that the deployment of these recorders occurred after the belugas had left the area.

The sequential detections in November, first at PLN60, then at PLN40, and finally at PL50, are consistent with a southward overall movement in the fall as belugas migrate towards the Bering Strait. All tracks from satellite-tagged eastern Beaufort Sea belugas indicate that these animals follow the shelf edge along northern Alaska toward Wrangel Island when leaving the Beaufort Sea. They do not appear to cut through the eastern central Chukchi Sea (Richard et al., 2001) and are not the most plausible source for the calls detected at the Point Lay stations in November. On the other hand, all three eastern Chukchi Sea belugas with tags transmitting into November passed offshore of Point Lay (Suydam et al., 2005). Thus, it appears more likely that belugas from the eastern Chukchi Sea stock were the source of these Point Lay detections.

This study provided clear evidence for the consistent presence of belugas from as early as 13 April 2008 until early June in the northeastern Chukchi Sea. The first calls were detected not at the southernmost station of the array, located 80 km northwest of Point Lay (PL50), but 100 km north at PLN60, which raises questions about the migration routes of belugas after they cross the Bering Strait. Detections appeared at PL50 and PLN40 on 18 April 2008 and at W50 one day later, while calls were still being recorded at PLN60. Stations PL50 and W50 are separated by 150 km, which indicates that belugas were distributed over a broad area and that several groups of belugas were present in the Chukchi Sea. The large, though likely underestimated, size of the eastern Beaufort Sea stock ($n_{\min}$ = 32 453; Allen and Angliss, 2010) also suggests that belugas are likely to be broadly distributed and split into numerous groups while transiting through the Chukchi Sea. Aerial surveys conducted from April to June in 1980–84 yielded beluga sightings very close to shore between Cape Lisburne and Point Barrow as early as 24 April (Moore et al., 1993). However, these surveys were primarily restricted to inshore waters (less than 30 km from shore) except from 24 May to 10 June 1984, when coverage extended farther offshore. A few belugas were sighted about 100 km northwest of Cape Lisburne. The current data show that during the spring migration, some belugas can be found at least 150 km from shore (PLN60) in the Chukchi Sea from mid-April to early June.

Except for PL50, which became relatively ice-free around mid-May (Fig. 3c) as a consequence of the open-water lead forming every spring along the northwestern Alaskan coast (Moore and DeMaster, 1998), all other stations were under more than 90% ice cover throughout the spring detection period (Fig. 3b–d). However, belugas have repeatedly been found in heavy ice (> 90% cover) conditions (e.g., Suydam et al., 2001) and are consistently associated with ice (Moore et al., 2000). They can navigate under pack ice between leads separated by up to 2.8 km and break thin ice forming in the leads (Fraker, 1979). Furthermore, belugas can breathe though holes broken in thicker ice by bowheads (R. Suydam, pers. comm. 2010). Our acoustic detections confirm the affinity of belugas for sea ice. In April, when ice conditions were heaviest and relatively uniform in the study area, the largest number of detection days occurred at PLN60, the most offshore station (Fig. 3b). In May, however, particularly off Point Lay, the detection period was longer at stations closer to shore (Fig. 5), where ice cover was lighter (Fig. 3c), suggesting that migrating belugas favored lighter ice conditions when available.

The substantial length of the detection period in the Chukchi Sea in spring (up to 37 consecutive days) can be interpreted as the belugas' spreading out of their numbers and migration in time and space. This explanation was proposed by Fraker (1979) as a means of reducing mortality risk associated with migrating through the pack ice for the population as a whole. The fact that two stocks with potentially different migration schedules transit through the Chukchi Sea could also result in an extended period of acoustic detections.

Eastern Chukchi and eastern Beaufort Sea belugas are believed to spend the winter in the Bering Sea (Hazard, 1988). Swimming speeds measured during the fall migration ranged from 1.6 to 6.4 km/h (Smith and Martin, 1994; Richard et al., 2001; Suydam et al., 2001). Assuming a direct path and a non-stop swimming speed of 4 km/h, belugas would have required a minimum of seven days to travel from the Bering Strait to PLN60 (about 650 km). Under this scenario, they would have had to leave no later than 7 April to reach this station by 13 April. More realistically, convoluted lead configuration, variable ice conditions during travel, and resting phases would likely increase travel distance and time. Nevertheless, the present departure time estimate is in agreement with previous reports suggesting that belugas leave the Bering Sea in late March or early April (Fraker et al., 1978).

Assuming that some of the detected belugas belonged to the eastern Chukchi Sea stock, it is worth noting that in spring 2008 belugas recorded at PL50 had an ice-free path to the Kasegaluk Lagoon from mid-May on (Fig. 3c). However, belugas typically do not arrive at the Lagoon before mid-June. Since detections at PL50 lasted until 2 June, some animals were present near this station for a minimum of two weeks while having the opportunity to head inshore. Although some of the detections at PL50 could reasonably be assigned to eastern Beaufort Sea belugas migrating past this recorder, it is also possible that some animals from the eastern Chukchi Sea stock were taking advantage of good foraging opportunities near PL50 along the ice edge, a typically productive environment (Dunbar, 1981), before heading inshore. The observation that belugas captured during the subsistence hunt in Kasegaluk Lagoon lack significant stomach content suggests that they do not feed while in the lagoon (Suydam et al., 2005) and that they may need to build up reserves before they move inshore. Belugas are known to prey on the ice-associated arctic cod (*Boreogadus* *saida*) (Seaman et al., 1982), and predation on that species may be a good motivator in all seasons (Moore et al., 2000). However the distribution of arctic cod in the Chukchi Sea, particularly in spring, is poorly known. Belugas seen at coastal summer aggregations have also been observed moving back and forth between the coast and the ice edge, presumably to feed (Frost et al., 1993).

It is reasonable to assume that some of the recorded calls were produced by eastern Beaufort Sea belugas, since the eastern Beaufort Sea stock is considerably larger (n_{min} = 32 453; Allen and Angliss, 2010) than the eastern Chukchi Sea stock (n_{min} = 3710; Small and DeMaster, 1995). After transiting through the Chukchi and Beaufort seas, eastern Beaufort Sea belugas are observed by Inuvialuit offshore of Banks Island's west coast as early as May and June, which coincides with the onset of ice break-up (Fig. 1), and were first seen in the Gulf of Amundsen on 23 May in 1977 (Fraker, 1979; Norton and Harwood, 1986). Between 1974 and 1977, belugas migrating toward the eastern Beaufort Sea were seen off Barrow as early as 21 April and as late as 3 June (Fraker, 1979). Thus, it is likely that the earliest detections in this study were associated with migrating eastern Beaufort Sea belugas.

Passive acoustic monitoring provides an efficient and cost-effective way to monitor belugas throughout the year, under the ice, in remote areas and is not limited by factors typically affecting visual surveys, such as darkness and poor weather conditions. However, this method also has its drawbacks. Only vocalizing animals can be detected, and differences in vocalization rates between age classes or sex classes could bias our perception of beluga distribution. Additionally, belugas vocalize at high frequency (e.g., Belikov and Bel'kovich, 2006). These frequencies attenuate rapidly, and the detection range of recorders is thus limited. In the case of the array configurations chosen for this study, belugas detected at one sensor could not be heard by the others except for the closest recorders (8 km spacing) in some cases. Because of the spacing, location, and duty cycle of recorders during the overwinter deployment, a number of migrating belugas were likely undetected, in particular those migrating along the shore (Moore et al., 1993). The failure to detect these animals could bias our results against the detection of eastern Chukchi Sea belugas, which may be more likely to follow the coast en route to their coastal aggregation sites in Kasegaluk Lagoon.

CONCLUSIONS

Belugas were detected in the Chukchi Sea in every month between April and November. Our detections in the summer were restricted to the northeastern Chukchi Sea, but they ranged more broadly in the spring, probably as a consequence of the large number of belugas migrating through the area towards summer concentration areas. The spring detections of belugas most likely included individuals from both the eastern Chukchi and eastern Beaufort Sea stocks. Whether both stocks migrate simultaneously or not remains unknown. The considerably longer migration undertaken by eastern Beaufort Sea belugas to reach their summer grounds in the southeastern Beaufort Sea, where they arrive around the time when eastern Chukchi Sea animals arrive in Kasegaluk Lagoon, suggests that the eastern Beaufort Sea belugas pass through the Chukchi Sea earlier. However, considering the lack of knowledge on spring movements by eastern Chukchi Sea belugas, one cannot rule out their presence in the Chukchi Sea as soon as conditions allow. Additional acoustic monitoring would contribute to explaining variation in beluga use of the Chukchi Sea in spring, summer, and autumn.

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REFERENCES

Allen, B.M., and Angliss, R.P. 2010. Alaska marine mammal stock assessments, 2009. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-206. 276 p. http://www.afsc.noaa.gov/techmemos/nmfs-afsc-206.html.

Belikov, R.A., and Bel'kovich, V.M. 2006. High-pitched tonal signals of beluga whales (*Delphinapterus leucas*) in a summer assemblage off Solovetskii Island in the White Sea. Acoustical Physics 52:125–131, doi:10.1134/S1063771006020023.

———. 2008. Communicative pulsed signals of beluga whales in the reproductive gathering off Solovetskii Island in the White Sea. Acoustical Physics 54:115–123, doi:10.1134/S1063771008010168.

Brown Gladden, J.G., Ferguson, M.M., Friesen, M.K., and Clayton, J.W. 1999. Population structure of North American beluga whales (*Delphinapterus leucas*) based on nuclear DNA microsatellite variation and contrasted with the population structure revealed by mitochondrial DNA variation. Molecular Ecology 8:347–363, doi:10.1046/j.1365-294X.1998.00559.x.

Cavalieri, D., Markus, T., and Comiso, J. 2004. AMSR-E/Aqua Daily L312.5 km brightness temperature, sea ice concentration, & snow depth polar grids V002, [Oct. 20th 2007–Jan. 5th 2008]. Boulder, Colorado: National Snow and Ice Data Center. Digital media (updated daily).

Delarue, J., Martin, B., and Yurk, H. 2010. Killer whale acoustic detections in the Chukchi Sea: Insights into their ecology and stock affiliation. Alaska Marine Science Symposium, 18–22 January 2010, Anchorage, Alaska.

Dunbar, M. 1981. Physical causes and biological significance of polynyas and other open water in sea ice. In: Stirling, I., and

Cleator, H., eds. Polynyas in the Canadian Arctic. Canadian Wildlife Service Occasional Paper 45. 29–43.

ESRI. 2006. ArcView 9.2. Redlands, California: ESRI.

Finley, K.J. 1982. The estuarine habit of the beluga or white whale *Delphinapterus leucas*. Cetus 4(2):4–5.

Ford, J.K.B. 1989. Acoustic behaviour of resident killer whales (*Orcinus orca*) off Vancouver Island, British Columbia. Canadian Journal of Zoology 67:727–745.

Fraker, M.A. 1979. Spring migration of bowhead (*Balaena mysticetus*) and white whales (*Delphinapterus leucas*) in the Beaufort Sea. Ottawa: Fisheries and Oceans Canada. 36 p.

Fraker, M.A., Sergeant, D.E., and Hoek, W. 1978. Bowhead and white whales in the southern Beaufort Sea. Beaufort Sea Project Technical Report 7. Victoria, British Columbia: Department of Fisheries and the Environment. 114 p.

Frost, K.J., and Lowry, L.F. 1990. Distribution, abundance, and movements of beluga whales, *Delphinapterus leucas*, in coastal waters of western Alaska. In: Smith, T.G., St. Aubin, D.J., and Geraci, J.R., eds. Advances in research on the beluga whale, *Delphinapterus leucas*. Canadian Bulletin of Fisheries and Aquatic Sciences 224:39–57.

Frost, K.J., Lowry, L.F., and Carroll, G. 1993. Beluga whale and spotted seal use of a coastal lagoon system in the northeastern Chukchi Sea. Arctic 46:8–16.

George, J.C., and Suydam, R. 1998. Observations of killer whale (*Orcinus orca*) predation in the northeastern Chukchi and western Beaufort seas. Marine Mammal Science 14:330–332.

Gurevich, V.S. 1980. Worldwide distribution and migration patterns of the white whale (beluga), *Delphinapterus leucas*. Report of the International Whaling Commission 30: 465–480.

Hazard, K. 1988. Beluga whale *Delphinapterus leucas*. In: Lenfter, J.W., ed. Selected marine mammals of Alaska: Species accounts with research and management recommendations. Washington, D.C.: U.S. Marine Mammal Commission. 195–235.

Heide-Jørgensen, M.P. 2008. Narwhal *Monodon monoceros*. In: Perrin, W.F., Würsig, B., and Thewissen, J.G.M., eds. Encyclopedia of marine mammals. San Diego: Academic Press. 783–787.

Karlsen, J.D., Bisther, A., Lydersen, C., Haug, T., and Kovacs, K. 2002. Summer vocalisations of adult male white whales (*Delphinapterus leucas*) in Svalbard, Norway. Polar Biology 25:808–817, doi:10.1007/s00300-002-0415-6.

Moore, S.E., and DeMaster, D.P. 1998. Cetacean habitats in the Alaskan Arctic. Journal of Northwest Atlantic Fishery Science 22:55–69.

Moore, S.E, Clarke, J.T., and Johnson, M.M. 1993. Beluga distribution and movements offshore northern Alaska in spring and summer, 1980–1984. Report of the International Whaling Commission 43:375–386.

Moore, S.E., DeMaster, D.P., and Dayton, P.K. 2000. Cetacean habitat selection in the Alaskan Arctic during summer and autumn. Arctic 53:432–447.

Norton, P., and Harwood, L.A. 1986. Distribution, abundance and behavior of white whales in the Mackenzie Estuary. Environmental Studies Revolving Funds, Report 036. 73 p.

O'Corry Crowe, G.M., Suydam, R.S., Rosenberg, A., Frost, K.J., and Dizon, A.E. 1997. Phylogeography, population structure and dispersal patterns of the beluga whale *Delphinapterus leucas* in the western Nearctic revealed by mitochondrial DNA. Molecular Ecology 6:955–970.

O'Corry-Crowe, G.M., Dizon, A.E., Suydam, R.S., and Lowry, L.F. 2002. Molecular genetic studies of population structure and movement patterns in a migratory species: The beluga whale (*Delphinapterus leucas*) in the western Nearctic. In: Pfeiffer, C.J., ed. Molecular and cell biology of marine mammals. Melbourne, Florida: Krieger Publishing Company.

Richard, P.R., Martin, A.R., and Orr, J.R. 2001. Summer and autumn movements of belugas of the Eastern Beaufort Sea stock. Arctic 54:223–236.

Simard, Y., Roy, N., Giard, S., Gervaise, C., Conversano, M., and Ménard, N. 2010. Estimating whale density from their whistling activity: Example with St. Lawrence beluga. Applied Acoustics 71:1081–1086, doi:10.1016/j.apacoust.2010.05.013.

St. Aubin, D.J., Smith, T.G., and Geraci, J.R. 1990. Seasonal epidermal molt in beluga whales, *Delphinapterus leucas*. Canadian Journal of Zoology 68:339–367.

Seaman, G.A., Frost, K.J., and Lowry, L.F. 1982. Foods of belukha whales (*Delphinapterus leucas*) in western Alaska. Cetology 44:1–19.

Shapiro, A.D. 2006. Preliminary evidence for signature vocalizations among free-ranging narwhals (*Monodon monoceros*). Journal of the Acoustical Society of America 120:1695–1705.

Sjare, B.L., and Smith T.G. 1986. The vocal repertoire of white whales, *Delphinapterus leucas*, summering in Cunningham Inlet, Northwest Territories. Canadian Journal of Zoology 64:407–415.

Small, R.J., and DeMaster, D.P. 1995. Alaska marine mammal stock assessments 1995. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-57. 93 p. http://www.nmfs.noaa.gov/pr/sars/region.htm.

Smith, T.G., and Martin, A.R. 1994. Distribution and movements of belugas, *Delphinapterus leucas*, in the Canadian High Arctic. Canadian Journal of Fisheries and Aquatic Sciences 51:1653–1663.

Stirling, I., Calvert, W., and Spencer, C. 1987. Evidence of stereotyped underwater vocalizations of male Atlantic walruses (*Odobenus rosmarus rosmarus*). Canadian Journal of Zoology. 65:2311–2321.

Suydam, R.S., Lowry, L.F., Frost, K.J., O'Corry-Crowe, G.M., and Pikok, D., Jr. 2001. Satellite tracking of eastern Chukchi Sea beluga whales into the Arctic Ocean. Arctic 54:237–243.

Suydam, R.S., Lowry, L.F., and Frost, K.J. 2005. Distribution and movements of beluga whales from the eastern Chukchi Sea stock during summer and early autumn. OCS Study MMS2005-035.http://www.mms.gov/alaska/reports/2005rpts/2005_035.pdf.