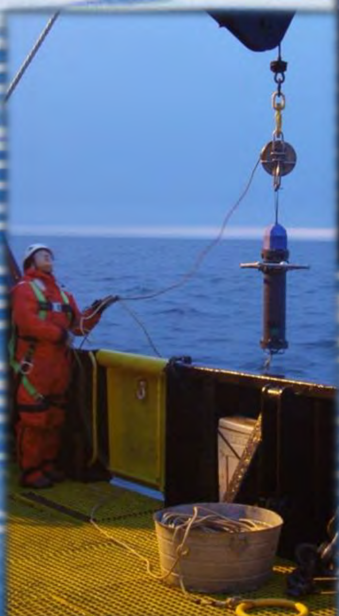
NORTHEASTERN CHUKCHI SEA
JOINT ACOUSTIC MONITORING PROGRAM 2014–2015






Prepared for

Shell Exploration & Production Company
Anchorage, Alaska

Prepared by

JASCO Applied Sciences (Canada) Ltd.

Report Authors
Héloïse Frouin-Mouy
Jeff MacDonnell
Julien Delarue
Xavier Mouy
Bruce Martin
David Hannay

Final Report
Document 01214
29 Jun 2016

Suggested citation:

Frouin-Mouy, H., J. MacDonnell, J. Delarue, X. Mouy, B. Martin, and D. Hannay. 2016. Northeastern Chukchi Sea Joint Acoustic Monitoring Program 2014–2015. Document #01214. Technical report by JASCO Applied Sciences for Shell Exploration & Production Company.

Cover photos, bottom left clockwise: JASCO Autonomous Multichannel Acoustic Recorder G2 (Julien Delarue, JASCO); bearded seal (U.S. Fish and Wildlife Service); bowhead whale (Fisheries and Oceans Canada); and Pacific walrus (Eric Lumsden, JASCO).

Contents

Figures

Tables

1. Introduction

This report presents the results of the winter 2014–2015 and summer 2015 seasons of the regional Acoustic Monitoring Program in the northeastern Chukchi Sea conducted for Shell Exploration & Production Company. These underwater acoustic recorder deployments were designed to extend the dataset collected under the multi-year Chukchi Sea Environmental Science Program (CSESP) using methods and study locations that are consistent with those from the previous years of the program: 2007–2014. Shell fully funded the 2014–2015 program.

Shell began baseline acoustic monitoring in the Chukchi Sea in summer 2006 and 2007 as a component of their Arctic marine mammal research programs. In 2007, ConocoPhillips initiated sponsorship of CSESP that included an acoustic monitoring component. Shell and ConocoPhillips jointly sponsored CSESP in 2008 and both companies have contributed support through 2014. Statoil USA Exploration and Production, Inc. contributed to joint sponsorship from 2010 to 2012. The Bioacoustics Research Program (BRP), based at the Cornell Laboratory of Ornithology, made the first acoustic measurements in summer 2006 and participated in the program in summer 2008. JASCO Applied Sciences Ltd. (JASCO) has conducted consecutive summer and winter acoustic recording studies since summer 2007 and has presented program results in yearly reports similar to this one.

1.1. Objectives of the Acoustic Monitoring Program

The objectives are to:

1. Document baseline ambient noise conditions.
2. Characterize sounds produced by oil and gas exploration activities.
3. Examine the spatial and temporal distribution of marine mammals based on acoustic detections of their vocalizations[1].

The Acoustic Monitoring Program is meeting these objectives using autonomous acoustic recording systems deployed on the seabed for long periods, across a large area of the northeastern Chukchi Sea. The data acquired under this program cover a continuous period of more than seven years (2007 to present) at multiple locations. In terms of temporal and spatial coverage, the data represent one of the largest and most comprehensive sets of underwater acoustic recordings, totaling over 54 years of acoustic data. They include millions of marine mammal calls and thousands of hours of vessel noise, seismic survey noise, and weather and ice-related sounds.

Ambient noise conditions are discussed in Section 3.1. Anthropogenic sound characterization specifically related to seismic survey exploration and vessel traffic, is discussed in Sections 3.2 and 3.3, respectively. Spatio-temporal distribution of vocalizing marine mammals is discussed in Section 3.4.

[1] Although many sounds made by marine mammals do not originate from vocal cords, the term “vocalization” is used as a generic term to cover all sounds produced by marine mammals that are discussed in this report. The term “call” is used synonymously for brevity.

The majority of this report addresses Objective 3. The Acoustic Monitoring Program was partly designed to gather information about several marine mammal species' spatial and temporal distributions, habitat usage, calling behaviors, and migration paths. One emphasis of the study was to localize vocalizing bowhead whales (*Balaena mysticetus)* in offshore areas near oil and gas exploration leases because bowheads are an important food source to subsistence hunters in the area.

The bowhead migration patterns close to the Alaskan coast are well understood by local subsistence whalers. Migration in offshore areas, however, was poorly understood at the beginning of this program in 2006. In parallel with results from tagging studies led by the Alaska Department of Fish and Game (see e.g., Quakenbush et al. 2010), the results of the passive acoustic monitoring studies have and continue to improve our understanding of bowhead fall migration routes and timing. For instance, passive acoustic data collected from recorders deployed north of Hanna Shoal in winter 2011–2012 and 2012–2013 helped us better understand migration behavior by gathering information from areas that were not sampled, because data collection by means other than acoustic recordings is difficult to achieve. The difficulties arise due to the frequently adverse weather conditions, ice presence, and remoteness.

Objective 3 includes the collection of new data on walrus (*Odobenus rosmarus*) habitat use in the northeastern Chukchi Sea. In parallel with the results from tagging studies led by the U.S. Geological Survey (see e.g., Jay et al. 2012), the 2007 to 2009 acoustic recorder deployments provided new and significant information about walrus presence and migration timing (Martin et al. 2009, Delarue et al. 2010a, Martin et al. 2010). Calls from walruses near large terrestrial haul-outs, primarily near Point Lay, were identified acoustically in several years. These data also showed walruses moving between on-shore haul-outs and the Hanna Shoal foraging areas. The 2010 deployments yielded data showing seismic survey noise might affect walrus communications (Delarue et al. 2011a).

Objective 3 also aims to document the occurrence of beluga whales in offshore areas. Large numbers of CSESP acoustic detections in spring indicate that beluga whales seasonally migrate through the lease areas of the northeastern Chukchi Sea. Low detection numbers in summer are consistent with the moderate overlap between the summer range of the eastern Chukchi Sea beluga population with the acoustic array (Hauser et al. 2014) and the small size of that population (Allen and Angliss 2013). Fall recordings within the lease areas also yielded far fewer detections than spring recordings, which suggest that the bulk of the fall migration path does not pass through the same areas, or that belugas are vocalizing less during the fall. Recent analyses of telemetry data suggest that the largest stock of belugas (eastern Beaufort Sea) generally migrates along the Chukchi shelf break in the fall, circumnavigating the acoustically instrumented study area. Indeed, belugas were not detected even in acoustic data collected north of Hanna Shoal in 2011 and 2012. Eastern Chukchi Sea belugas, however, migrate through our monitoring area, with a peak in November. The low fall detection rate reflects a small population traveling through a large study area with relatively sparse recorder coverage.

1.2. Overview of Marine Mammals Presence

The Acoustic Monitoring Program identified vocalizations from the following marine mammal species:

- Bowhead whale (*Balaena mysticetus*)
- Beluga whale (*Delphinapterus leucas*)
- Gray whale (*Eschrichtius robustus*)
- Fin whale (*Balaenoptera physalus*)
- Killer whale (*Orcinus orca*)
- Minke whale (*Balaenoptera acutorostrata*)
- Humpback whale (*Megaptera novaeangliae*)
- Walrus (*Odobenus rosmarus*)
- Bearded seal (*Erignathus barbatus*)
- Ribbon seal (*Histriophoca fasciata*)
- Ringed seal (*Pusa hispida*)

Some low-frequency sounds, possibly produced by fish, were also detected, but have not as of yet been classified.

Winter acoustic data (mid-October through July):

- Provided important information on migration timing and distribution of bowhead and beluga whales during their fall and spring migrations.
- Documented the prevalence of beluga and bowhead whales in coastal leads during the spring migration, even though some individuals migrated farther offshore through the lease areas.
- Documented the yearlong occurrence of ringed and bearded seals, the return of walruses in the spring and gray whales in early summer, and sporadic detections of ribbon seals and minke whales in the fall.

Summer acoustic data (August through mid-October):

- Provided information on the presence of several marine mammal species during the ice-free season, a time of increased species diversity and anthropogenic activity (with possible auditory effects, called "masking") in the northeastern Chukchi Sea.
- Confirmed the study area's importance to walruses and described movements between Hanna Shoal and shore haul-outs near Wainwright and Point Lay associated with the disappearance of sea ice.
- Consistently demonstrated the scarce acoustic presence of bowheads and belugas in the northeastern Chukchi Sea in July and August, and their return in late September and October coinciding with the onset of the fall migration in the area.

- Illustrated that vocalizing bowheads follow a fall migration corridor centered along the 71st parallel latitude as they move west past Barrow.
- Documented the annual recurrence of non-Arctic species including killer, fin, minke, and humpback whales, albeit these detections were low overall.

1.3. Recorder Deployments 2006–2015

In summer 2006, the Cornell Lab of Ornithology's Bioacoustics Research Program carried out an Acoustic Monitoring Program for Shell. Marine Autonomous Recording Units (MARUs) were deployed in two phases:

1. 6 recorders from mid-July to mid-August 2006 sampled acoustic data on a duty cycle at 10 kHz sampling rate.
2. 22 recorders from mid-August to mid-October 2006 sampled continuously at 2 kHz sampling rate.

Since July 2007, JASCO has conducted consecutive summer and winter passive acoustic studies with Autonomous Multichannel Acoustic Recorders (AMARs) and Autonomous Underwater Recorders for Acoustic Listening (AURALs), which sample at 16,000 and 16,384 Hz, respectively (Figure 1), which record acoustic frequencies of up to 8 kHz. The summer recording periods included four lines of recorders starting at Cape Lisburne, Point Lay, Wainwright, and Barrow and extending up to 135 miles off the coast. Additional clusters of recorders were deployed near lease blocks and well sites as follows:

- Summer 2008: Cornell deployed one cluster of 13 MARUs around the Klondike and one around the Burger well sites.
- Summer 2009: JASCO deployed clusters of 12 AMARs each around the Klondike and Burger well sites.
- Summer 2010: JASCO deployed clusters of seven AMARs each around the Klondike and Burger well sites, and in the Statoil lease area.
- Summer 2011: JASCO deployed a single AMAR at both the Klondike and Burger well sites, and one near the Statoil lease area.
- Summer 2012: JASCO deployed one AMAR each near the Klondike well site and in the Statoil lease area, and seven AMARs around the Burger well sites.
- Summer 2013: JASCO deployed one AMAR near the Klondike well site and one in the Statoil lease area, and eleven AMARs around the Burger well sites. We focused more on the Burger lease area as a continuation of the 2012 monitoring effort, which was focused on Shell's drilling activities.
- Summer 2014: JASCO deployed one AMAR near the Klondike well site, and six AMARs around the Burger well sites even though no drilling activities occurred there in this year.
- Summer 2015: for the vessel Sound Source Characterization (SSC), JASCO deployed three AMARs; for the drilling and zero-offset vertical seismic profiling (ZVSP) Sound Source Verification (SSV), JASCO deployed six AMARs along a radial from each drill site (Burger-

J and Burger-V); JASCO deployed one AMAR near the Klondike well site, and three AMARs around the Burger well sites.

During the winter recording periods, recorders were deployed in mid-October and retrieved the following year in July or August. The recorders typically operated for 7–10 months, limited mainly by battery life. Between 2007 and 2011, five to nine recorders were deployed throughout the program area. Starting in 2011, the winter program included six AURALs deployed on the northern side of Hanna Shoal, resulting in 15 winter recorders total. These stations were redeployed for winter 2012–2013, but not subsequently. Three nearshore recorders were deployed in winter 2013–2014 and winter 2014–2015 to document the movements of spring migrating bowhead and beluga whales.

The winter session recorders had the following duty cycles:

- 2007–2008: 5 recorders set to a 20% duty cycle.
- 2008–2009: 7 recorders set to a 17% duty cycle.
- 2009–2010: 8 recorders set to a 17% duty cycle.
- 2010–2011: 8 recorders set to a 17% duty cycle.
- 2011–2012: 9 recorders set to a 17% duty cycle and 6 recorders at Hanna Shoal set to a 12.5% duty cycle.
- 2012–2013: 9 recorders set to a 17% duty cycle and 6 recorders at Hanna Shoal set to a 12.5% duty cycle.
- 2013–2014: 8 recorders set to a 17% duty cycle.
- 2014–2015: 6 recorders set to a 17% duty cycle and 1 recorder set to a 24% duty cycle.

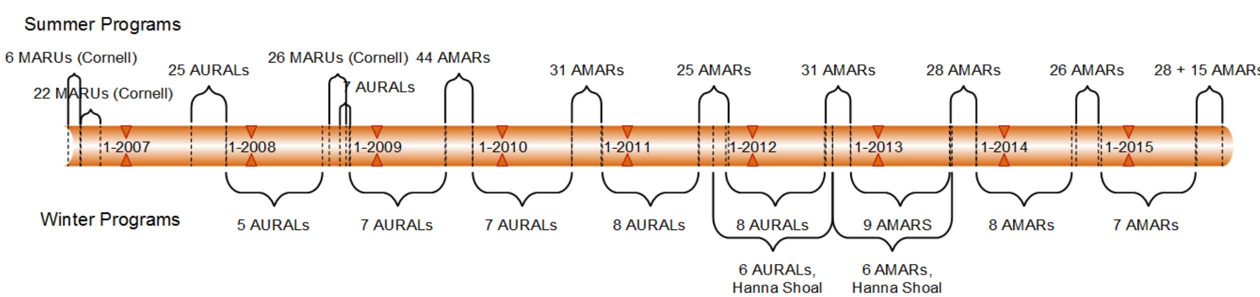


Figure 1. Timeline of Chukchi Sea Acoustic Monitoring Program, 2006 to 2015.The acoustic data acquired in 2014–2015 were analyzed to quantify ambient sound levels, the presence of anthropogenic activity, and the acoustic presence of marine mammals. The ambient noise measurements add to the growing knowledge of underwater Arctic soundscape baseline conditions, thus providing information for inter-annual comparisons. Although Objective 3 focused on bowhead whales, walruses, and beluga whales, this report also discusses the acoustic presence of other detected species.

2. Methods

2.1. Data Acquisition

2.1.1. Acoustic Recorders

All acoustic data were recorded using AMARs (JASCO Applied Sciences) with a single omnidirectional hydrophone and was powered by two D-cell alkaline battery packs.

- Winter 2014–2015: Acoustic data from seven AMARs (Table 1) were recorded on internal flash memory at 24-bit resolution and 16,000 samples per second (16 ksps). Each AMAR was fitted with a GTI−M8E hydrophone (−164 dB re 1 V/µPa nominal sensitivity) and set to 6 dB gain. The broadband noise floor was 67 dB re 1 µPa. One AMAR (W10) recorded data sampled at 375 ksps using the same hydrophone, with a 16-bit resolution.
- Summer 2015: 28 AMARs (Table 2) recorded acoustic data, used for the marine mammal analysis, on internal flash memory at multiple sample rates. Those AMARs were fitted with a GTI−M8E (Geospectrum Technologies Inc.) hydrophone (−164 dB re 1 V/µPa nominal sensitivity) and set to 6 dB gain. The broadband noise floor was 67 dB re 1 µPa. Additional sensitivity and noise information is reported in Table 3.

Table 1. Overwinter 2014–2015 recorder configurations.

Recording station	Sampling Rate (samples/s)	Duty Cycle (s)
CL5	16000 Sleep	300 1500
PL10	16000 Sleep	300 1500
PL50	16000 Sleep	300 1500
PLN40	16000 Sleep	300 1500
W10	16000 375000 Sleep	300 130 1370
W50	16000 Sleep	300 1500
WN40	16000 Sleep	300 1500

Table 2. Summer 2015 recorder configurations, used for marine mammal analysis.

Recording station	Sampling Rate (samples/s)	Duty Cycle (s)
B5	16000 375000 Sleep	150 60 990

B15	16000 Sleep	300 1500
B30	16000 Sleep	300 1500
BGJ16	64000 Sleep	1620 180
BGV16	64000 Sleep	1620 180
BG01	64000 Sleep	1620 180
BG02	64000 Sleep	1620 180
BG03	16000 375000	770 130
CL5	16000	Continuous
CL50	16000	Continuous
CLN120	16000 375000	770 130
CLN40	16000	Continuous
CLN90	16000	Continuous
HSW1	16000	Continuous
HSW2	16000	Continuous
HSW3	16000	Continuous
HSW4	16000	Continuous
KL01	16000	Continuous
PL10	16000	Continuous
PL30	16000	Continuous
PL50	16000	Continuous
PLN20	16000	Continuous
PLN40	16000 375000	770 130
PLN60	16000	Continuous
PLN80	16000	Continuous
W10	16000 375000	770 130
W30	16000	Continuous
W50	16000	Continuous

Table 3. Sensitivity and noise data for the hydrophone (M8E-35dB).

Nominal Sensitivity (dBV / µPa)	Maximum measureable SPL (dB re 1 µPa)	Sampling Rate (samples/s)	System Spectral Noise Floor (dB re 1 µPa^2/Hz)	Recording Bandwidth (Hz)
-164	171	16000	34-39	10-7600
		64000	28-33	10-30000
		375000	35-40	10-180000

Each AMAR was deployed on the seafloor with a rectangular frame that kept the top of the recorder and its hydrophone secured off the seafloor. A sinking ground line about 2.5 times the water depth connected the recorder to a small weight for grapple retrieval (Figure 2).

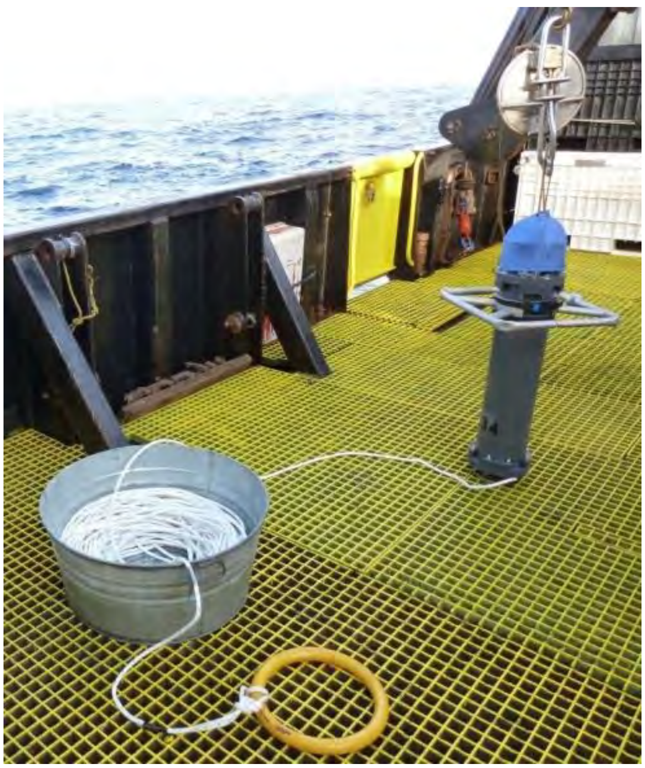


Figure 2. An AMAR just before it was deployed in the northeastern Chukchi Sea.

2.1.2. Winter 2014–2015 Recording Period

Acoustic data for the winter 2014–2015 recording period were acquired using seven AMARs deployed off Cape Lisburne, Point Lay, Wainwright, and Barrow (Figure 3). All recorders but W10 were set to record at 16 ksps for 5 min of every 30 min (i.e., a 17% duty cycle) due to battery limitations. Station W10 was set to record on the following duty cycle: 300 s at 16 ksps followed by 130 s at 375 ksps followed by 1370 s of sleep (Table 1).

The winter AMARs were deployed from 9–17 Oct 2014. Three recorders (PL10, PLN40, and W50) stopped prematurely. Four recorders performed as intended and acquired data from 298 to 323 days (Table 4).

Ice concentration data were obtained from the Ocean and Sea Ice SAF website (http://osisaf.met.no/archive/ice/). The grid size for these data is 10 km.

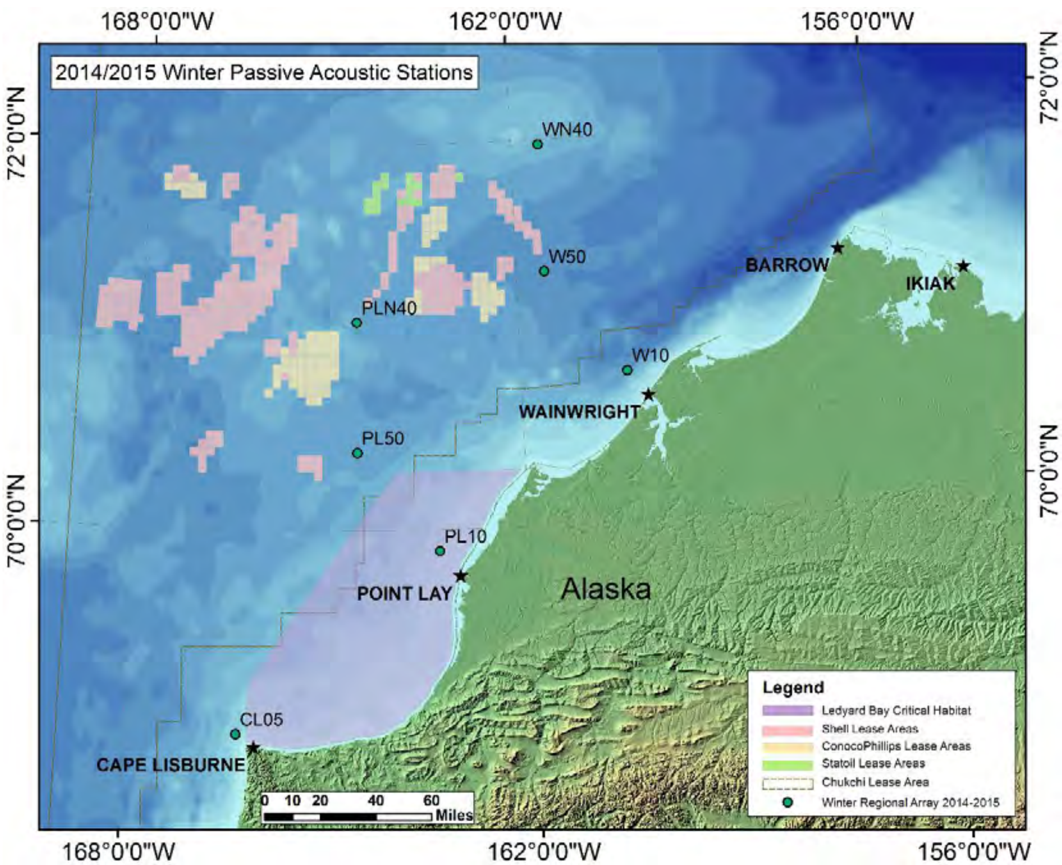


Figure 3. Winter 2014–2015 stations of the Acoustic Monitoring Program in the northeastern Chukchi Sea. Shades of blue represent water depth.

Table 4. Recorder locations (see Figure 3) and recording durations for the winter 2014–2015 Acoustic Monitoring Program. From deployment to the end of recording, the AMARs operated on 17% duty cycles (recording 5 min of every 30 min) or on 24% duty cycles (W10 recorded 300 s at 16 ksps, then 130 s at 375 ksps, followed by 1370 s of sleep). Dates are in UTC.

Station	Latitude (°N)	Longitude (°W)	Deployment	Record end	Recording days
CL5	68.94190	-166.37760	17 Oct 2014	10 Aug 2015	298
PL10	69.88900	-163.35300	9 Oct 2014	29 Nov 2014	52
PL50	70.40350	-164.58748	9 Oct 2014	11 Aug 2015	307
PLN40	71.08010	-164.58447	13 Oct 2014	9 Dec 2014	58
W10	70.77565	-160.32843	15 Oct 2014	11 Aug 2015	301
W50	71.31567	-161.54725	16 Oct 2014	27 Jan 2015	104
WN40	71.97425	-161.53547	12 Oct 2014	30 Aug 2015	323

2.1.3. Summer 2015 Recording Period

Acoustic data for the summer 2015 Regional Array were acquired with 26 AMARs. Eighteen AMARS were deployed along four lines extending offshore from Cape Lisburne, Point Lay, Wainwright, and Barrow. The lines ran perpendicular from the coastline for 50 nautical miles (mi) and then northward to approximately 120 mi offshore (Figure 4). Recorders WN20, WN40, WN60, and WN80 were not deployed in summer 2015 due to Hanna Shoal access restrictions from the US Fish and Wildlife Service. These recorders were repositioned to the boundary of the Hanna Shoal Walrus Use Area, at locations HSW1 through HSW4 (Figure 4). Three AMARs were deployed close to the Burger drill site. One AMAR was deployed near the Klondike well site. The sampling rates and duty cycles of the recorders are shown in Table 2.

For the vessel sound source characterizations (SSC), three AMARs were deployed (Table 6) perpendicular to the SSC track line to record vessel sound levels at multiple distances away from the vessels. Each vessel transited along the track line for 15 km (9.3 mi). The AMARs were deployed 0, 500, and 1000 m perpendicular to the track line (Figure 4).

For the Drilling and ZVSP SSVs, twelve AMARs were deployed; six AMARs were positioned along radials leading away from each drill site at the following distances: 0.5, 1, 2, 4, 8, and 16 km (Figure 4, Table 7). The vessel and drilling SSV results are discussed in Shell's 2015 90-day (Austin and Li 2016) and comprehensive reports (Ireland et al 2016).

Wind speeds were acquired from the meteorological buoy deployed by Shell near station KL01 in the Klondike lease area.

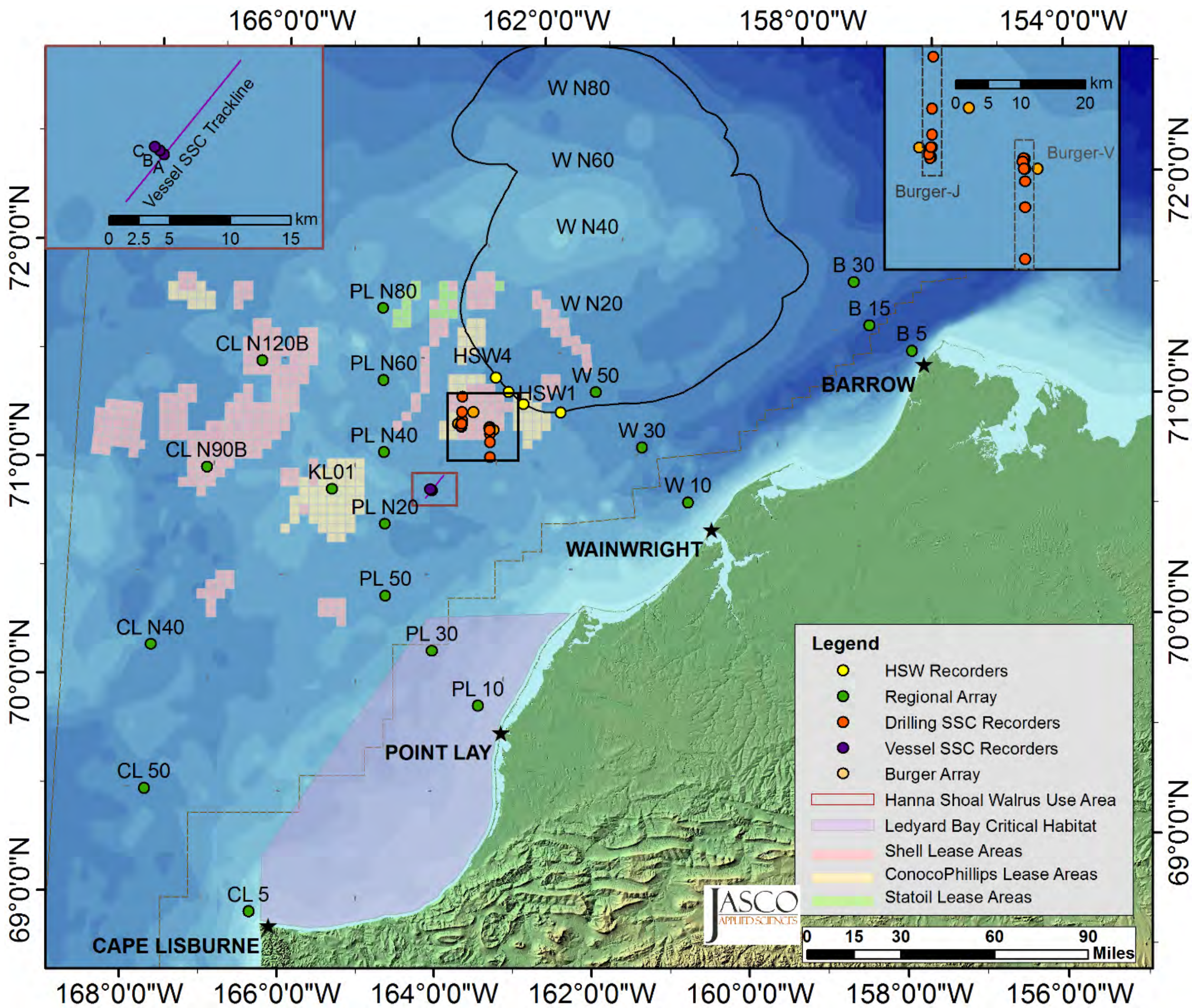


Figure 4. Recorder stations for the summer 2015 program in the northeastern Chukchi Sea. The inset map shows detail of the Burger array. Shades of blue represent water depth. The WN stations, monitored in previous years, are shown, but were not instrumented in 2015 due to restrictions entering the Hanna Shoal Walrus Use Area.

Table 5. Recorder locations (see Figure 4) and recording durations for the summer 2015 Acoustic Monitoring Program. Recorder duty cycles reported in Table 2. Dates are in UTC.

Station	Latitude (°N)	Longitude (°W)	Deployment	Record end	Recording days
B5	71.36312	-156.93725	13 Aug 2015	7 Oct 2015	56
B15	71.50410	-157.50108	13 Aug 2015	7 Oct 2015	56
B30	71.71168	-157.64853	13 Aug 2015	8 Oct 2015	57
BG01	71.19148	-163.52650	25 Jul 2015	2 Oct 2015	70
BG02	71.15777	-163.01905	25 Jul 2015	2 Oct 2015	70
BG03	71.24487	-163.30775	25 Jul 2015	2 Oct 2015	70
CL5	68.94148	-166.37508	10 Aug 2015	11 Oct 2015	63
CL50	69.49563	-167.78368	15 Aug 2015	11 Oct 2015	58

CLN40	70.15905	-167.78328	15 Aug 2015	9 Oct 2015	56
CLN90	70.98828	-167.09998	15 Aug 2015	4 Oct 2015	51
CLN120	71.48573	-166.34990	15 Aug 2015	3 Oct 2015	50
HSW1	71.22673	-162.04967	16 Aug 2015	2 Oct 2015	48
HSW2	71.27187	-162.58003	16 Aug 2015	2 Oct 2015	48
HSW3	71.33180	-162.78767	16 Aug 2015	2 Oct 2015	48
HSW4	71.40137	-162.96430	16 Aug 2015	2 Oct 2015	48
KL01	70.89727	-165.32893	14 Aug 2015	4 Oct 2015	52
PL10	69.88863	-163.35332	10 Aug 2015	12 Oct 2015	64
PL30	70.14688	-163.96303	11 Aug 2015	9 Oct 2015	60
PL50	70.40312	-164.58798	11 Aug 2015	9 Oct 2015	60
PLN20	70.73507	-164.58750	14 Aug 2015	8 Oct 2015	56
PLN40	71.06698	-164.58747	14 Aug 2015	4 Oct 2015	52
PLN60	71.39885	-164.58747	14 Aug 2015	3 Oct 2015	51
PLN80	71.73077	-164.58798	15 Aug 2015	3 Oct 2015	50
W10	70.77568	-160.32693	11 Aug 2015	6 Oct 2015	57
W30	71.04417	-160.92425	11 Aug 2015	6 Oct 2015	57
W50	71.31063	-161.53772	14 Aug 2015	5 Oct 2015	53

Table 6. Recorder locations (see Figure 4) and recording durations for the summer 2015 vessel sound source characterizations. Stations are listed alphabetically.

Station	Latitude (°N)	Longitude (°W)	Deployment	Record end	Recording days
VESS_A	70.88665	-163.92530	24 Jul 2015	16 Aug 2015	24
VESS_B	70.88958	-163.93557	24 Jul 2015	16 Aug 2015	24
VESS_C	70.89242	-163.94605	24 Jul 2015	16 Aug 2015	24

Table 7. Recorder locations (see Figure 4) and recording durations for the summer 2015 Drilling and ZVSP SSVs. Stations are listed alphabetically.

Station	Latitude (°N)	Longitude (°W)	Deployment	Record end	Recording days
BGJ-0.5KM	71.17752	-163.47752	24 Jul 2015	4 Oct 2015	72
BGJ-0.5KM	71.17768	-163.48027	24 Jul 2015	4 Oct 2015	72
BGJ-1KM	71.18172	-163.48033	24 Jul 2015	4 Oct 2015	72
BGJ-1KM	71.18098	-163.48498	24 Jul 2015	1 Oct 2015	69
BGJ-2KM	71.19125	-163.47083	24 Jul 2015	5 Oct 2015	73
BGJ-2KM	71.19137	-163.47618	24 Jul 2015	1 Oct 2015	69
BGJ-4KM	71.20907	-163.46935	24 Jul 2015	5 Oct 2015	73
BGJ-8KM	71.24485	-163.46653	24 Jul 2015	5 Oct 2015	73
BGJ-16KM	71.31647	-163.45523	24 Jul 2015	5 Oct 2015	73
BGV-0.5KM	71.17155	-163.07487	25 Jul 2015	5 Oct 2015	72
BGV-0.5KM	71.17230	-163.08018	25 Jul 2015	25 Sep 2015	62

BGV-1KM	71.16732	-163.07903	25 Jul 2015	3 Oct 2015	70
BGV-1KM	71.16793	-163.08457	25 Jul 2015	8 Oct 2015	75
BGV-2KM	71.15843	-163.07433	25 Jul 2015	3 Oct 2015	70
BGV-2KM	71.15817	-163.08033	25 Jul 2015	2 Oct 2015	69
BGV-4KM	71.14025	-163.07643	25 Jul 2015	3 Oct 2015	70
BGV-8KM	71.10460	-163.07978	25 Jul 2015	3 Oct 2015	70
BGV-16KM	71.03300	-163.08455	25 Jul 2015	3 Oct 2015	70

2.2. Data Analysis Overview

Acoustic data were analyzed using a combination of automated and manual techniques. Ocean sound levels and the proportion to which anthropogenic activities contributed to them were quantified using automated procedures (Sections 2.4.1 through 2.4.3).

Marine mammal calls were detected and classified both manually and with JASCO's automated acoustic analysis software suite. Because of their conservation status and their importance to the Alaska North Slope communities, calls of three species—bowhead and beluga whales (Section 2.4.5) and walruses (Section 2.4.6)—were more thoroughly analyzed, using both manual and specialized automated approaches, than those of other species (Table 8). Bearded seal calls were detected with a generic automated detector (Section 2.4.4) and by manually analyzing 5% of the recorded data. Calls of other species were detected by manually analyzing 5% of the recorded data. Marine mammal call rates vary throughout the year and might depend on the calling animal's age and sex. Furthermore, several individuals might call simultaneously. Thus, the number of recorded calls of a species does not necessarily represent its abundance. Call counts should instead be interpreted as an index of acoustic occurrence.

Aside from establishing the acoustic occurrence of members of a species, manual analysis (Section 2.3) was performed to identify call types and to evaluate the performance of automated detector performance and classification methods. The automated detection and classification suite processed the entire dataset; it was the primary method used to determine the number of detected calls as a function of time at each recorder station. Seismic survey pulses were also identified and seismic signal and ambient sound levels calculated by the automated detector.

Table 8. Endangered Species Act (ESA) conservation status (Department of the Interior and U.S. Fish & Wildlife Service 2002) of marine mammal species in the northeastern Chukchi Sea and their generalized occurrence and tendency to vocalize. The first four species are of special interest for this report.

Species	ESA conservation status	Period	Occurrence	Vocalization tendency	Analysis method	
					Automated	Manual
Bowhead whales	Endangered	Apr–Jun	Common	High, decreasing	✓	✓
		Jul–Aug	Occasional	Low		
		Sep–Dec	Common	High, increasing		
Walruses	Candidate for listing	Jun–Oct	Abundant	High	✓	✓
		Nov–Dec	Occasional	High		

Beluga whales	–	Apr–Jun	Common	High	✓	✓
		Jul–Dec	Occasional	Moderate		
Bearded seals	–	Nov–Jun	Abundant	High	✓	✓
		Jul–Oct	Abundant	Low, increasing		
Fin whales	Endangered	Aug–Oct	Occasional	Low, increasing		✓
Gray whales	De-listed in 1994; Not threatened	Jul–Oct	Common	Low		✓
Humpback whales	Endangered	Aug–Sep	Occasional	Low to moderate		✓
Killer whales	–	Jul–Oct	Occasional	Low		✓
Minke whales	–	Aug–Oct	Occasional	Low	✓	✓
Ribbon seals	–	Sep–Nov	Occasional	Low		✓
Ringed seals	Threatened	All year	Abundant	Low		✓
Spotted seals	–	All year	Abundant	Unknown		

2.3. Manual Data Analysis

Four trained analysts used JASCO's PAMlab software to visually examine spectrograms and to listen to audio playback of calls, as necessary. The software provided a consistent set of tools for documenting the duration and bandwidth of each marine mammal call. All analysts had several years of experience classifying Arctic marine mammal vocalizations in previous Chukchi Sea datasets.

The purpose of the manual analysis was to:

- Assess where and when the target species (bowhead whales, walruses, beluga whales, and bearded seals) were acoustically present
- Identify non-target and extralimital species. In previous years, several species, such as killer and fin whales, were recorded occasionally. Acoustic detections of such species are valuable because they help us understand these animals' current habitat use in the Chukchi Sea and to describe changes in habitat use over time, the latter possibly stemming from environmental changes, including changes in ice conditions and prey availability, and possibly due to anthropogenic activity. Manual analysis is especially important in this context because automated classifiers are not configured and tested for all these species
- Assess how well automated classifiers perform. Precision and recall methods were used to quantitatively assess classifier performance by comparing outputs of the automated classifiers with the manual classifications for each species.

The probability of detection by our 5% manual analysis protocol is discussed in Appendix A.3, Probability of Detection by Manual Analysis. The probability is dependent on the number of calls in a file. This protocol was determined to be a reasonable compromise between the cost of the analysis and the probability of detecting the target species.

2.3.1. Manual Analysis Protocol

Five percent of the winter 2014–2015 and summer 2015 data from all operational recorders were analyzed manually.

The winter acoustic data were acquired on a duty-cycle, recording for 5 min every 30 min, yielding 48 sound files per day. The middle 30 s sample of every other data file was manually analyzed. Analysts annotated one call per species for all extracted 30 s samples and stations to record each species in the dataset. In addition, analysts annotated all marine mammal calls in a subset of samples randomly selected across days and stations. Automated detector performance was evaluated with these fully-annotated samples (see Appendix A.1).

The summer acoustic data were acquired continuously and stored in 30-minute sound files, which yielded 48 files per day. The middle 90 s sample of each 30 min file was manually analyzed. Analysts annotated one call per species per sample. Similar to the winter acoustic data treatment, analysts annotated all identified marine mammal vocalizations in a subset of samples randomly selected across days and stations to evaluate the performance of the automated detectors.

2.3.2. Analysis Validation

The lead analyst, Julien Delarue, reviewed a random subset of annotations from all analysts to ensure calls were accurately classified, to give the analysts feedback on their classifications, and to help classify calls that were difficult to attribute to a known call type. The lead analyst consulted with external researchers when new or unknown call types were detected.

The annotation review entailed verifying a sample of annotations of target (bowhead whales, walruses, beluga whales, and bearded seals) and non-target species, specifically focusing on annotations of less common species or those outside the expected range or residency period of common species, and identifying species initially tagged as "Unknown" by reviewing sample sounds.

2.4. Automated Data Analysis

There were 12.4 TB of acoustic data collected during the summer and winter programs. We used a specialized computing platform capable of rapidly processing acoustic data at hundreds of times faster than it was collected. The system performed automated analysis of total ocean noise, seismic survey sounds, vessel noise, and possible marine mammal calls as described previously (Section 2.2). Figure 5 outlines the stages of the automated analysis. Walrus, bowhead, and beluga whale calls were detected and classified with algorithms coded in MATLAB programming software (Mathworks Inc.) and executed separately on the computing platform (described in Sections 2.4.5 and 2.4.6).

Detailed descriptions of the algorithms and an analysis of the classifiers' precision and recall are documented in Delarue et al. (2015, Appendix A, Automated Detection and Classification of Marine Mammal Vocalizations and Anthropogenic Noise).

We also classified the dominant sound source in each minute of data as "Vessel", "Seismic", or "Ambient". To minimize the influence of anthropogenic sources on ambient sound level estimates, we defined ambient levels from individual minutes of data that did not have an anthropogenic detection within one hour on either side of that minute. This resulted in more accurate estimates of daily sound exposure levels from each source class, cumulative distribution functions of sound pressure levels, and exceedance spectra.

As first performed in 2012, we calculated the per-minute expected detection ranges for bowhead moan type calls based on the time-varying background noise level. The methods and results are described in Appendix D, Estimating the Detection Range of Bowhead Moans.

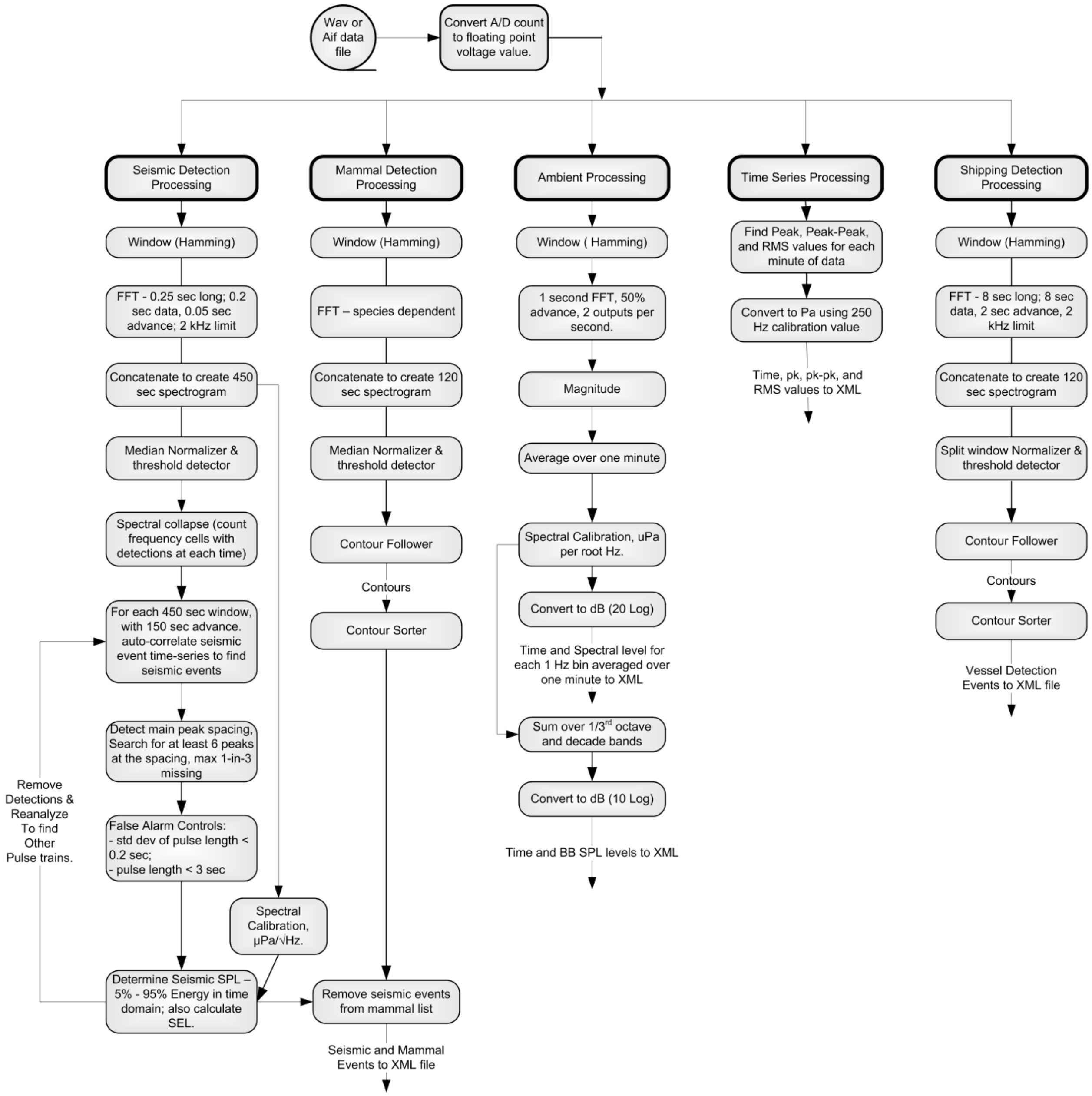


Figure 5. Major stages of the automated acoustic analysis software suite.

2.4.1. Total Ocean Noise and Time Series Analysis

The total ocean noise levels were quantified in 1 Hz frequency bins each second and these were averaged to produce sound spectral density values for each minute of recording. Further analyses yielded 1/3-octave band levels, decade band levels, and broadband sound pressure levels for each minute of data. More details about noise analysis methods and results are provided in Appendix B, Ambient Noise Results.

2.4.2. Vessel Noise Detection

Vessel detection was performed in two steps: (1) Constant, narrowband tones produced by the ship's propulsion system and other rotating machinery (Arveson and Vendittis 2000) were detected (Appendix A.4, Vessel Noise Detection). These are also referred to as tonals. (2) The root-mean-square sound pressure levels (SPL) were assessed for each minute in the 40–315 Hz frequency band, which commonly contains the majority of sound energy produced by mid-sized to large vessels. Background estimates of the shipping band SPL and broadband SPL were compared to their median values over the 12 h window, centered on the current time.

Shipping detections were defined by three criteria:

- The SPL in the shipping band was at least 3 dB above the median.
- At least 5 shipping tonals (0.125 Hz bandwidth) were present.
- The SPL in the shipping band was within 8 dB of the broadband SPL (Figure 6).

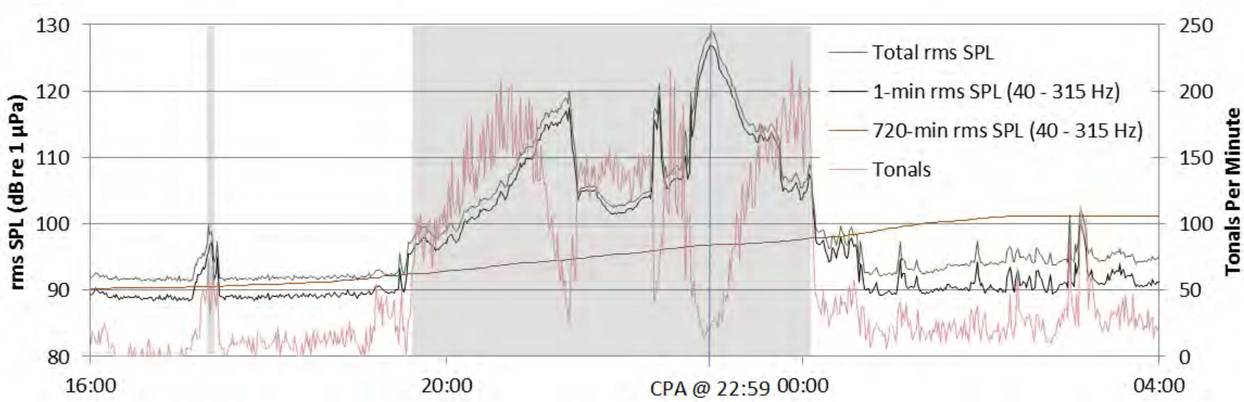


Figure 6. Example of broadband and in-band SPL, and the number of tonals detected per minute as a ship approached a recorder, stopped, and then departed. The shaded area is the period of shipping detection. Fewer tonals are detected at the ship's closest point of approach (CPA) at 22:59 because of masking by broadband cavitation noise and due to Doppler shift that affects the tone frequencies.

2.4.3. Seismic Survey Event Detection

Seismic pulse sequences were detected using correlated spectrogram contours. We calculated 300 s long spectrograms with 4 Hz frequency resolution and a 0.05 s time resolution (Reisz window). All frequency bins were normalized to their medians over the 300 s window. The detection threshold was three times the median value at each frequency. Contours were created by joining the time-frequency bins above threshold in the 7–1000 Hz band using a 5 × 5 bin kernel. Any contour 0.2–6 s with a bandwidth of at least 60 Hz was retained for further analysis.

An "event" time series was created by summing the normalized value of the frequency bins in each time step that contained detected contours. The event time series is auto-correlated to look for repeated events. The correlated data space was normalized to its median and a detection threshold of 3 was applied. Peaks larger than their two nearest neighbors were identified and the peaks list searched for entries with a set repetition interval. The allowed spacing between the minimum and maximum time peaks is 4.8 to 65 s, which captures the normal range of seismic pulse periods. Where at least six regularly spaced peaks occurred, the original event time series was searched for all peaks that matched the repetition period within a tolerance of 0.25 s. The duration of the 90% rms SPL window of each peak was determined from the originally sampled time series, and pulses more than 3 s long were rejected. For details on minimizing false alarms and measuring noise levels, see Appendix A.5, Seismic Survey Detection).

The performance of the seismic detector was evaluated on seismic airgun data from PLN80 in summer 2010 and determined to be highly precise ($P = 0.9997$; $R = 0.9949$), where precision (P) and recall (R) are explained in Section 2.4.7.

2.4.4. Generic Marine Mammal Call Detection

A specialized detector identified calls from walruses and from bowhead and beluga whales. A generic detector identified bearded seal calls.

Similar to seismic survey detection, automated detection of marine mammal vocalizations is achieved by comparing contour features in the frequency spectrum of signals. Analysis details are in Delarue et al. (2015, Appendix A.4, Bearded Seal Call Detection).

2.4.5. Bowhead and Beluga Whale Call Detection

Bowhead moans and beluga whistles were automatically detected and separately classified in two steps:

1. Time-frequency contours are detected and extracted from a normalized spectrogram using a tonal detector developed by Mellinger et al. (2011).
2. Each contour is represented by 46 features and presented to two-class random forest classifiers (i.e., bowhead whale vs. “other”, beluga whale vs. “other”).

Random forest classifiers are trained using the manually annotated calls. See Appendix A.2, Bowhead and Beluga Call Detection and Classification (Delarue et al. 2015), for a full technical description of the process and an evaluation of the performance of these classifiers.

The bowhead calls that can be detected include a variety of simple moans, as described by Clark and Johnson (1984) and Ljungblad et al. (1982). Although many song notes are structurally different and more complex than the moans targeted by the detector, most songs incorporate some moans in at least one of their phrases (Delarue et al. 2009), which makes this method ideal for detecting songs. Songs are a dominant component of the bowhead acoustic repertoire in fall, winter, and spring (Delarue et al. 2009).

2.4.6. Walrus Grunt Detection

The steps below detail the process used to quantify walrus calls using the walrus grunt detector/classifier, which is based on time-frequency representation of the acoustic signal:

1. The spectrogram was calculated and then segmented into time-frequency objects.
2. For each object, a set of contour features that represented salient grunt characteristics were extracted from the 20–1000 Hz frequency band of the spectrogram. Features included, but

were not limited to, minimum frequency, maximum frequency, frequency distribution, and frequency and amplitude modulation indices.

3. Extracted features for each object were then presented to a five-class random forest classifier to determine the class of the sound in the analyzed frame (i.e., walrus grunt, bowhead, seismic, bearded seal, or "other").

A full technical description of the detection/classification process is given in Delarue et al. (2015, Appendix A.3, Walrus Grunt Detection and Classification).

2.4.7. Detector and Classifier Performance Evaluation

The performance of the marine mammal detectors/classifiers was assessed by comparing the automated detections/classifications with manual detections for all fully annotated, manually analyzed recordings. For the winter 2014–2015 data, the analysis protocol (see Section 2.3.1) yielded a test dataset of 82 fully annotated samples. For the summer 2015 data, manual analysis yielded a test dataset of 67 fully annotated samples.

Detector and classifier performance was measured by calculating the precision (P) and recall (R) indices (see Appendix A.6.3, Precision and Recall in Delarue et al. 2015). These values characterize the relationship between the detector/classifier and the dataset. R describes the proportion of calls detected; P measures the proportion of accurate classifications. P and R were calculated separately for different signal-to-noise ratios: < 0 dB, 0–5 dB, > 5–10 dB, and > 10 dB. Those results are presented in Appendix A, Automated Detection and Classification of Marine Mammal Vocalizations and Anthropogenic Noise. The P and R values are then used to correct the number of automated detections and to estimate call counts (see Appendix A.2, Detector/Classifier Performance). Table 9 summarizes the performance of the detectors used for each species for all detected vocalizations, with the majority of signal-to-noise ratios being 0–5 dB.

Table 9. Performance of the automated detectors and classifiers (precision, P, of winter periods and recall, R) applied to the winter 2014–2015 and summer 2015 datasets.

Species	Winter 2014–2015		Summer 2015	
	P	R	P	R
Bowhead	0.97	0.34	0.92	0.53
Walrus	0.96	0.28	0.96	0.28
Beluga	0.65	0.55	0.92	0.61
Bearded seal	0.78	0.67	0.79	0.43

2.4.8. Acoustic Continuity Index

Much current research into soundscape characterization is directed at developing analysis metrics or indexes that separate the contribution or effects of anthropogenic from natural sound sources within large datasets. Metrics under investigation include the Acoustic Diversity Index, acoustic richness, temporal and frequency entropies, and the Acoustic Complexity Index (see for example Desjonquères et al. (2015)). Several studies have found that the Acoustic Diversity

Index and Acoustic Complexity Index are correlated with presence of vocalizing biota, both in-air and in-water. However, the definition of the index, in particular the Acoustic Complexity Index, does not fully define how to normalize the results, which leads to a wide range of possible values depending on how they are implemented.

Existing results from Acoustic Complexity Index investigations suggest that it can provide an indication of time and frequency bands that contain continuous anthropogenic sounds. In an effort to better describe the Chukchi Sea soundscape, we implemented a variation of the Acoustic Complexity Index that carefully normalizes the metric, and results in a central tendency to a value of 1, and we refer to this metric at the Acoustic Continuity Index (ACI) to differentiate it from the Acoustic Complexity Index.

The ACI is computed by subtracting adjacent fast Fourier transform FFT time slices over a frequency band of interest (Table 15), normalizing it by the energy in both time slices, then averaging over each minute. This process can be replicated using simulated time series to obtain the expected distribution that has the central value of 1 and a spread that depends on the number of time-frequency bins averaged. The values below "1" occur when the spectrum does not change from one FFT to the next, i.e. continuous sources. The values above "1" are caused by variable or transient sources that do change between FFT bins. The modeled and measured distributions are then subtracted and the differences summed for the values above and below "1", and expressed as a percentage of the total number of samples examined. A value of "-50%" means that 50% of the data is below the expected distribution, which means that a noise source is present reduces the energy variability, i.e. a continuous noise source. Values around 0% mean no deviation from random distributions, and positive values indicate that there are sources present that create short-term fluctuations in the sound, i.e. transients. This method is able to identify when there are continuous *and* transient noise sources that are affecting the character of the soundscape. This metric requires long-term data sets to be a useful indicator. The results were summed and presented for each month of recordings.

3. Results

Tables and figures in this section that are preceded by a letter refer to tables and figures in the appendices.

3.1. Received Ocean Sound Levels

The received ocean sound levels at Station PLN40, a representative station, illustrate the acoustic characterization methods applied to all stations. The winter 2014–2015 recorder at PLN40 stopped recording early, thus data from PL50 are used as a surrogate for PLN40 for winter 2014–2015. The received sound levels from all other stations are in Appendix B, Ambient Noise Results.

3.1.1. Winter 2014–2015 Recording Period

The 1-min received broadband sound levels at PL50 varied between 77 dB and 131 dB re 1 µPa (Figure 7, top). For the whole study area, freeze-up began in early November and was complete by the mid-December. Ice began retreating in early May, and the study area was essentially ice-free by early July. When ice was present and temperatures began to fall, localized high intensity ice-cracking impulses occurred (Figure 7, bottom). The presence of ice reduces or eliminates wind-generated waves and wave-breaking noise. Scattering at the rough under-ice surface highly attenuates sound propagation under ice at frequencies above 200 Hz (Greene and Buck 1964, Diachok 1976, Roth et al. 2012). These phenomena produce lower sound levels above approximately 50 Hz for most of the ice-covered period (Figure 7, bottom).

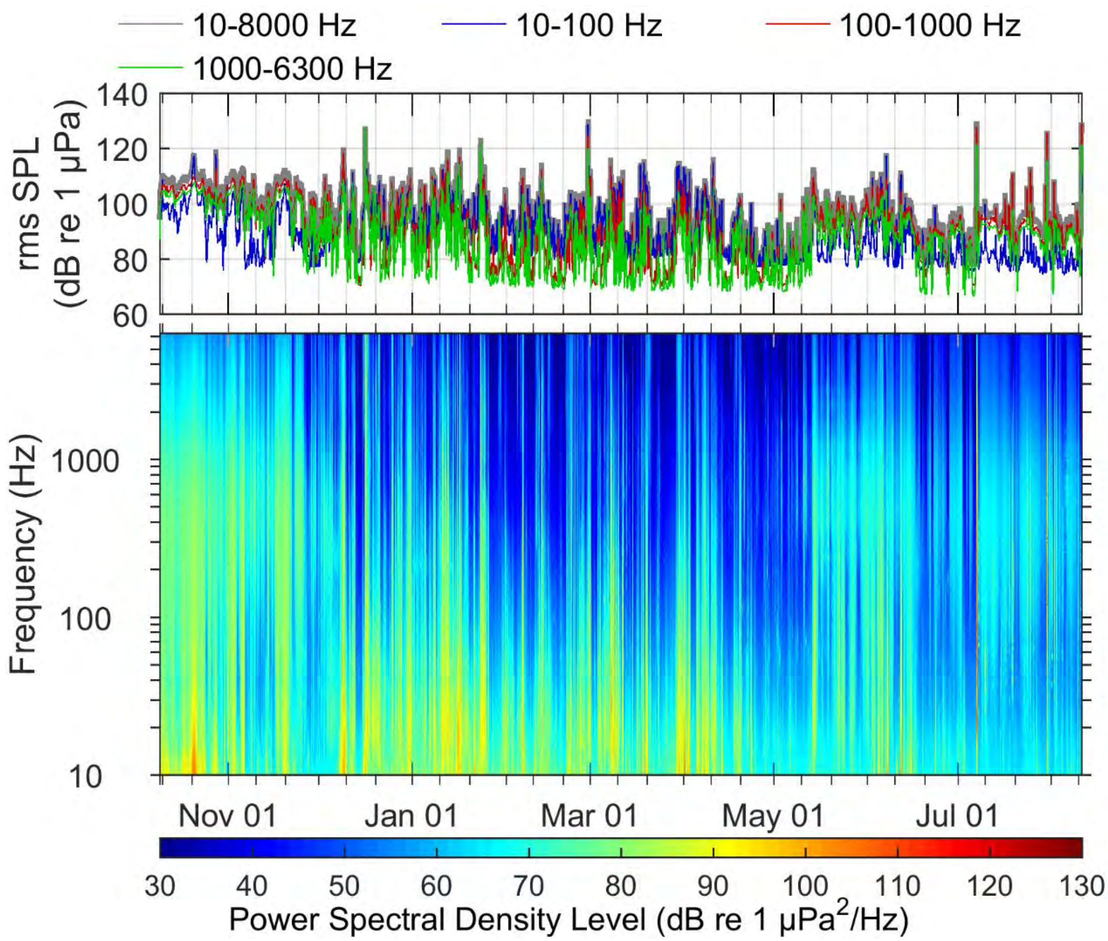


Figure 7. (Top) Broadband and decade-band sound pressure levels (SPL) for winter 2014 Station PL50. (Bottom) Spectrogram of underwater sound recorded from October 2014 to August 2015.The 1/3-octave mean SPL values (over time) were consistently about 15 dB higher than the 1/3-octave median SPL values calculated over the entire recording period (Figure 8). This large difference is attributed to a large number of brief but high intensity ice-cracking events that contribute to the mean but have little influence on the median. The L_{50} spectral levels consistently decreased by approximately 10 dB/decade over the entire frequency range.

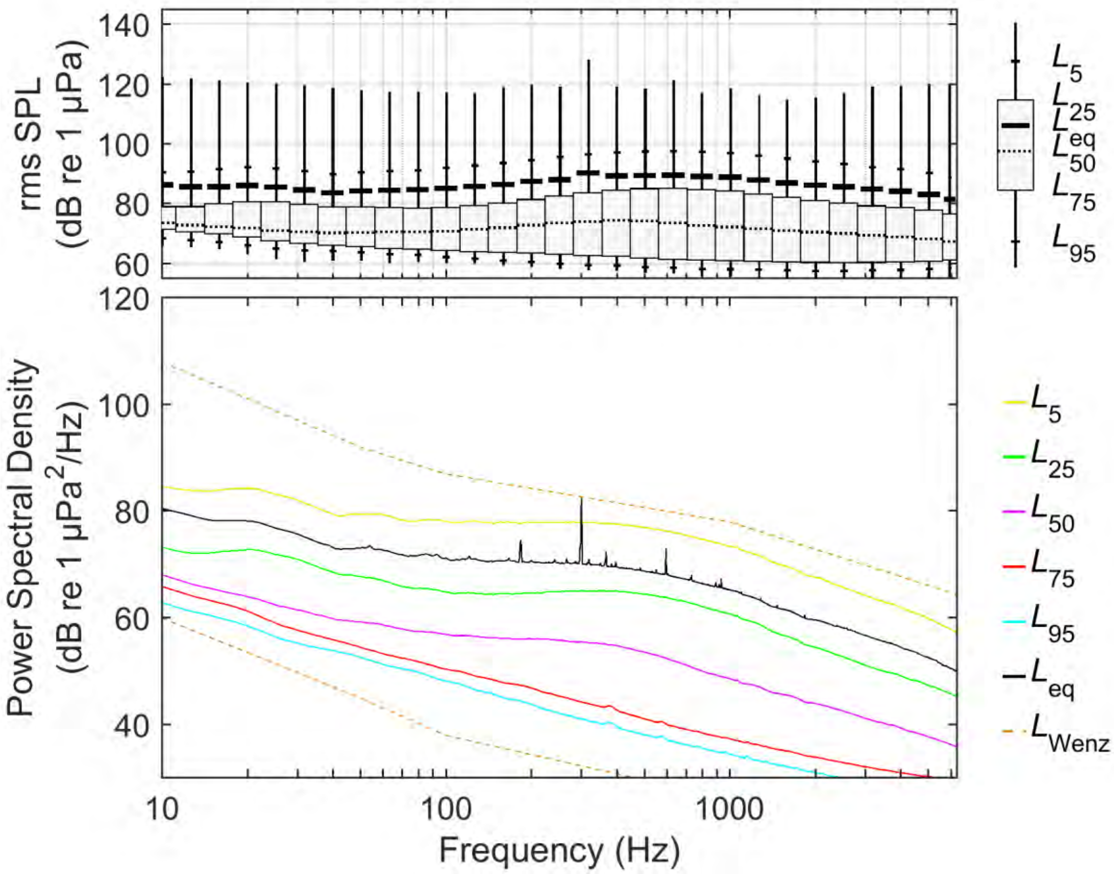


Figure 8. (Top) Distribution of 1/3-octave band sound pressure levels (SPL) at winter Station PL50.(Bottom) Mean (L_{eq}) and percentile exceedance levels of the power spectral density. The dashed lines are the limits of prevailing noise from the Wenz curves.

Summer 2015 Recording Period

Broadband received sound levels at Station PLN40 ranged from 95 to 125 dB re 1 µPa, peaking (along with wind speed) on 29 Aug (Figure 9). Broadband rms SPLs were weakly correlated ($r^2 = 0.333$) with wind speed (Figure 10). In 2014, noise at this station was strongly correlated with wind speed ($r^2 = 0.859$). This year there were more vessel detections than 2014, which is discussed further in Section 3.3.

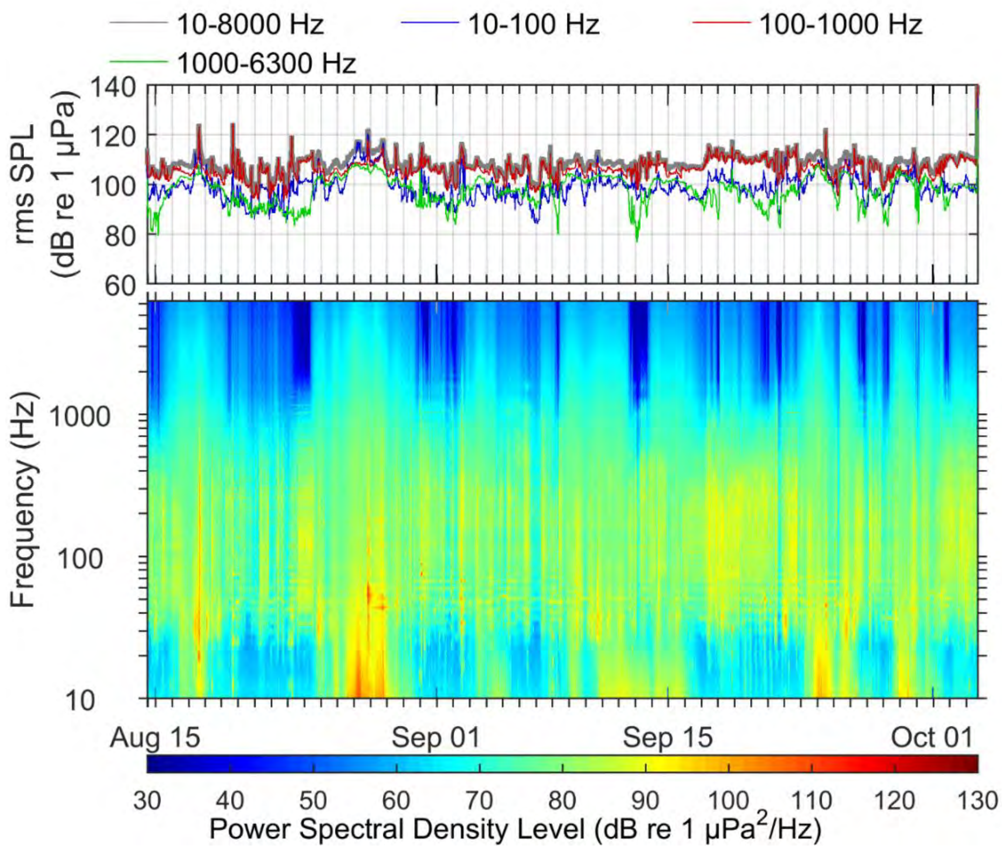


Figure 9. (Top) Broadband and decade-band sound pressure levels (SPL) for summer 2015 Station PLN40 and (bottom) spectrogram of underwater sound August to October 2015.

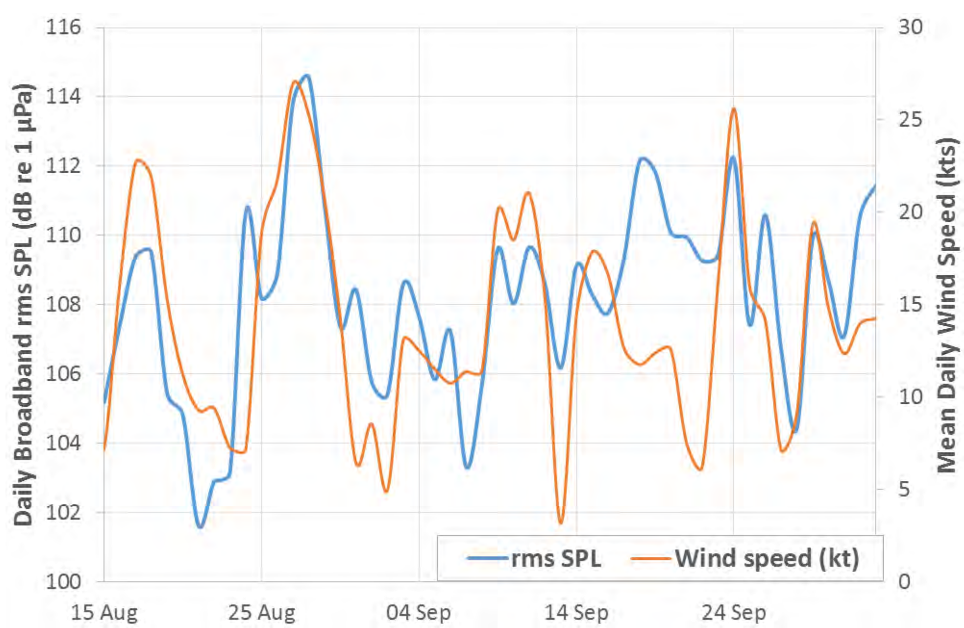


Figure 10. Mean daily wind speed recorded at Klondike and mean daily broadband rms SPL measured at Station PLN40 located 32 km away from Klondike.

Above 300 Hz, the 1/3-octave band mean SPL and median SPL decrease as the frequency increases (Figure 11). Generally, the spectral levels decrease for frequencies above 500 Hz, which is a common characteristic of ambient noise spectra (Wenz 1962). The L_{50} spectra decrease from 75.6 to 55.0 dB re 1 μPa^2/Hz over the frequency range 500 to 5000 Hz, a decrease of 20.6 dB/decade. This is slightly higher than expected for wind driven noise spectra (Ma and Nystuen 2005) due to the increase from shipping noise (Section 3.3). Spectral exceedance levels are above the Wenz limits of prevailing noise for both the L_5, from 100–400 Hz, and for the L_{eq} at 180, 260, and 300 Hz due to tones, presumably from vessels that may have been closer to the station for prolonged durations.

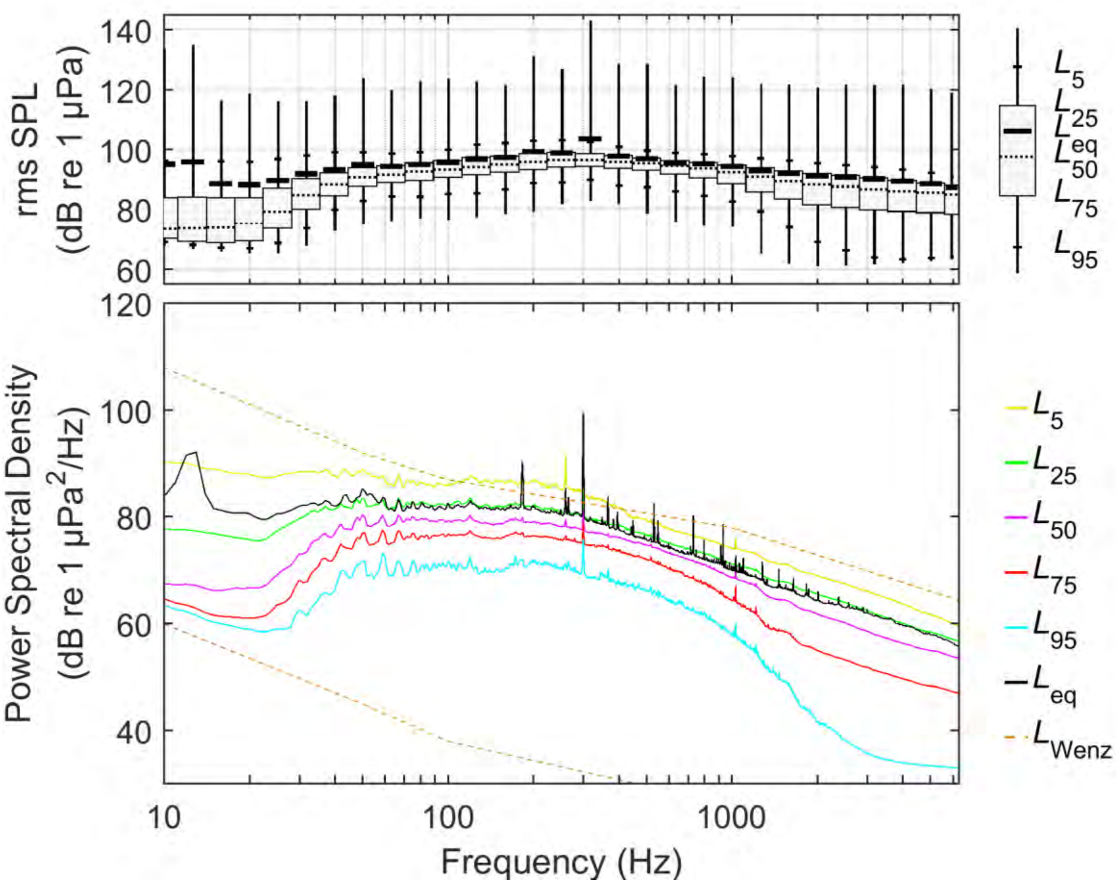


Figure 11. (Top) Distribution of 1/3-octave band sound pressure levels (SPL) at summer Station PLN40. (Bottom) Mean (L_{eq}) and percentile exceedance levels of the power spectral density. The dashed lines are the limits of prevailing noise from the Wenz curves.

The distribution of sound exposure levels (SELs) was measured for each station; PLN40 is shown in Figure 12. Sections 2.4.2 and 2.4.3 detail the sound sources that were classified. Vessel sounds were detected on all but four days. The peak daily SEL (SEL 24 h) occurred on 27 Aug (excluding vessel noise from deployment and retrieval) and was associated with a weather event (Figure 10). Daily SEL plots for the other stations are shown in Appendix B, Ambient Noise Results.

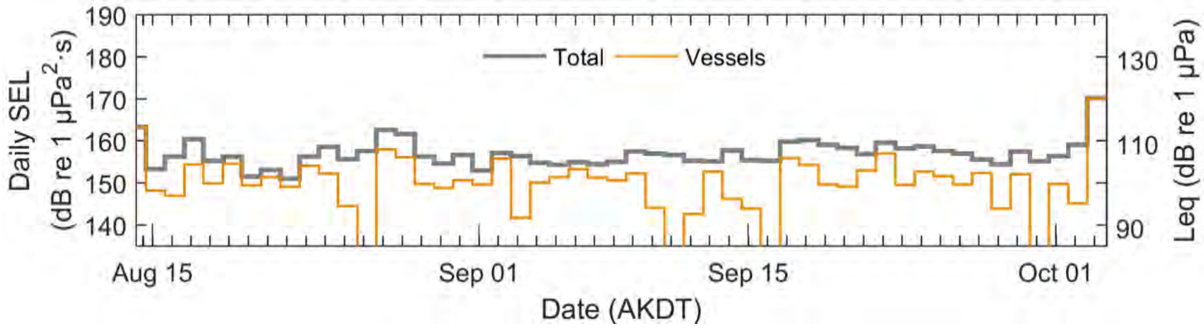


Figure 12. Daily sound exposure level (SEL 24 h) distributions (10 Hz–8 kHz) at PLN40 summer 2015. The data were divided into total, vessel, and seismic classes; however, seismic survey sounds were not detected. Note 24 h L_{eq} is 49.4 dB less than daily SEL.

3.2. Seismic Survey Event Detections

3.2.1. Winter 2014–2015 Recording Period

Seismic airgun pulses were not detected in the winter 2014–2015 period.

3.2.2. Summer 2015 Recording Period

Seismic survey source sounds were detected using the automated detection algorithm described in Section 2.4.3. Because the only seismic survey sounds that we detected (18 Aug and 2 Sep at CLN120) had a very low signal to noise ratio, they did not contribute significantly to the daily SEL (Figure 13). Figure 14 is a spectrogram of seismic survey sounds.

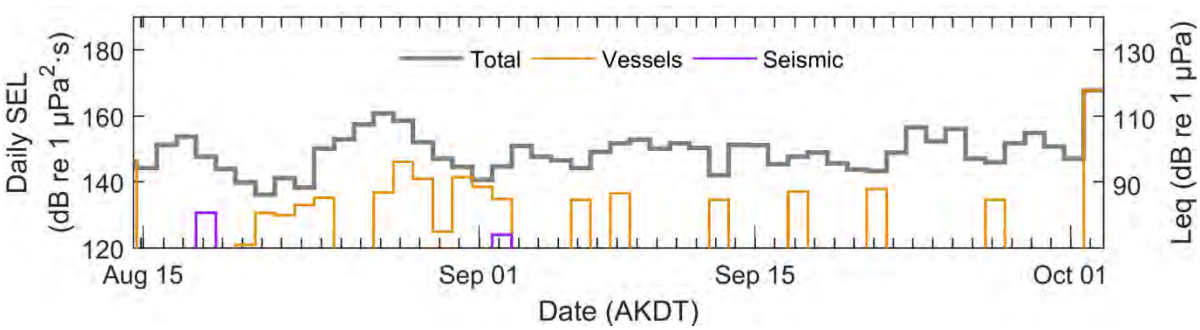


Figure 13. Daily sound exposure level (SEL 24 h) distributions (10 Hz–8 kHz) at CLN120 summer 2015 , divided into total, vessel, and seismic classes. Note 24 h L_{eq} is 49.4 dB less than daily SEL.

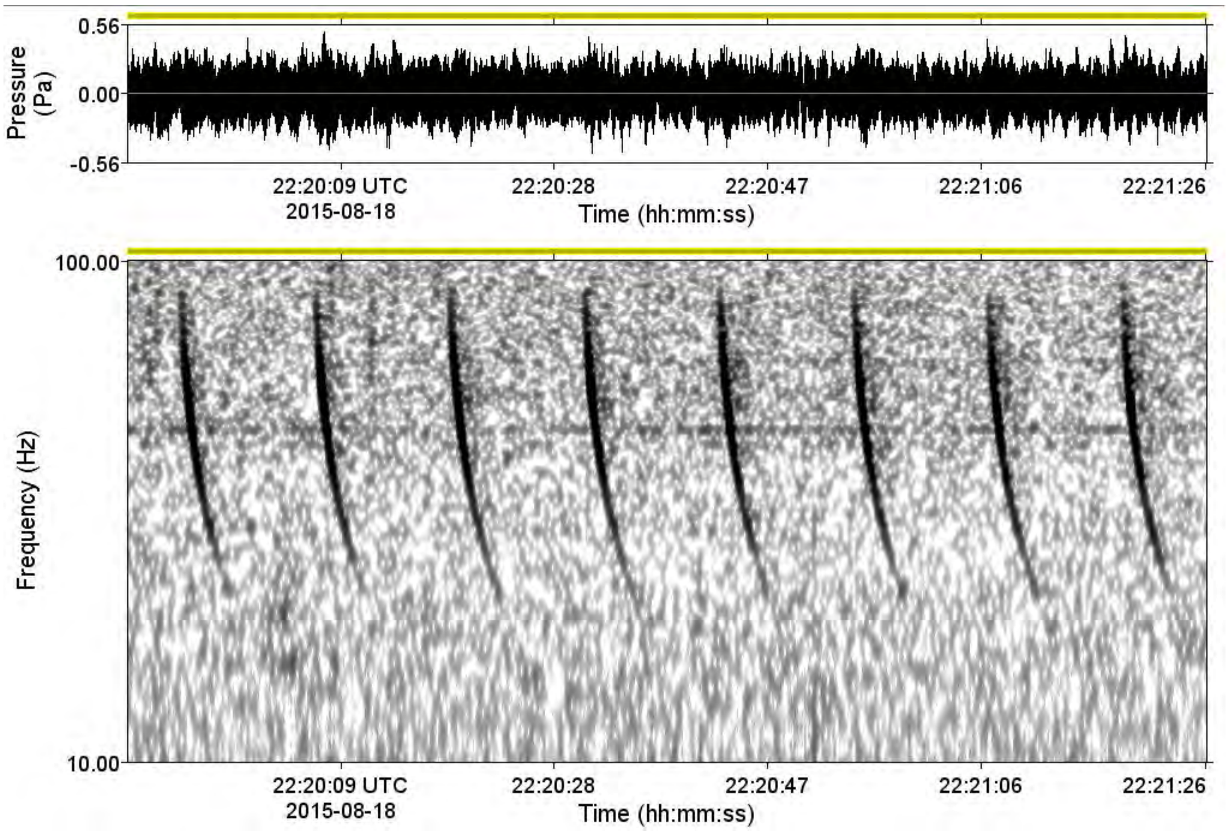


Figure 14. (Top) Pressure signature and (bottom) spectrogram of seismic pulses from an airgun array, at summer Station CLN120 on 18 Aug 2015. Frequency resolution: 0.122 Hz; Frame size: 1.0 s; Time step: 0.05 s; Hamming window.

3.3. Vessel Noise Detections, Summer 2015 Recording Period

The results from detected vessels showed each vessel's passage through the closest point of approach (CPA) to the recorder station, by hour. Vessel detections were lowest at the Cape Lisburne and Wainwright stations (Figure 15, Figure 16, and Appendix B, Ambient Noise Results B–27 to B–31) and highest at Burger and Barrow. Station BG01 had the most daily vessel passages with an average of 2.9 per day during summer, due to vessel traffic around the Burger drill site. Overall, there were more vessels detected in the Chukchi Sea in summer 2015 than in previous years, which contributed significantly to increased noise levels.

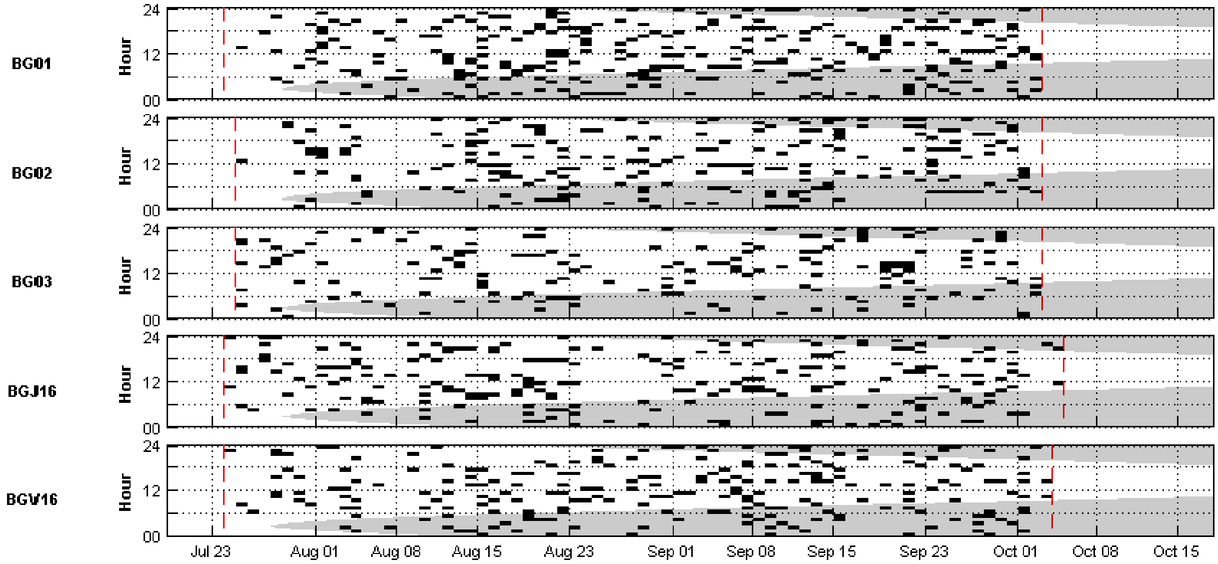


Figure 15. Vessel detections each hour (vertical axis) versus date (horizontal axis) at five stations (BG01 to BG_V16) from 19 Jul to 18 Oct 2014 The grey areas indicate hours of darkness. Vertical dashed lines indicate AMAR deployment and retrieval.

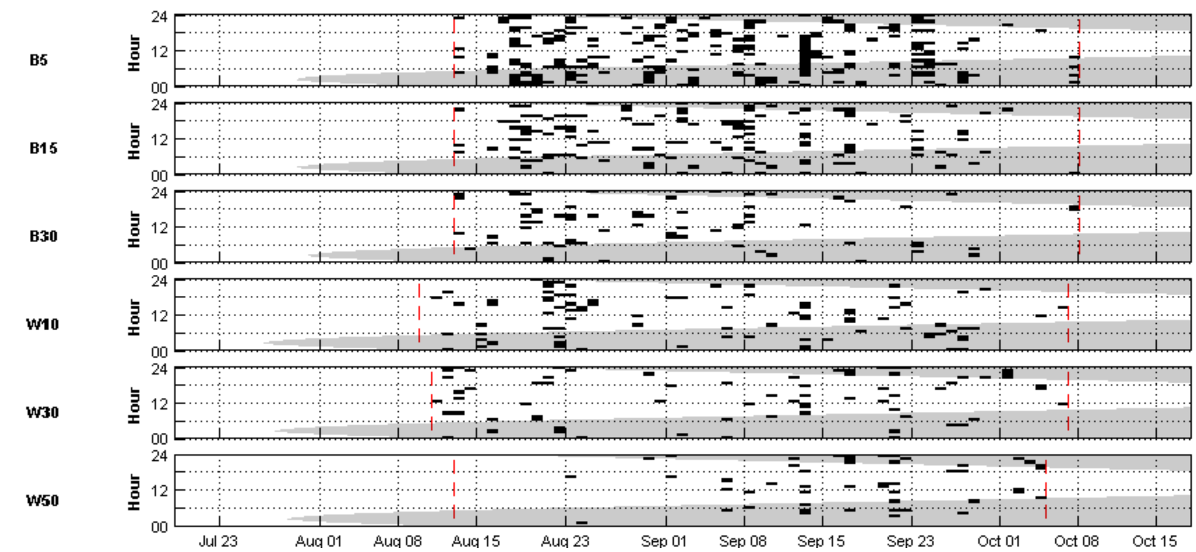


Figure 16. Vessel detections each hour (vertical axis) versus date (horizontal axis) at six stations (B5 to W50) from 19 Jul to 18 Oct 2014. The grey areas indicate hours of darkness. Vertical dashed lines indicate AMAR deployment and retrieval.

3.4. Marine Mammal Call Detections

The numbers of detected vocalizations in the winter and summer datasets are presented in the following sections. Calls from these species were detected using a combination of manual analyses and automated detector/classifiers. Vocalizations by other cetaceans and pinnipeds were detected manually only.

Marine mammal acoustic occurrence at each station is presented as time series of the daily proportion of 5-min or 30-min sound files (winter and summer, respectively) with manual detections for each species.

Species-specific detections are described using the daily average number of automatic detections corrected by performance indicators (See Appendix A.7, Call Count Estimation in Delarue et al. 2015) or the sum of call counts per period. The automated detections were compiled based on manual detection results, i.e., automated detections for a given file were counted only if a call was manually detected within that file for a given species. The corrected numbers of automated detections more closely represented the actual number of vocalizations for a species. Call counts were then averaged over periods that reflected temporal trends in detections, and subsequently mapped.

3.4.1. Summary of Manual Call Detections

In the winter 2014–2015 data, 20,327 sounds were annotated manually, of which 19,377 were classified as marine mammal calls (Table 10). In the summer 2015 data, 13,481 sounds were annotated manually, of which 11,808 were classified as marine mammal calls (Table 11).

Station CL5 accounted for more than quarter of all winter call detections, the result of high numbers of bearded seal and bowhead whale calls there. Bearded seals were the most commonly detected species in the winter dataset, accounting for 57% of all identified annotations, followed by bowhead whales (20%). Walruses, beluga whales, and ringed seals accounted for 7.6%, 7.5%, and 6.8%, respectively, of identified annotations. There were fewer detections at PL10, PLN40, and W50 because these recorders operated for shorter times than the other winter recorders.

In the summer recording period, walrus and bowhead whale calls accounted for 64.6% and 22.9% of all identified calls, respectively; bearded seal calls accounted for 5.7%; other species contributed negligibly (2.2% or less). Stations BG02, PLN40, BG01, PL50, KL01, and PLN20 had few annotations overall. The number of walrus annotations at each station strongly influenced the total number of marine mammal annotations. Stations B5, B15, B30, and PLN60 were the only stations where the high number of summer marine mammal annotations were driven by bowhead whale, not walrus, calls. Differences in the number of unknown calls between stations could be attributed to differences in environmental noise between stations and/or the data analyst’s experience identifying calls.

Table 10. Winter 2014–2015 call detections: Marine mammal annotations resulting from the manual analysis of 5% of the data from each station, listed in order of increasing total detections.

Station	Bearded seal	Bowhead whale	Walrus	Ringed seal	Beluga whale	Gray whale	Ribbon seal	Killer whale	Spotted seal	Unknown	**Total**
PL10	169	70	105	32	0	1	0	0	0	62	**439**
PLN40	16	389	3	4	56	0	0	0	0	43	**511**
W50	533	57	22	61	5	0	0	0	0	42	**722**
WN40	2160	0	776	70	43	0	0	0	0	23	**3072**
PL50	2021	471	185	409	356	1	0	1	0	293	**3737**
W10	3122	869	356	310	510	148	0	0	0	362	**5677**
CL5	3085	2008	27	438	484	0	1	0	1	125	**6169**
Total	**11106**	**3864**	**1474**	**1324**	**1454**	**150**	**1**	**1**	**1**	**950**	**20327**

Table 11. Summer 2015 call detections: Marine mammal annotations resulting from the manual analysis of 5% of the data from each station, listed in order of increasing total detections. Spotted seal sounds were not detected due to a lack of knowledge about their calls (see Section 3.4.13). WA: walrus; BW: bowhead whale; BS: bearded seal; WW: beluga whale; GW: gray whale; RS: ringed seal; KW: killer whale; FW: fin whale; HW: humpback whale; MW: minke whale; UN: unidentified sound.

Station	WA	BH	BS	WW	GW	RS	KW	FW	HB	MW	UN	**Total**
BG02	0	0	0	2	0	0	0	0	0	0	0	**2**
BG_V16	0	0	0	0	0	0	0	0	0	0	2	**2**
PLN40	9	0	1	0	0	0	0	0	0	0	18	**28**
BG01	0	0	0	0	0	0	0	0	0	0	29	**29**
PL50	27	0	8	0	2	0	2	0	0	0	7	**46**
KL01	26	4	3	0	7	0	0	0	0	0	7	**47**
PLN20	26	0	20	0	0	0	0	0	0	0	9	**55**
HSW4	62	0	5	1	0	0	1	0	0	0	4	**73**
CLN90	111	0	4	0	0	0	3	0	0	0	20	**138**
HSW2	76	27	1	0	0	0	5	0	0	0	48	**157**
CLN40	47	0	18	0	2	2	16	0	0	0	78	**163**
PL30	148	0	1	0	14	0	0	0	0	0	9	**172**
CL50	71	0	4	0	5	0	1	34	0	4	56	**175**
HSW3	198	0	4	0	0	0	7	0	0	0	10	**219**
BG03	169	9	0	0	3	0	3	0	0	0	76	**260**
PLN60	50	143	39	0	10	1	3	0	0	0	50	**296**
HSW1	321	31	6	0	1	0	13	0	0	0	40	**412**
CLN120	214	158	39	0	0	0	17	2	0	0	70	**500**
B5	13	418	73	89	59	1	2	0	0	0	79	**734**
W10	474	5	89	0	25	2	5	0	0	0	142	**742**
PLN80	319	319	74	2	0	0	11	0	0	0	73	**798**
W30	477	31	92	0	14	0	18	0	0	0	198	**830**
B15	50	491	126	51	2	75	2	0	0	0	53	**850**
CL5	981	0	4	0	0	1	13	0	2	0	108	**1110**

Station	WA	BH	BS	WW	GW	RS	KW	FW	HB	MW	UN	**Total**
W50	1023	100	26	0	43	0	18	0	0	0	264	**1474**
B30	161	965	29	22	5	182	1	0	0	0	201	**1566**
PL10	2573	0	4	0	0	0	4	0	0	0	22	**2603**
Total	**7626**	**2701**	**670**	**167**	**192**	**264**	**145**	**36**	**2**	**4**	**1673**	**13481**

3.4.2. Bowhead Whale Call Detections

3.4.2.1. Winter 2014–2015 Recording Period

Bowhead whale calls were detected at all stations but WN40 during the fall migration, although calls were only detected at W10 for eight days. The highest number of detection days (n = 69) occurred at CL5 (Table C–1). The area with the highest mean daily call counts shifted from the Wainwright-Point Lay stations in November to the Cape Lisburne-Point Lay area in January (Figure C–1). This shift generally coincides with ice formation and is consistent with the westerly heading of migrating bowhead whales in fall. Overall, call counts were highest at CL5, then at PLN40 and PL50 during the fall migration (Figure 17). Detections at the Point Lay stations occurred in two successive waves, whereas detections were more uniformly distributed temporally at CL5 (Figure 18). Detections lasted until late November/early December at W10 and W50, 9 Jan at PL50 and as late as 23 Jan at CL5.

The first spring detections occurred on 25 Mar at CL5. The lack of spring detections at W50, PLN40, and PL10 is because these recorders had stopped recording earlier. Bowhead whale calls were not detected at WN40 (Table C–1). The bulk of the detections at CL5 occurred between late March and mid-May. The detection period at W10 ranged from early April until the end of June, although detections continued at a low rate throughout July. At PL50, detections only occurred sporadically from April to July (Figure 18). Mean daily call counts were highest at W10, followed closely by CL5 (Figure 17). In April and May, call counts were higher at stations closer to shore where ice concentrations were slightly lower than offshore (Figure C–1). In June and July, call counts occurred only at PL50 and W10 (Figure C–1).

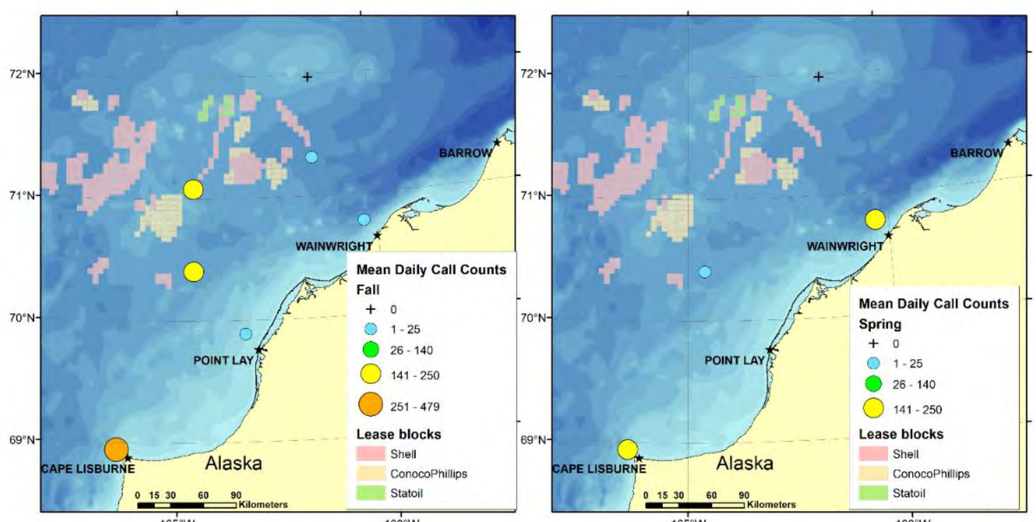


Figure 17. Bowhead whale mean daily call count[2] at winter 2014–2015 stations in the Chukchi Sea. (Left) Fall migration 14 Oct 2014 to 23 Jan 2015. (Right) Spring migration 25 Mar to 30 Jul 2015.

[2] Corrected sum of automated call detections in all files with manual detections divided by number of active recording days.

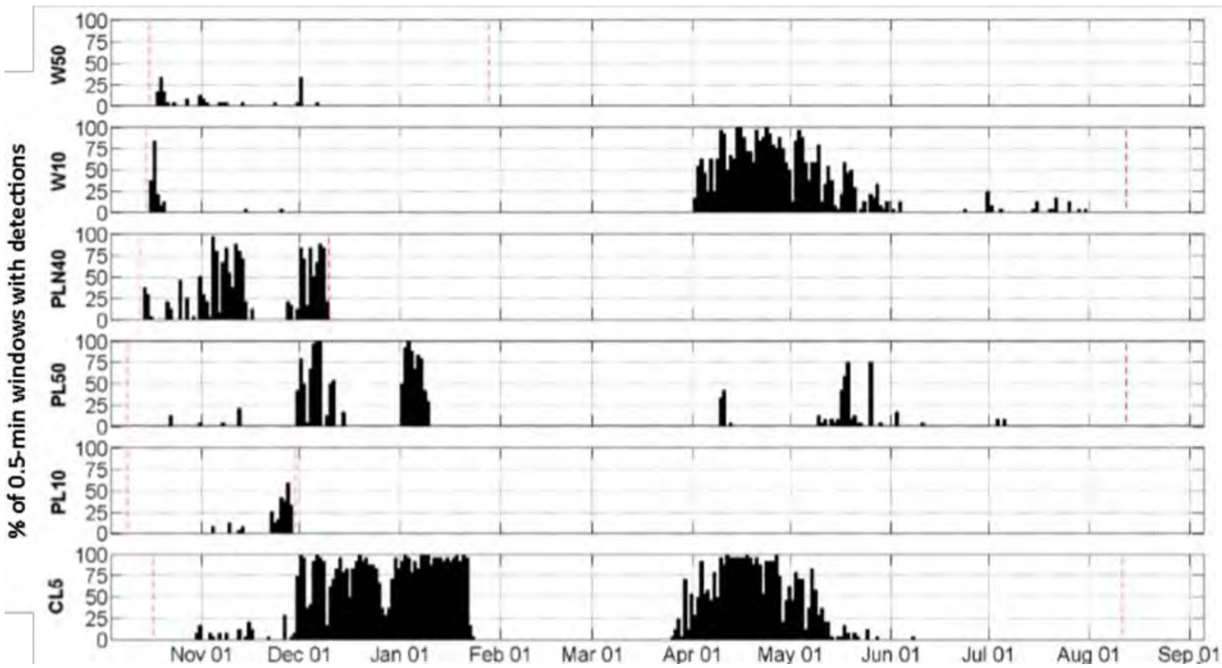


Figure 18. Winter 2014–2015 daily bowhead call detections: Daily proportion of sound files with call detections based on the manual analysis of 5% of the acoustic data recorded early October 2014 through late August 2015 in the northeastern Chukchi Sea for each station. Forty-eight sound files lasting 5 min were recorded each day, spaced every 30 min. Stations are ordered from (top) northeast to (bottom) southwest. The vertical red dashed lines indicate the recording start and end dates.

Most bowhead whale calls that we detected consisted of frequency-modulated narrowband moans (typically without harmonics), moans with harmonic structure, and the complex calls defined as broadband, pulsed, and often strident (Figure 19; Ljungblad et al. 1982, Clark and Johnson 1984). By fall, these calls became increasingly organized into stereotyped sequences called songs (Delarue et al. 2009). From the second week of November, detections at all stations consisted almost exclusively of songs. The early spring detections were also usually songs, but typically less stereotypical than those in November. Songs became increasingly disorganized as the spring migration progressed. By June, most detections consisted of non-stereotyped moans and/or complex call sequences.

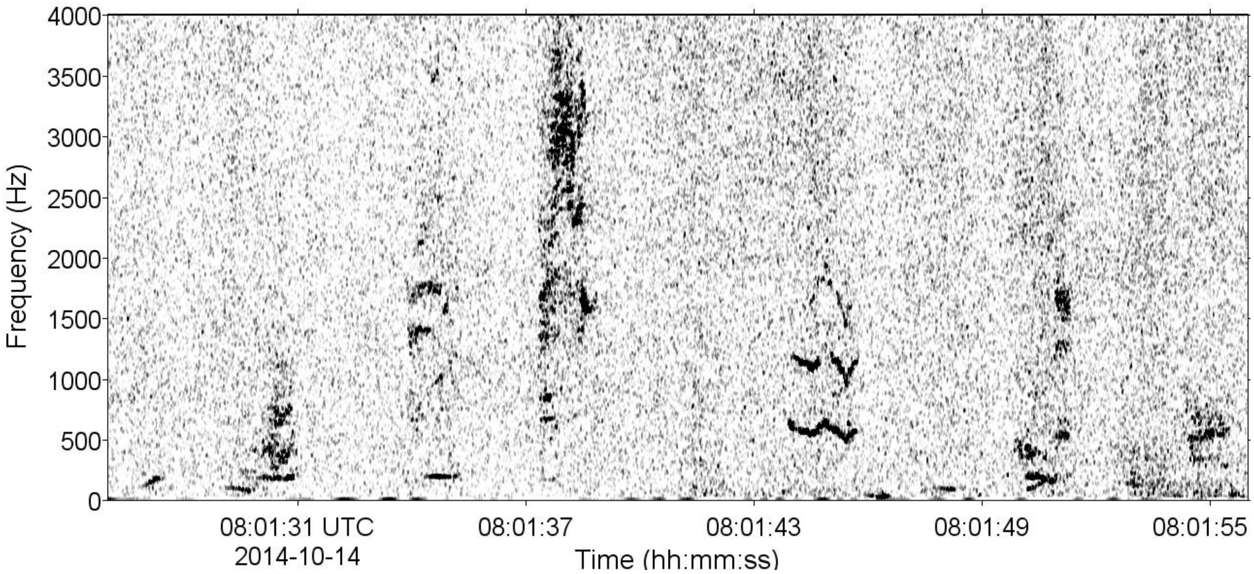


Figure 19. Spectrogram of bowhead vocalizations at Station PLN40, 14 Oct 2014. Frequency resolution: 1 Hz; Frame size: 0.06 s; Time step: 0.006 s; Hamming window.

3.4.2.2. Summer 2015 Recording Period

Bowhead whale calls were detected at half of active stations (B5, B15, B30, BG03, CLN120, HSW1, HSW2, KL01, PLN60, PLN80, W10, W30, and W50). The proportion of recording days with detections ranged from 1.9 % (KL01) to 77.2% (B30) and averaged 25.3% across all stations (Table C–2), but these detections were not uniformly distributed. Aside from sporadic detections in August at the Barrow and northern Point Lay stations, bowhead whale calls were generally not detected in the Chukchi Sea until late August. Most detections can be split into two main periods (Figure C–2):

1. Late August to 13 Sep: A first wave of detections at the most offshore stations (e.g. PLN80, CLN120, and B30). (Figure 20; Appendix C, Marine Mammal Detection Results).
2. 13 Sep to 25 Sep: A slightly more widespread wave of detections is visible and strongest in the northeastern part of the study area. The bulk of fall detections off Barrow (95% at B5, 80% at B15 and 75% at B30) ended on 23 Sep, with two lower pulses of detections occurring between 25 Sep and 8 Oct (retrieval) at B15 and B30 (Figure 20; Appendix C, Marine Mammal Detection Results).

Mean daily call counts were highest near or north of 71° N (Figure 21). The highest call count detections occurred at PLN80, followed by B30, B15, and W50. There were few detections south of 70.5° N.

Because bowheads vocalize primarily in the range of 100–1000 Hz, we investigated the influence of ambient noise in this decade band on bowhead detections. This analysis focused on the fall detection period, from 1 to 30 Sep for six representative stations (B5, B15, B30, CLN120, PLN60, and PLN80). Bowhead detections at PLN60 were slightly negatively correlated (not significant) with decade band (100–1000 Hz) SPL. Detections at all Barrow stations were strongly negatively correlated with decade band (100–1000 Hz) SPL (B5: $r = -0.81$, $p < 0.0001$; B15: $r = -0.79$, $p < 0.0001$; B30: $r = -0.75$, $p < 0.0001$; Figure 22).

Bowhead detections at CLN120 and PLN80 were not correlated with decade band (100–1000 Hz) SPL.

Noise levels at PLN80 and B30 did not increase during the three days separating the two waves of detection at these stations (see Appendix B, Ambient Noise Results), which suggests that call masking is not a likely factor in the synchronous drop in detections.

The detected calls consisted mostly of simple moans, although an increasing proportion of complex calls occurred near the end of the recording period.

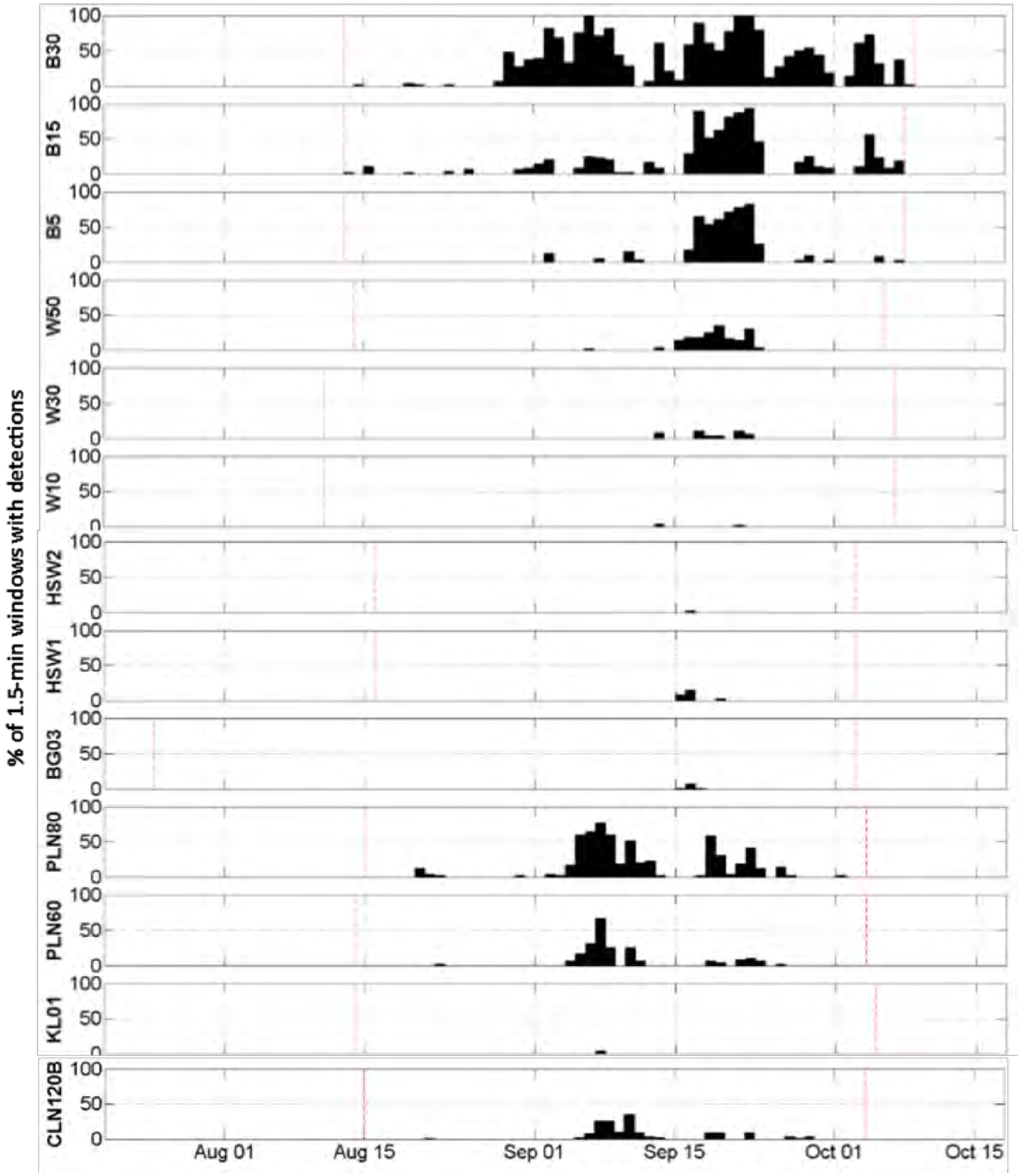


Figure 20. Summer 2015 daily bowhead call detections in the northeastern Chukchi Sea: Daily proportion of sound files with call detections based on the manual analysis of 5% of the acoustic data recorded late July through early October 2015. Forty-eight sound files were recorded each day. The vertical red dashed lines indicate the recording start and end dates. Stations are ordered from (top) northeast to (bottom) southwest. Stations without call detections are omitted.

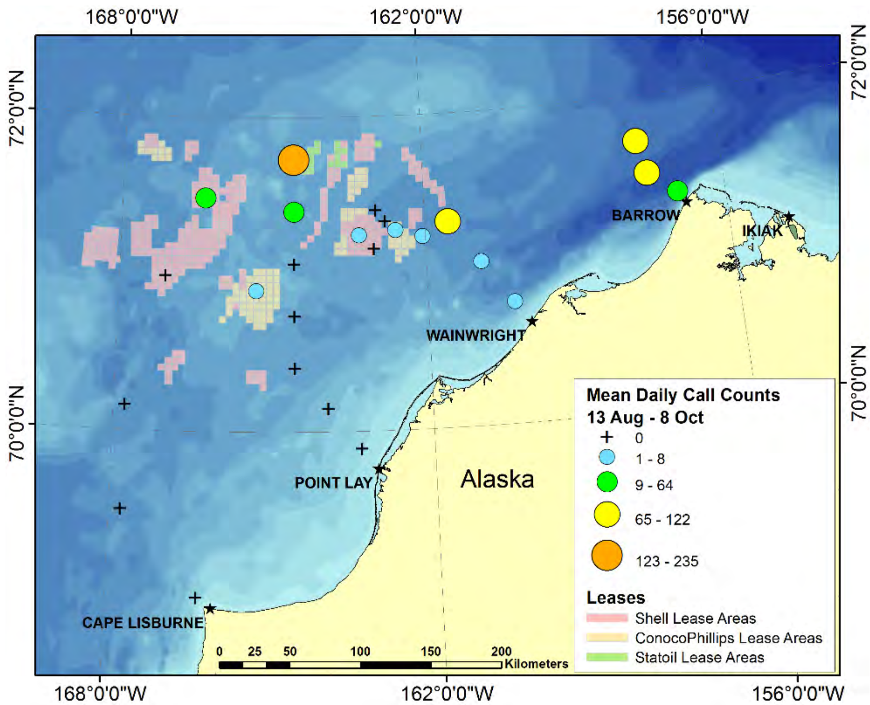


Figure 21. Mean daily bowhead whale call counts (calculated as the sum of automated call detections in all files with manual detections divided by the number of active recording days) for 13 Aug to 8 Oct at all summer 2015 stations in the northeastern Chukchi Sea.

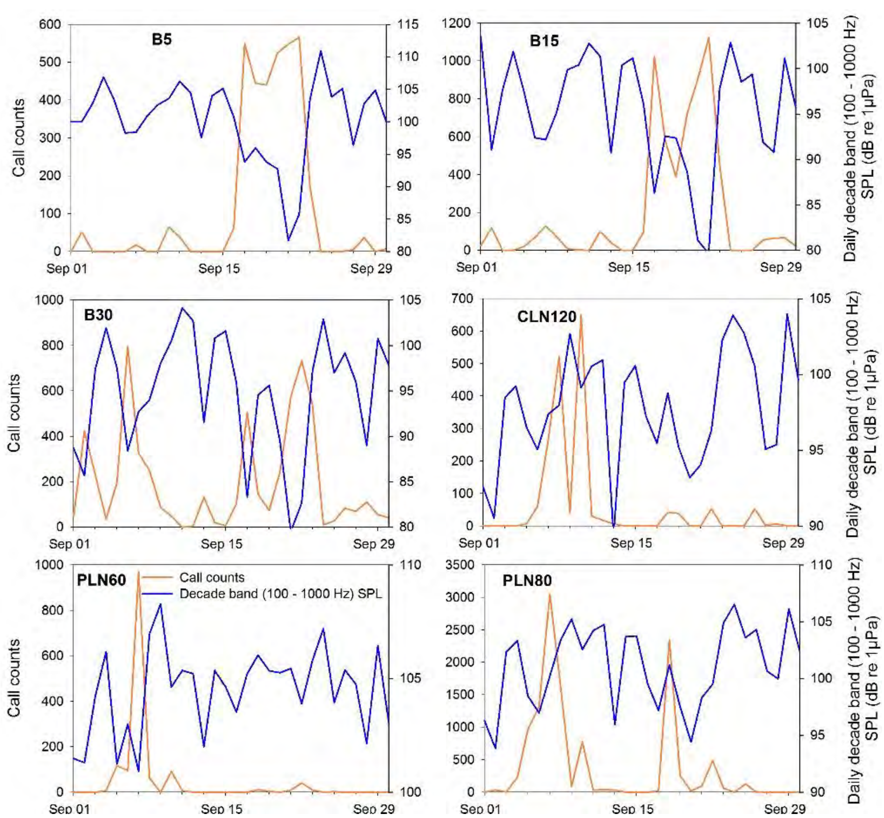


Figure 22. Time series of daily bowhead whale call counts and mean decade band (100–1000 Hz) SPL at B5, B15, B30, CLN120, PLN60, and PLN80 from 1 to 30 Sep 2015.

3.4.3. Walrus Call Detections

3.4.3.1. Winter 2014–2015 Recording Period

There were few walrus call detections in fall and none in winter. The number of detection days ranged from 0 at WN40 and PL50 to 14 at PL10. Most fall detections occurred before mid-November (Table C–3).

An isolated detection occurred on 1 May at W10 (Figure 23). Spring detections started on 4 Jun at PL50. Walrus calls were detected only three days in early June at CL5. At PL50, sporadic detections spread over 27 days from early June to early July. At W10, spring detections spread over 28 days with most of detections occurring from mid-June to early July. Detections occurred almost daily (64 days of detections) at WN40 from early June until the end of August when the recorder was retrieved. There were no spring detections at W50, PLN40, and PL10 because these recorders were inactive when walruses were in the study area.

Call counts were highest at W10 in June and at WN40 from early July onward. Call detections were lowest at the stations closer to shore (W10) and those farther from Hanna Shoal (PL50) (Figure 24; Figure C–3).

Detected walrus calls consisted predominantly of a variety of grunt-like sounds (Figure 25); knocks and bell sounds were detected intermittently (Stirling et al. 1983, Stirling et al. 1987, Schusterman and Reichmuth 2008).

Figure 23. Winter 2014–2015 daily walrus call detections: Daily proportion of sound files with call detections based on the manual analysis of 5% of the acoustic data recorded early October 2014 through late August 2015 in the northeastern Chukchi Sea for each station. Forty-eight sound files lasting 5 min were recorded each day, spaced every 30 min. Stations are ordered from (top) northeast to (bottom) southwest. The vertical red dashed lines indicate the recording start and end dates.

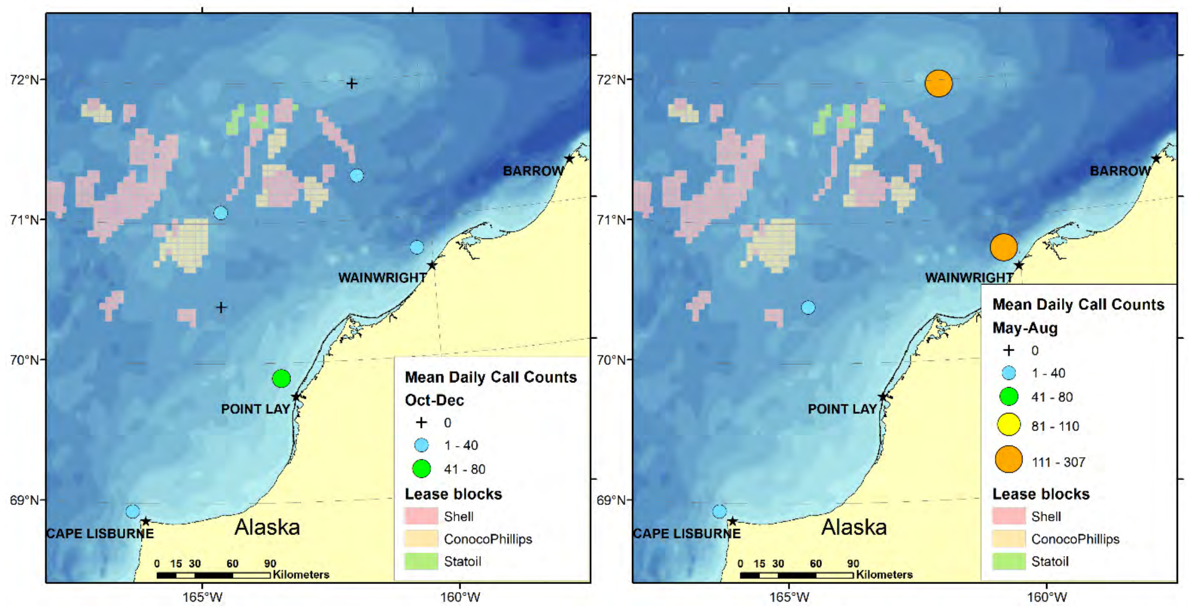


Figure 24. Walrus mean daily call count[3] at winter 2014–2015 stations in the Chukchi Sea. (Left) Winter presence from 9 Oct to 31 Dec 2014. (Right) Spring presence from 1 May to 31 Aug 2015.

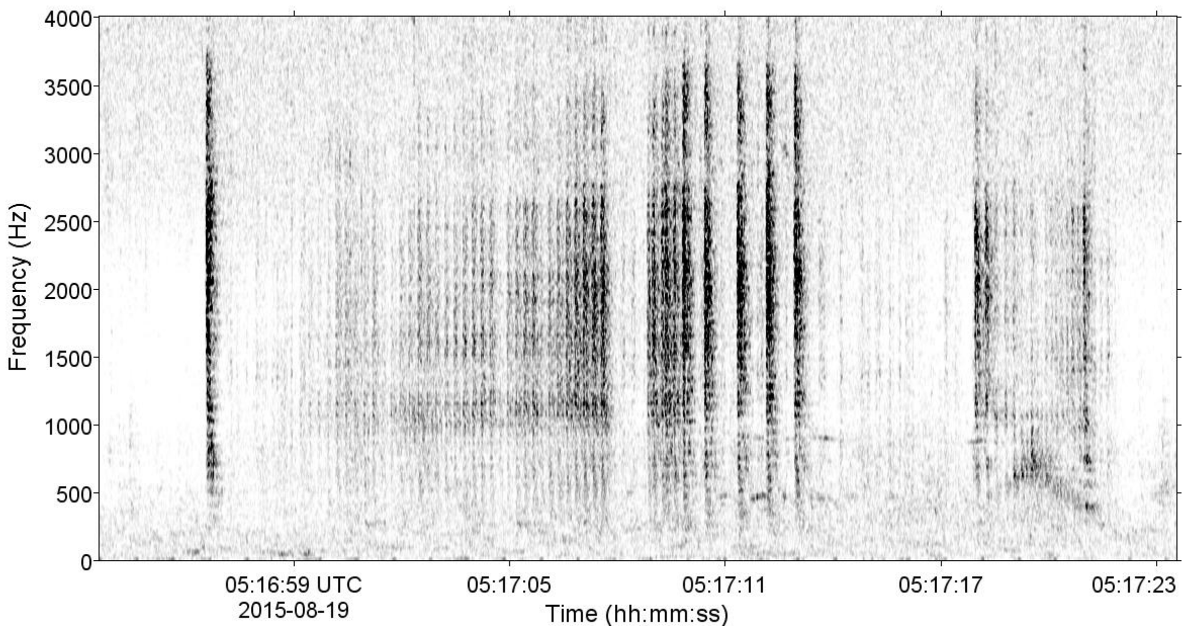


Figure 25. Spectrogram of walrus grunts recorded at Station WN40, 19 Aug 2015. Frequency resolution: 8 Hz, Frame size: 0.05 s; Time step: 0.01 s; Hamming window.

3.4.3.2. Summer 2015 Recording Period

Walruses were detected at most of stations in summer 2015 (Table C–4). In summer, 1.8–98.4% of recording days had detections, with an average of 39% across all stations (Table C–4).

[3] Corrected sum of automated call detections in all files with manual detections divided by number of active recording days.

Walruses were most often detected at the Wainwright stations, the nearshore Cape Lisburne station, and at PL10. At the latter, walruses were detected almost continuously after mid-August. At most other stations, detections were concentrated in peaks that occurred simultaneously across the area. The most prominent peaks occurred in the third week of August and the first week of September (Figure 26; Appendix C, Marine Mammal Detection Results).

An analysis into the effects of ambient noise levels on walrus detections revealed that the only stations where call counts were strongly negatively correlated with decade band SPL in the 100–1000 Hz band—the frequency band walruses use—were CL5 ($r = -0.80$, $p < 0.001$) and PL10 ($r = -0.47$, $p = 0.009$; Figure 27).

Mean daily call counts were highest at PL10, followed by CL5, W30, and W50. Call counts were generally low around Burger, offshore of Point Lay, and at the Barrow stations (Figure 28). In the last two weeks of August, walrus mean daily call counts were highest at PL10, CL5, and the offshore Wainwright stations. From the rest of the recording period, call count maxima occurred at PL10. Other detection hotspots were CL5 and W50 in September and October (Figure C–4).

Manually-detected walrus calls included various grunts, knocks, and bell calls as described by Stirling et al. (1983), Stirling et al. (1987), and Schusterman and Reichmuth (2008). The automated call detector targeted grunts because they are more frequent and have a longer detection range than the other call types (JASCO unpublished data).

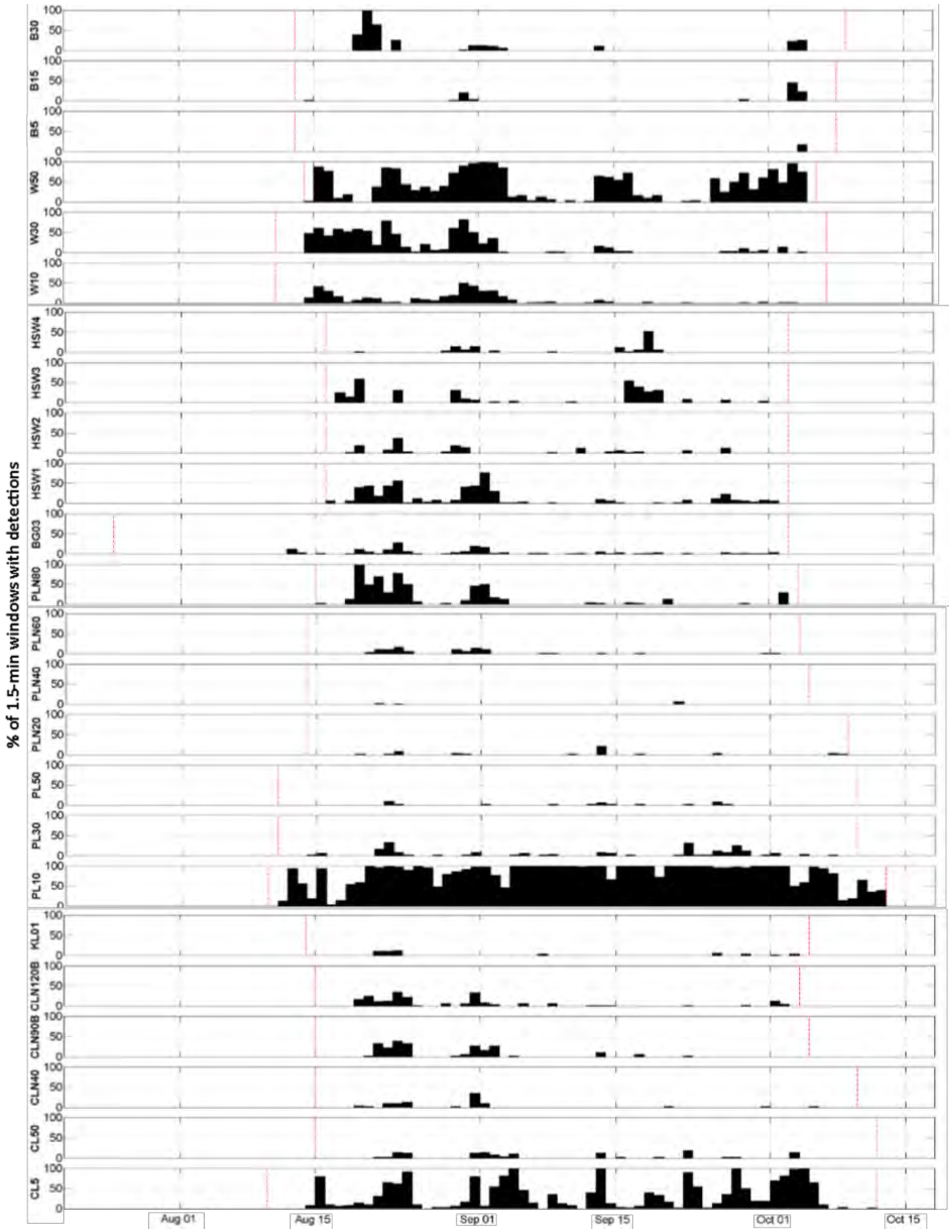


Figure 26. Summer 2015 daily walrus call detections: Daily proportion of sound files with call detections based on the manual analysis of 5% of the acoustic data recorded late July through early October 2015. Forty-eight sound files were recorded each day. The vertical red dashed lines indicate the recording start and end dates. Stations are ordered from (top) northeast to (bottom) southwest.

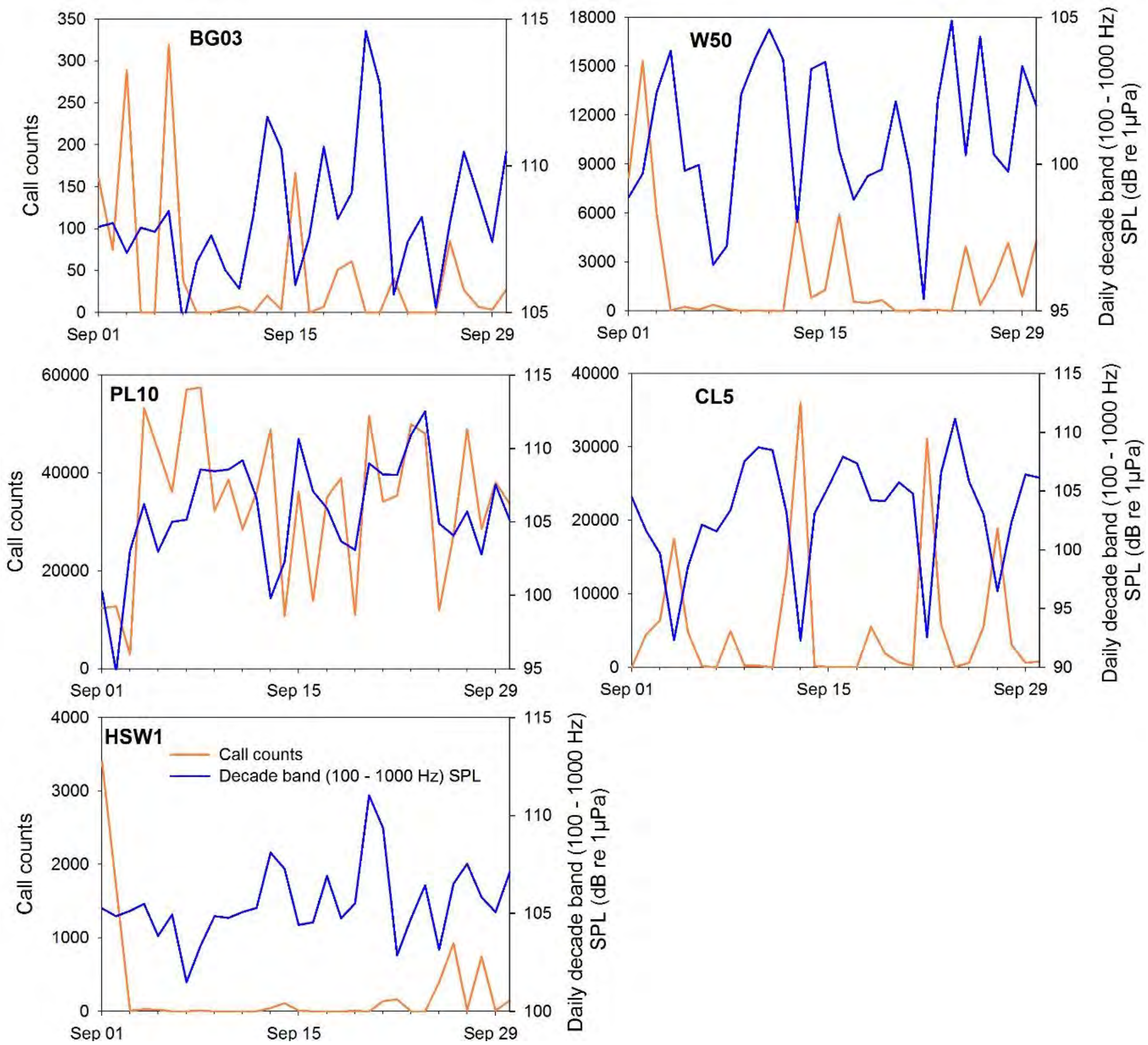


Figure 27. Time series of daily walrus call counts and mean decade band (100–1000 Hz) SPL at Stations BG03, W50, PL10, CL5, and HSW1.

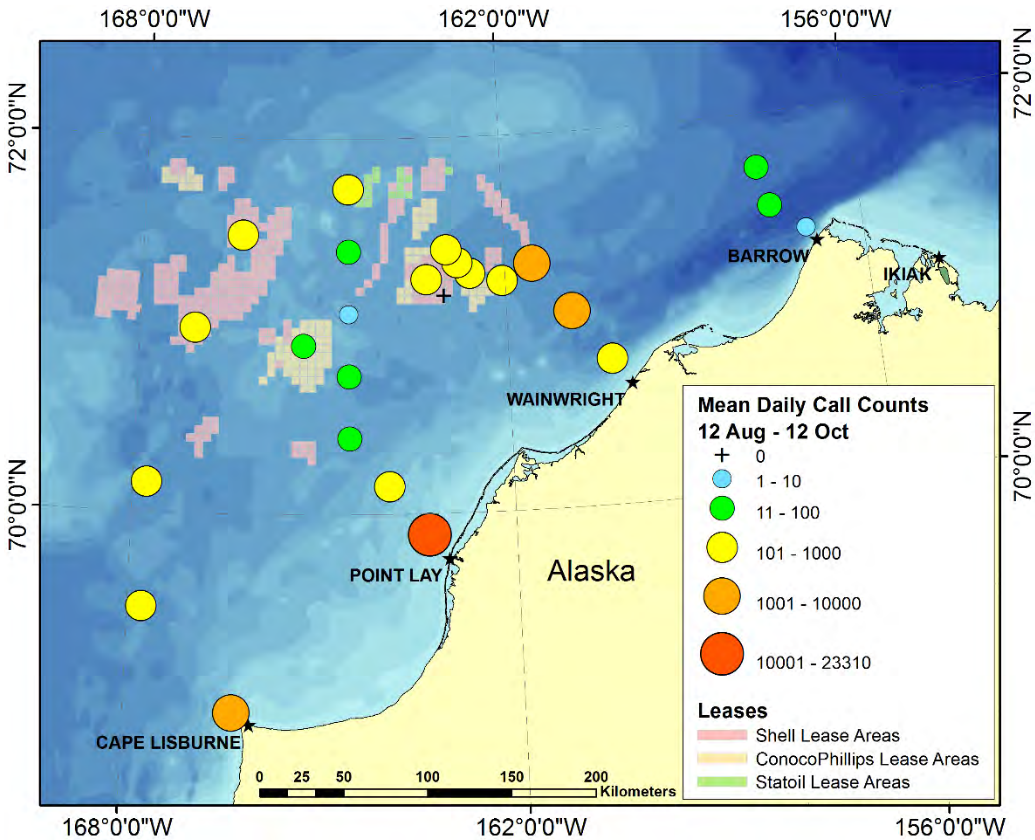


Figure 28. Mean daily walrus call counts (calculated as the sum of automated call detections in all files with manual detections divided by the number of active recording days) for 12 Aug to 12 Oct at all summer 2015 stations in the northeastern Chukchi Sea.

3.4.4. Beluga Whale Call Detections

3.4.4.1. Winter 2014–2015 Recording Period

Beluga calls were not detected at PL10. While this is not unusual in the fall, the lack of spring detections is associated with the lack of data at this station during this period.

In fall 2014, beluga calls were not detected at WN40, but they were detected at other stations between 3 (W50) and 12 (PLN40) days (Figure 29). The first detections occurred on 31 Oct at PLN40; the last ones on 30 Nov at CL5 (Table C–5). The call counts in fall were lower than in the spring (Figure C–5).

Spring detections started on 25 Mar at CL5. Most detections occurred before the end of May. In April and May, the highest call counts were recorded at CL5, followed by W10, and PL50 (Figure C–5). The main period of detection at each of these three stations was shifted by few days as whales progressed along the migration path, from CL5 to W10. Call counts were lower at station farther from shore (Figure 30).

The detected beluga calls included a variety of whistles, buzzes, chirps, and other high-frequency calls previously described for that species (Figure 31; Karlsen et al. 2002, Belikov and Bel'kovich 2006, Belikov and Bel'kovich 2008).

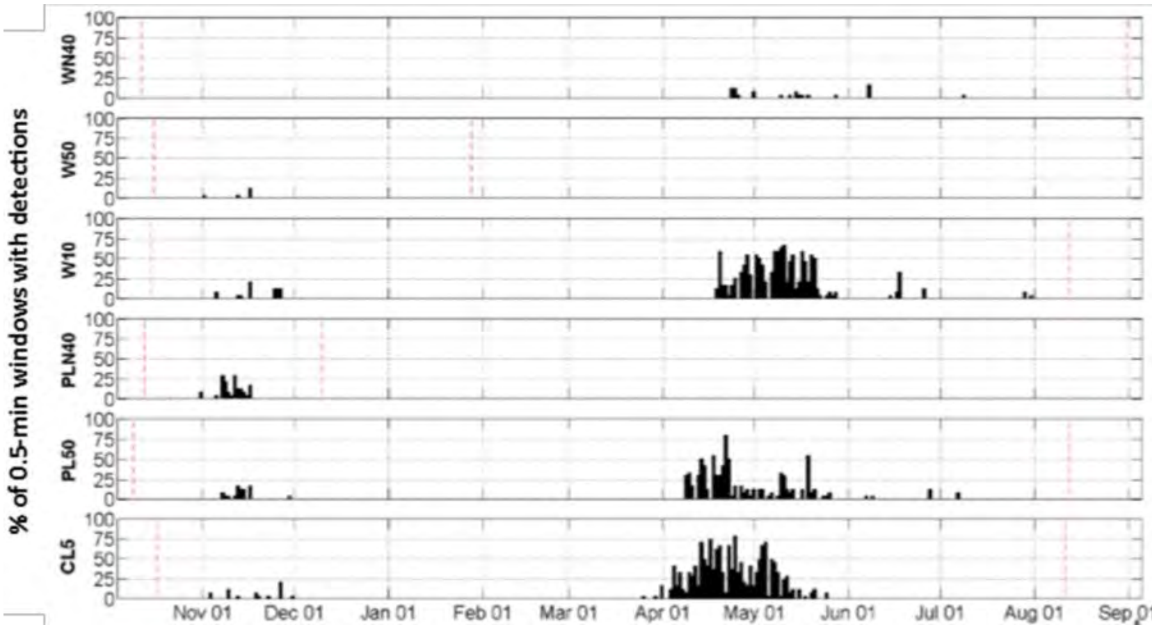


Figure 29. Winter 2014–2015 daily beluga whale call detections: Daily proportion of sound files with call detections based on the manual analysis of 5% of the acoustic data recorded early October 2014 through late August 2015 in the northeastern Chukchi Sea for each station. Forty-eight sound files lasting 5 min were recorded each day, spaced every 30 min. Stations are ordered from (top) northeast to (bottom) southwest. The vertical red dashed lines indicate the recording start and end dates.

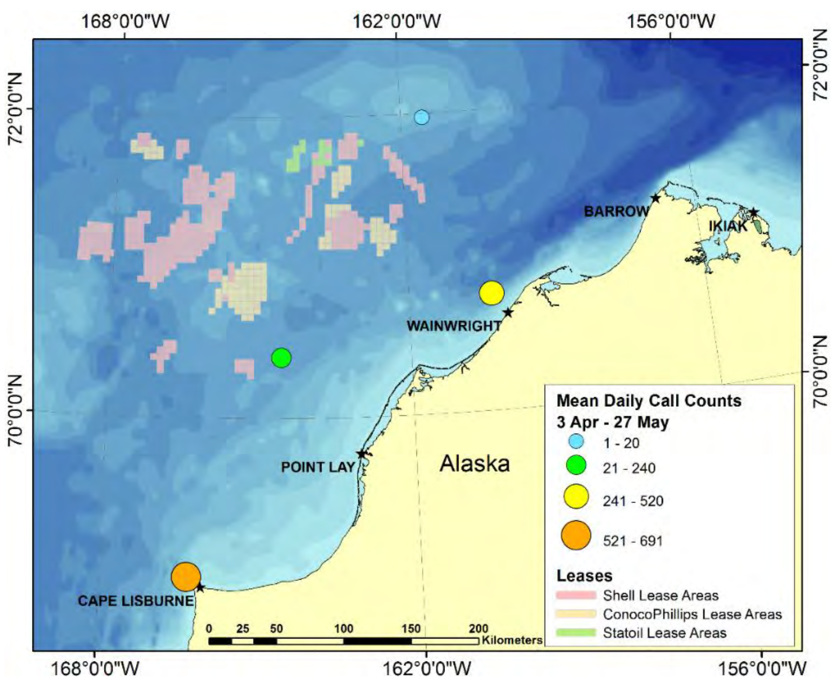


Figure 30. Beluga whale mean daily call counts[4] in the Chukchi Sea at all active winter 2014–2015 stations from 3 Apr to 27 May 2015.

[4] Corrected sum of automated call detections in all files with manual detections divided by the number of recording days.

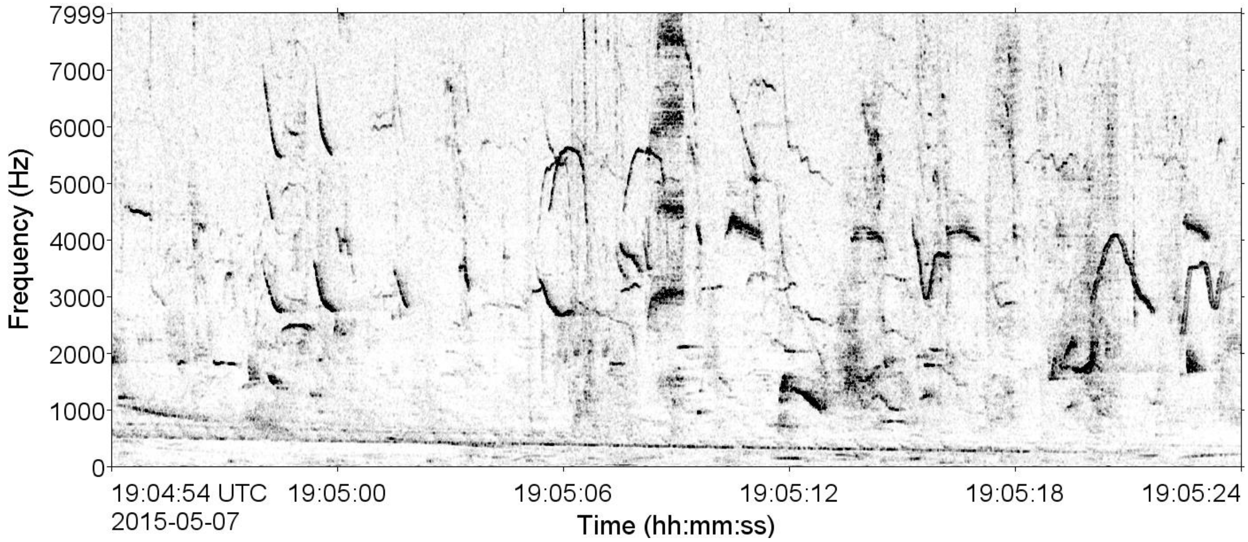


Figure 31. Spectrogram of beluga calls recorded 7 May 2015 at Station W10. Frequency resolution: 1 Hz, Frame size: 0.06 s; Time step: 0.006 s; Hamming window.

3.4.4.2. Summer 2015 Recording Period

Beluga whale calls were detected at a few stations (B5, B15, B30, BG02, HSW4, and PLN80; Figure 32). The proportion of days with detections ranged from 2% at PLN80 to 11% at B5 with a mean of 6.2% across these stations (Table C–6). Stations off Barrow had the highest call counts (Figure 33). Most of detections occurred between mid-September and early October.

By configuring Station B5, CLN120, PLN40, and W10 to record on a duty cycle with a sampling rate alternating between 16 and 250 ksps, we were able to run the automatic detector on echolocation clicks beluga whales produce while they forage. Validation of click detections showed that most detections were false alarms triggered by noise. Using a threshold of 151 beluga click detections per file gave a Precision of 1, a Recall of 0.33, and an F score of 0.71. With this threshold, very few files contained beluga clicks at Stations B5 (2), CLN120 (2), PLN40 (0), and W10 (2). Adding click detections therefore did not improve the probability of detecting belugas in the 2015 summer data.

Detected signals included a mixture of whistles and pulsed calls.

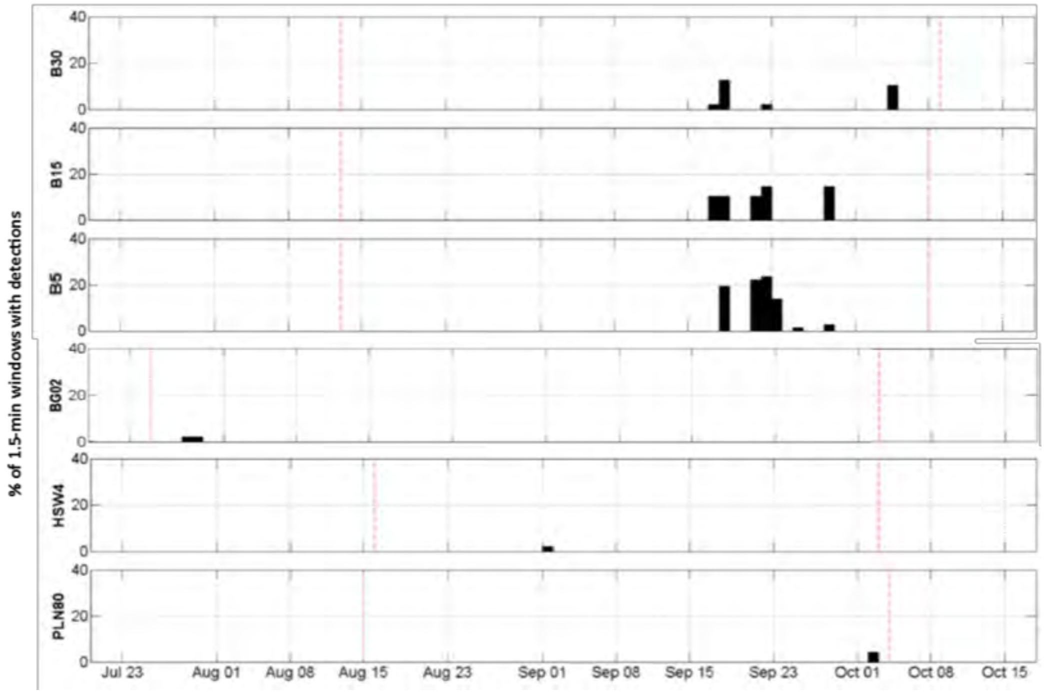


Figure 32. Summer 2015 daily beluga call detections in the northeastern Chukchi Sea: Daily proportion of sound files with detections based on the manual analysis of 5% of the acoustic data recorded late July through early October 2015. Forty-eight sound files were recorded each day. Red dashed lines indicate record start and end. Stations are ordered from (top) northeast to (bottom) southwest. Stations without call detections were omitted.

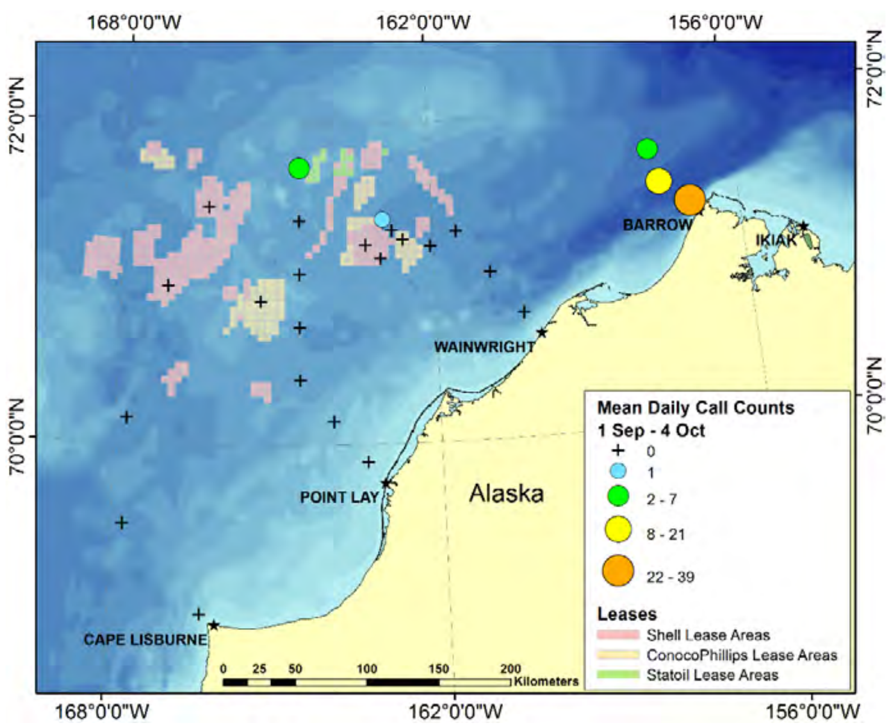


Figure 33. Mean daily beluga call counts (calculated as the sum of automated call detections in all files with manual detections divided by the number of active recording days) for 1 Sep to 4 Oct at all summer 2015 stations in the northeastern Chukchi Sea.

3.4.5. Bearded Seal Call Detections

3.4.5.1. Winter 2014–2015 Recording Period

Bearded seals were detected at all stations. The number of detection days ranged from 6 at PLN40 to 198 at CL5 (Table C–7). Detections were rare in October, but began increasing in November at CL5 and PL10, December at the Wainwright stations, but not until late January at PL50. Sustained calling occurred for longer periods at the inshore stations (CL5 and W10) and shorter periods at the offshore stations (PL50 and WN40). Starting mid-June, detections decreased rapidly and stopped completely over a few days at all stations. The last detection occurred from mid- to late June, depending on stations. Detections continued longer at stations farther northeast (W10 and WN40), with a two-week lag between CL5 and WN40 (Figure 34).

Call counts overall were highest at CL5 and W10 (Figure 35). They were lowest at PL10, PLN40, and W50 because those recorders stopped before the peak of vocal activity (April–June). Monthly call counts were similar across stations in November and December (Figure C–6). Call counts varied most widely between stations in January after which time they rose in parallel at all stations, but were consistently lower at WN40, except in May when all stations had similarly high call counts. June call counts were highest at stations farther northeast (Figure C–7).

The detected calls consisted primarily of upsweeping and downsweeping trills (Figure 36) previously described in Frouin-Mouy et al. (2016).

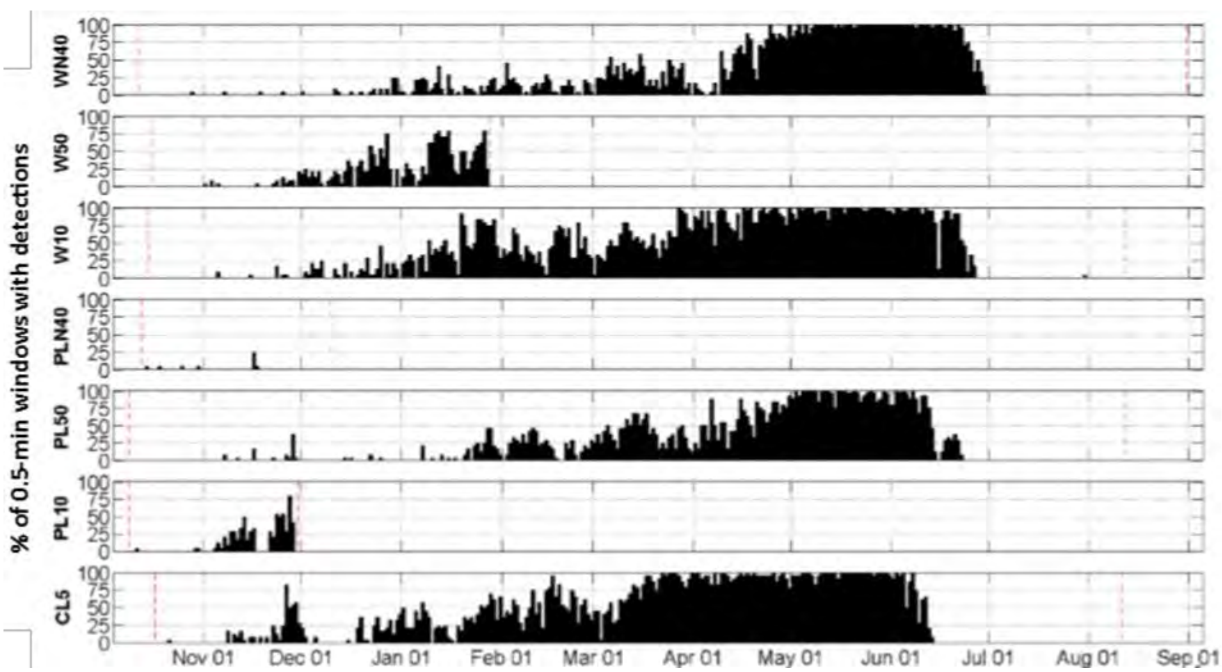


Figure 34. Winter 2014–2015 daily bearded seal call detections: Daily proportion of sound files with call detections based on the manual analysis of 5% of the acoustic data recorded early October 2014 through late August 2015 in the northeastern Chukchi Sea for each station. Forty-eight sound files lasting 5 min were recorded each day every 30 min. Stations are ordered from (top) northeast to (bottom) southwest. The red dashed lines indicate the record start and end dates.

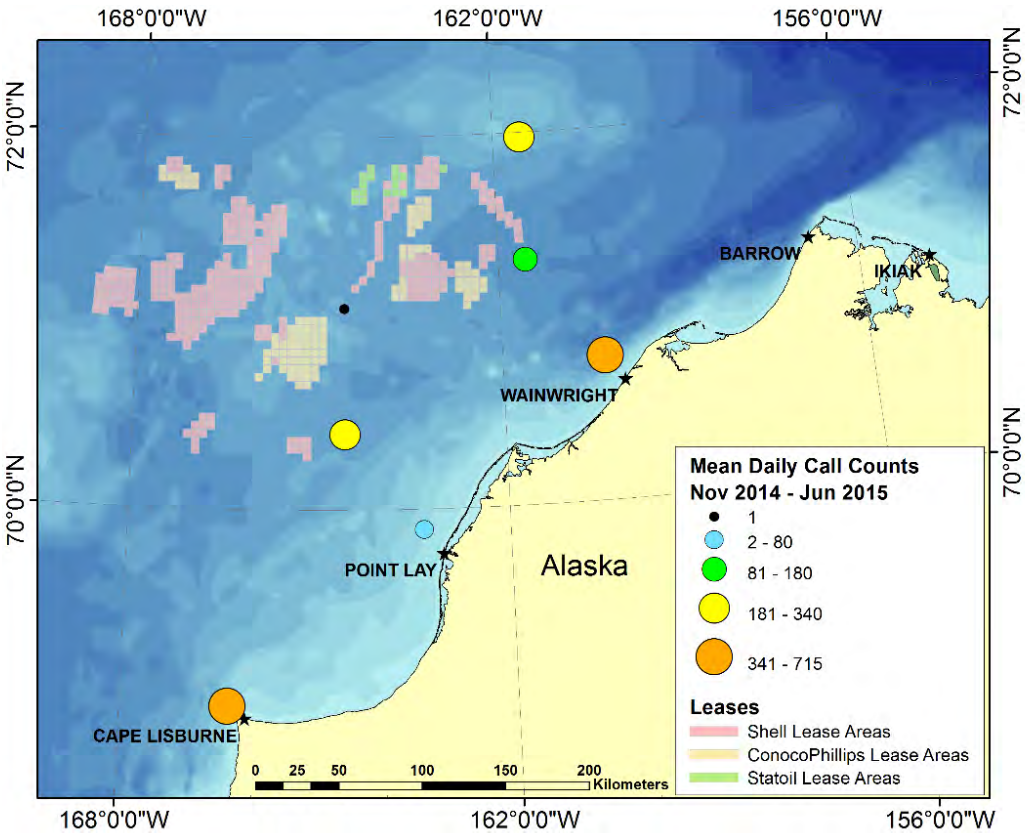


Figure 35. Bearded seal mean daily call counts[5] in the Chukchi Sea from Nov 2014 through Jun 2015 at all winter 2014–2015 stations.

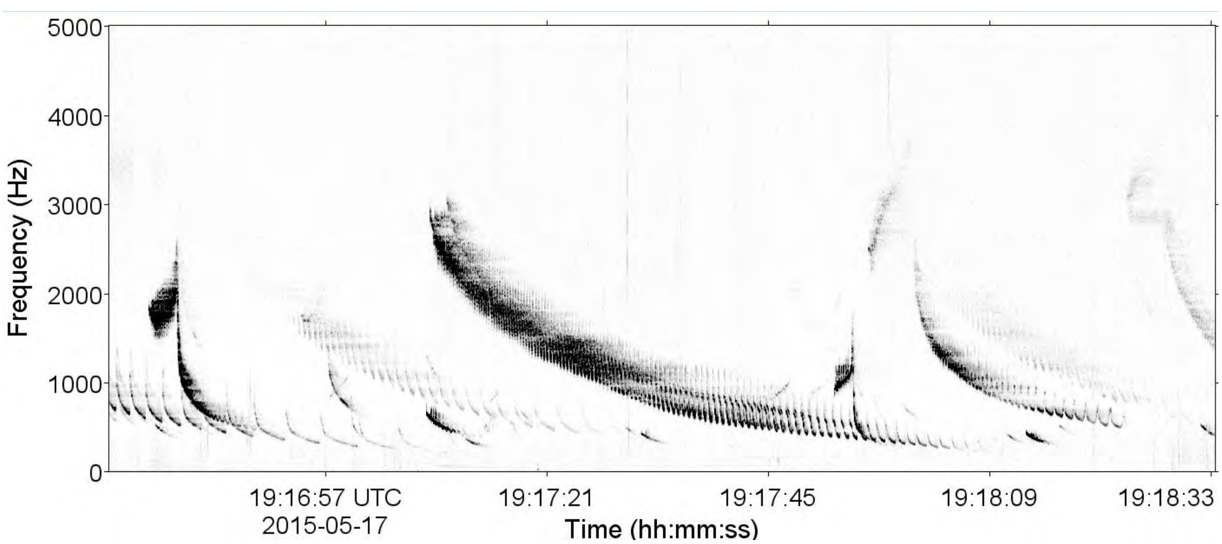


Figure 36. Spectrogram of bearded seal calls recorded 17 May 2015 at Station WN40. Frequency resolution: 2 Hz, Frame size: 0.128 s; Time step: 0.032 s; Hamming window.

[5] Corrected sum of automated call detections in all files with manual detections divided by the number of recording days.

3.4.5.2. Summer 2015 Recording Period

Bearded seal calls were detected at all stations except BG01, BG02, BG03, and BGV-16. The proportion of recording days with detections ranged from 1.67 to 52% with a mean of 18.3% across stations (Table C–8). There were few detections before 1 Sep (Figure 37). Detections increased progressively starting in mid-September.

Mean daily call counts were highest at the northernmost stations (north of 70° N) particularly at B15, W10, and PLN80. Call counts were low west and along a line running from Point Lay through Klondike to CLN120 (Figure 38) and generally increased with increasing distance from shore (Figures C–7).

In summer bearded seal calls exhibited more temporal variability and were easily distinguished from the long, complex, spiraling calls common during the spring breeding season (Frouin-Mouy et al. 2016).

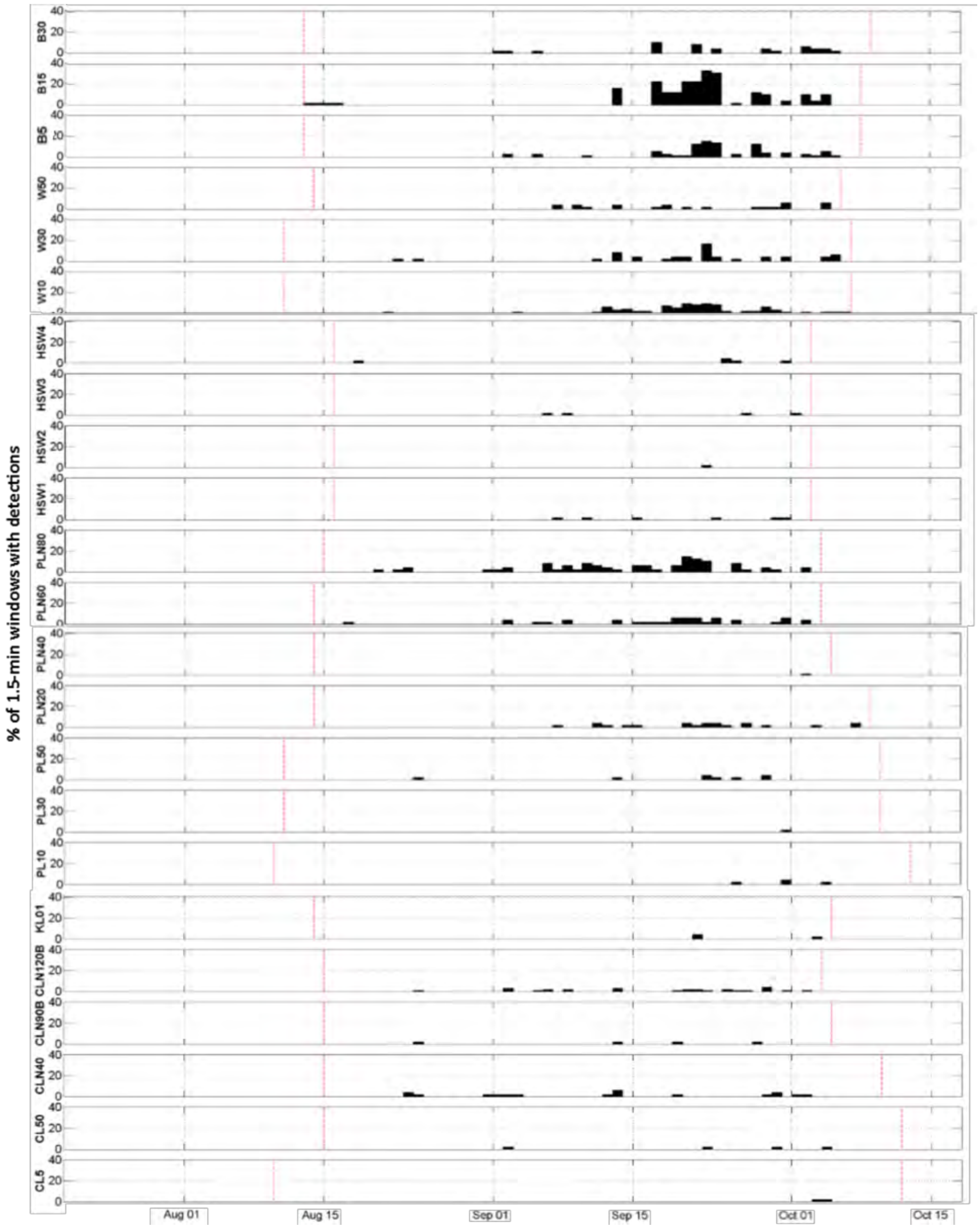


Figure 37. Summer 2015 daily bearded seal call detections: Daily proportion of sound files with call detections based on the manual analysis of 5% of the acoustic data recorded late July through early October 2015.

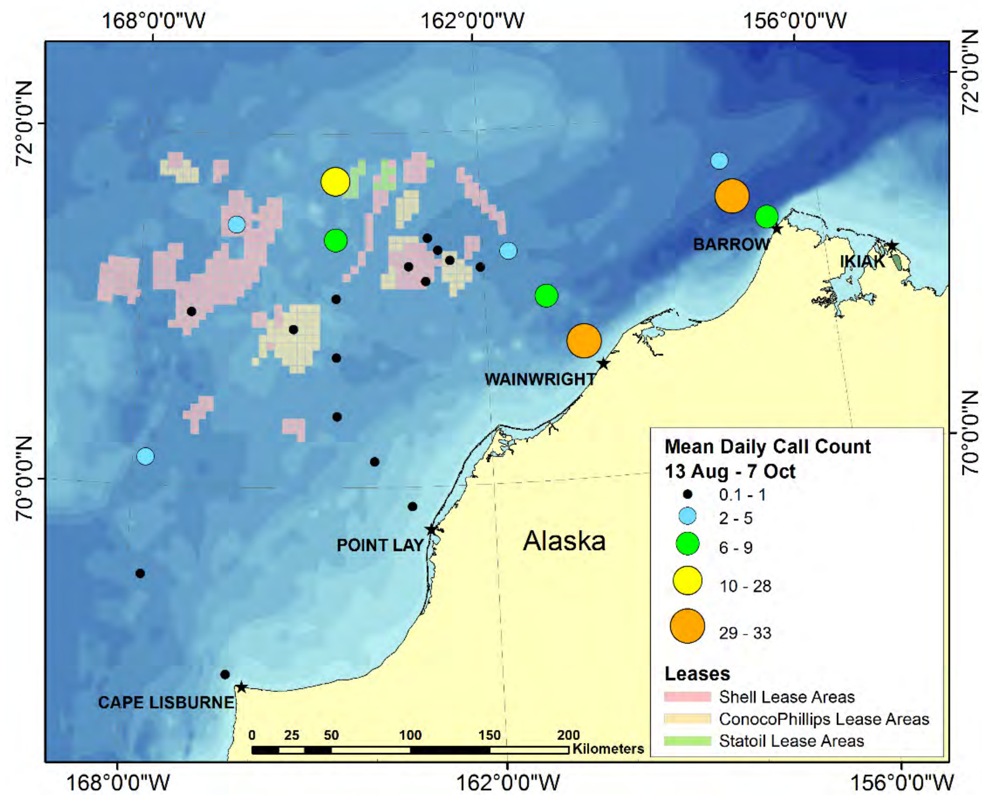


Figure 38. Mean daily bearded seal call counts (calculated as the sum of automated call detections in all files with manual detections divided by the number of active recording days) for 13 Aug to 7 Oct at all summer 2015 stations in the northeastern Chukchi Sea.

3.4.6. Fin Whale Call Detections

3.4.6.1. Winter 2014–2015 Recording Period

There were no fin whale detections during the 2014–2015 winter recording period.

3.4.6.2. Summer 2015 Recording Period

Fin whale calls were detected at two stations (CLN120 and CL50) starting on 5 Sep (Table 12). CL50 had seven days of detections between 5 Sep and 3 Oct. Most calls were broadband signals sweeping down from 50 to 20 Hz (Figure 39).

Table 12. Summer 2015 fin whale call detections: Dates of first and last call detections, both possible (i.e., record start and end) and actual, and the number and percentage of days on which a call was detected in the northeastern Chukchi Sea. Stations without call detections were omitted.

Station	Record start	First detection	Last detection	Record end	Detection days	% Days with detection
CLN120	15 Aug	6 Sep	6 Sep	3 Oct	1	2
CL50	15 Aug	5 Sep	3 Oct	11 Oct	7	12.1

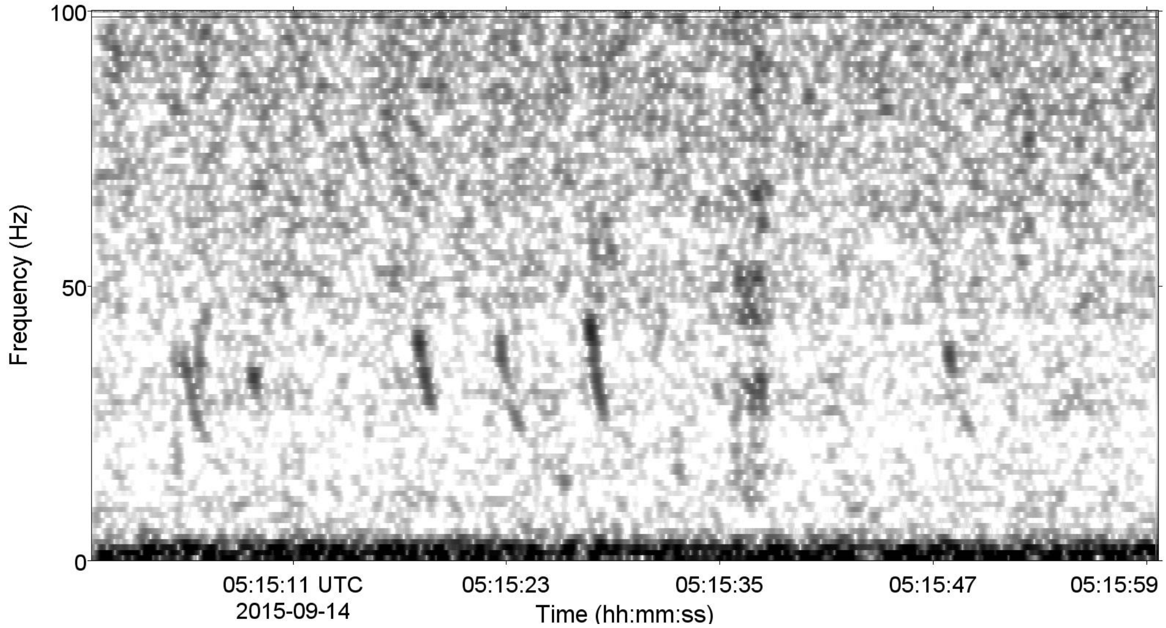


Figure 39. Spectrogram of fin whale calls recorded at Station CL50 on 14 Sep 2015. Frequency resolution: 1 Hz; Frame size: 1 s; Time step: 0.01 s; Hamming window.

3.4.7. Gray Whale Call Detections

3.4.7.1. Winter 2014–2015 Recording Period

Gray whale calls were detected at three stations. PL10 had one late November 2014 detection. W10 had 30 detection days from 17 Jun to 11 Aug. The earliest spring detection occurred at PL50 on 11 Jun (Table 13).

Most of the detections were low-frequency moans (Figure 40), with additional contributions from pulses and bonging signals (Crane and Lashkari 1996).

Table 13. Winter 2014–2015 gray whale call detections: Dates of first and last call detections, both possible (i.e., record start and end) and actual, and the number of days on which a call was detected manually for each station in the northeastern Chukchi Sea. The recorders operated for 5 min every 30 min.

Station	Record start	First detection	Last detection	Record end	Detection days	% Days with detection
W10	15 Oct	17 Jun	11 Aug	11 Aug	30	10%
PL50	9 Oct	11 Jun	11 Jun	11 Aug	1	0.3%
PL10	9 Oct	26 Nov	26 Nov	29 Nov	1	1.9%

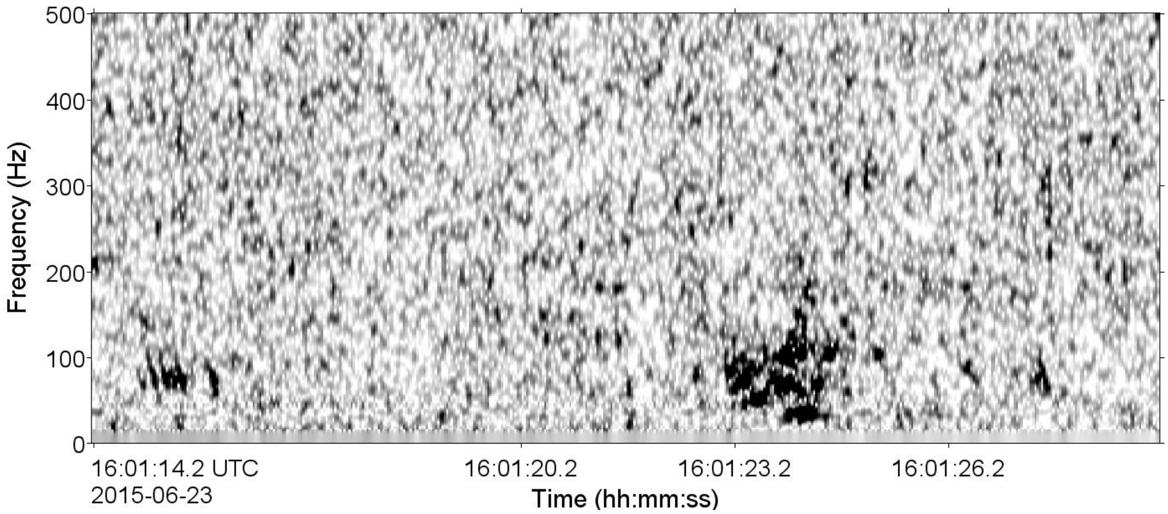


Figure 40. Spectrogram of gray whale moan recorded on 23 June 2015 at Station W10. Frequency resolution: 1 Hz; Frame size: 0.06 s; Time step: 0.006 s; Hamming window.

3.4.7.2. Summer 2015 Recording Period

Gray whale calls were detected at stations B30, B15, B5, W50, W30, W10, HSW1, BG03, PLN60, PL50, PL30, KL01, CLN40, and CL50. The proportion of recording days with detections was low on average (6.3%), but as high as 16.4% at W50 (Table C–9). At W10, most detections occurred in August. Most W50 detections occurred in the second half of September. These detections coincided with a recurring visual observations during Aerial Surveys for Arctic Marine Mammals (ASAMM) in late September near this recorder. Few gray whale calls were detected past mid-September in the rest of the study area (Figure 41).

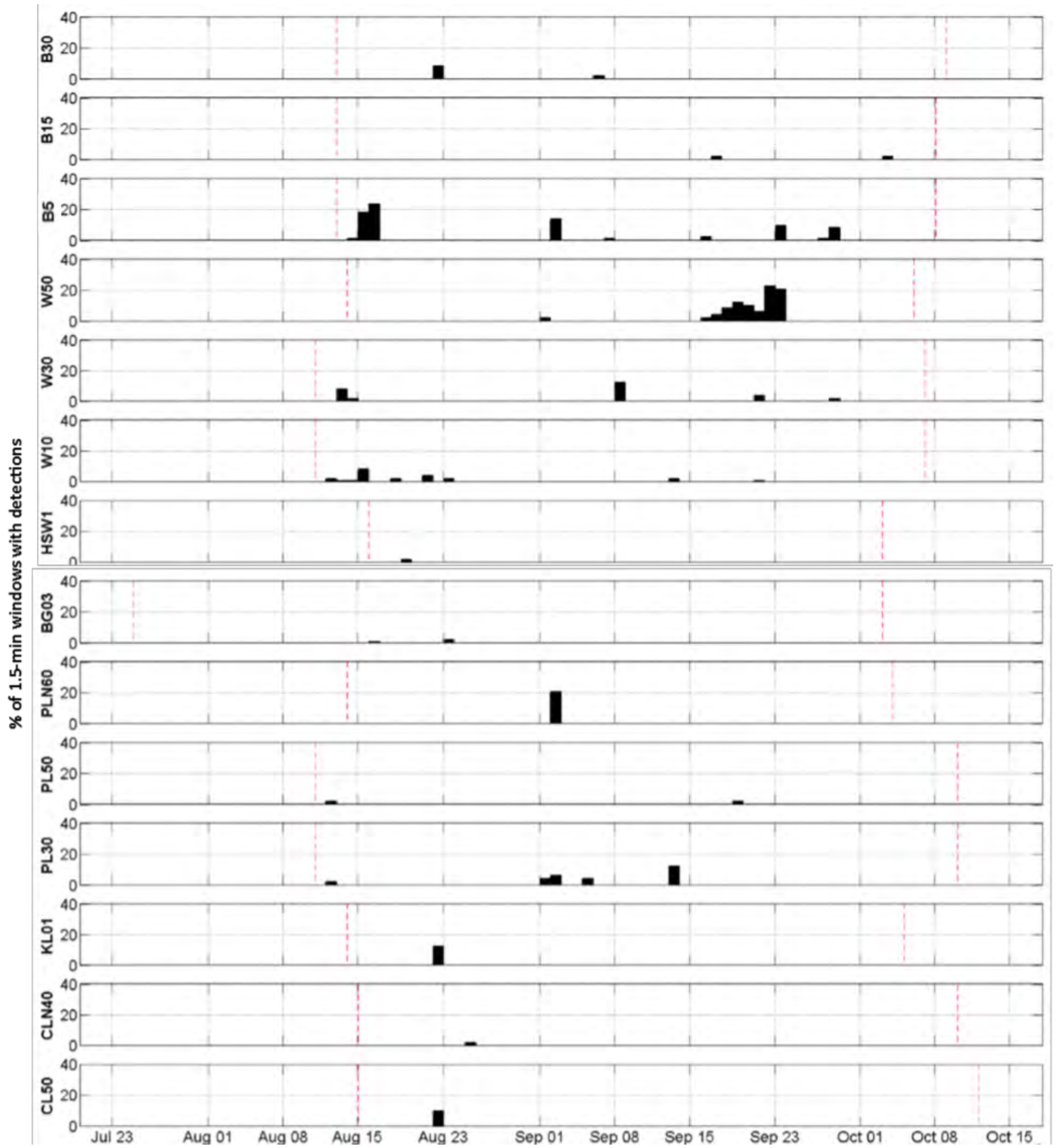


Figure 41. Summer 2015 daily gray whale call detections: Daily proportion of sound files with call detections based on the manual analysis of 5% of the acoustic data recorded late July through early October 2015. Forty-eight sound files were recorded each day. Red dashed lines indicate record start and end. Stations are ordered from (top) northeast to (bottom) southwest. Stations without call detections were omitted.

3.4.8. Humpback Whale Call Detections

3.4.8.1. Winter 2014–2015 Recording Period

Humpback whale calls were not detected in the winter 2014–2015 data.

3.4.8.2. Summer 2015 Recording Period

Humpback whale calls were detected twice on 11 Aug 2015 at CL5.

Detections (Figure 42) consisted mainly of moans and grunts (Thompson et al. 1986).

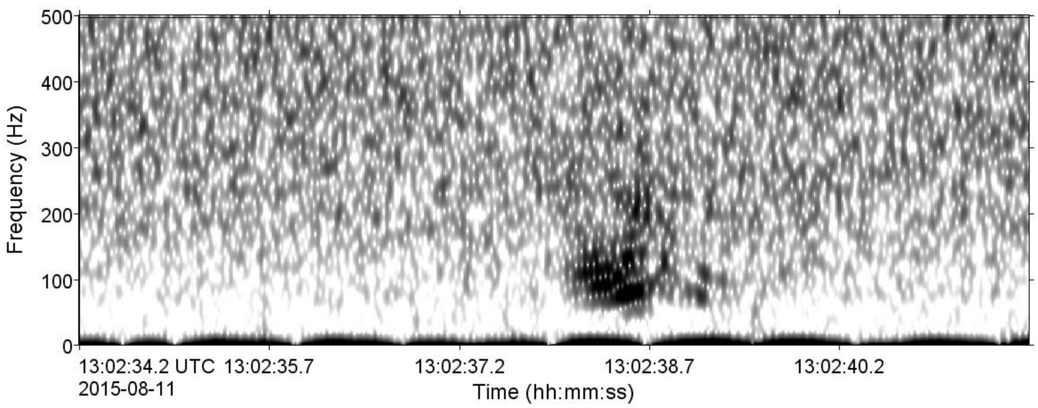


Figure 42. Spectrogram of humpback whale call recorded at Station CL5 on 11 Aug 2015. Frequency resolution: 1 Hz; Frame size: 0.08 s; Time step: 0.01 s; Hamming window.

3.4.9. Killer Whale Call Detections

3.4.9.1. Winter 2014–2015 Recording Period

Killer whale calls were detected once on 29 Jul 2015 at PL50. The detected calls (Figure 43) consisted mostly of pulsed calls (Ford 1989).

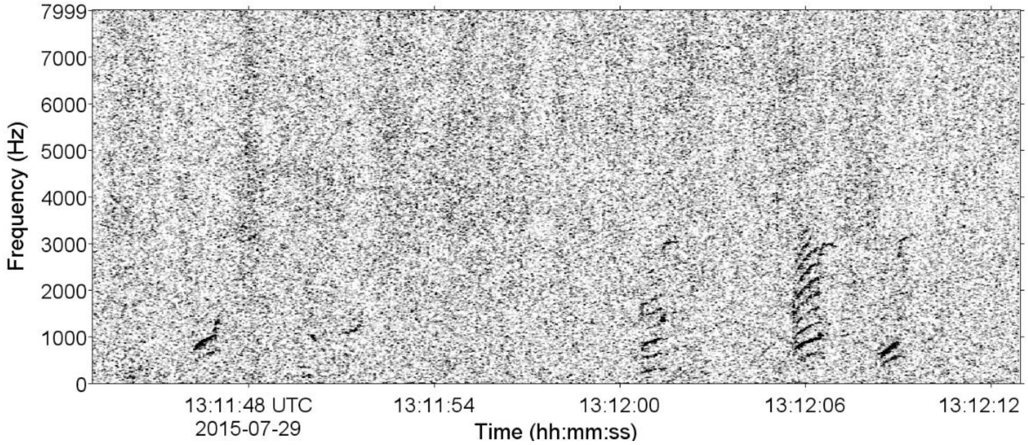


Figure 43. Killer whale call spectrogram from detections at Station PL50, 29 Jul 2015. Frequency resolution: 1 Hz; Frame size: 0.06 s; Time step: 0.006 s; Hamming window.

3.4.9.2. Summer 2015 Recording Period

Killer whale calls were detected between one and five days at 20 different stations. Detections started at CL5 on 15 Aug. Most detections occurred at multiple stations from 13 to 28 Sep (Figure 44; Table C–10). The cluster of detections at W50 in late September coincided with the gray whale detection cluster at the same station. The detected calls consisted mostly of pulsed calls and whistles (Ford 1989).

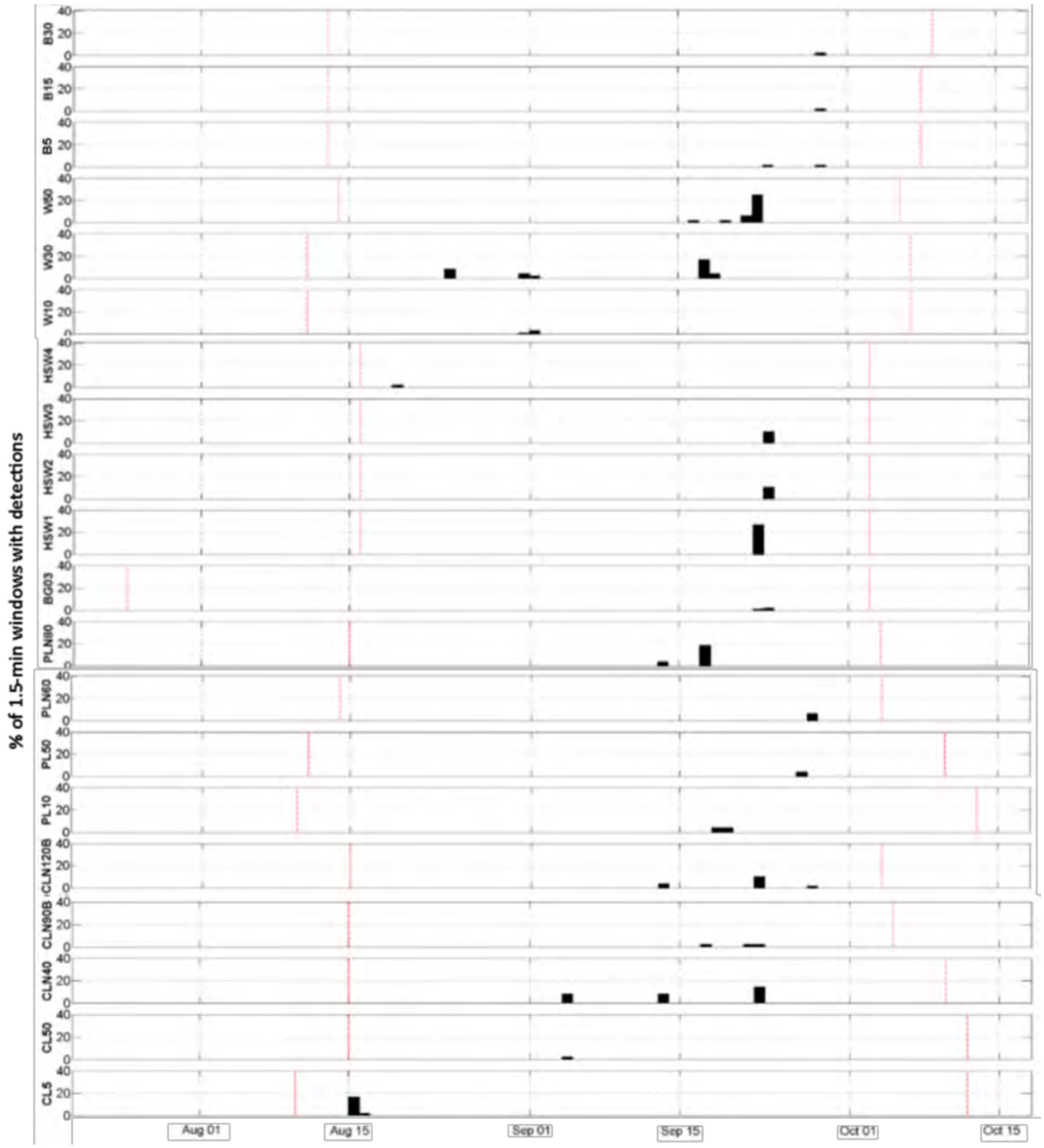


Figure 44. Summer 2015 killer whale call detections: Daily proportion of sound files with call detections based on the manual analysis of 5% of the acoustic data recorded late July through early October 2015.

3.4.10. Minke Whale Call Detections

3.4.10.1. Winter 2014–2015 Recording Period

Minke whale calls were not detected in the winter 2014–2015 data.

3.4.10.2. Summer 2015 Recording Period

Minke whale boing sounds (Rankin and Barlow 2005; Figure 45) were detected at CL50 on 1 and 22 Sep 2015.

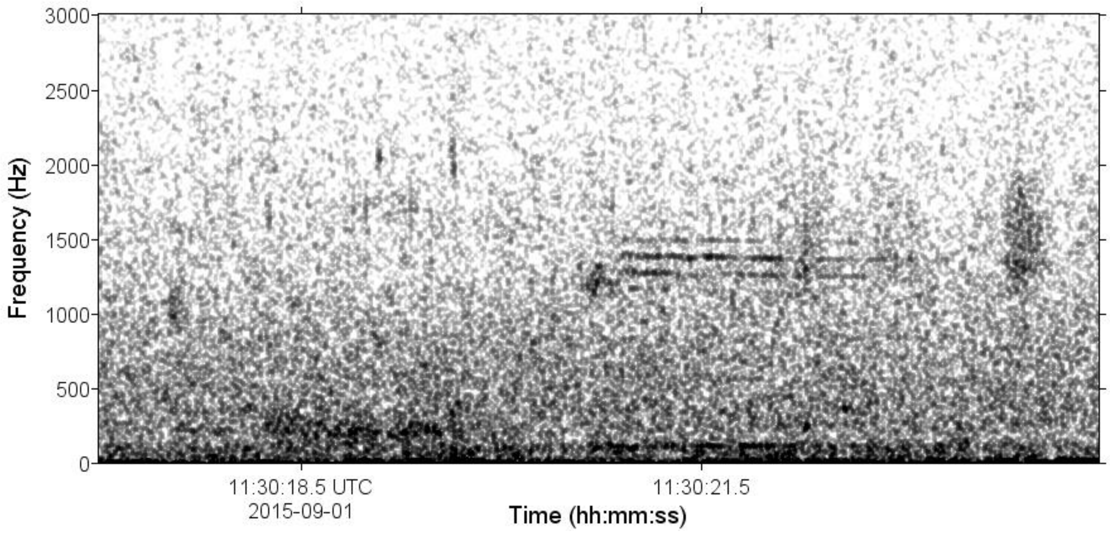


Figure 45. Minke whale boing call recorded 1 Sep 2015 at Station CL50. Frequency resolution: 2 Hz; Frame size: 0.06 s; Time step 0.006 s; Hamming window.

3.4.11. Ribbon Seal Call Detections

3.4.11.1. Winter 2014–2015 Recording Period

A ribbon seal downsweep (Figure 46) described by Watkins and Ray (1977) was detected once on 21 Nov 2014 at CL5.

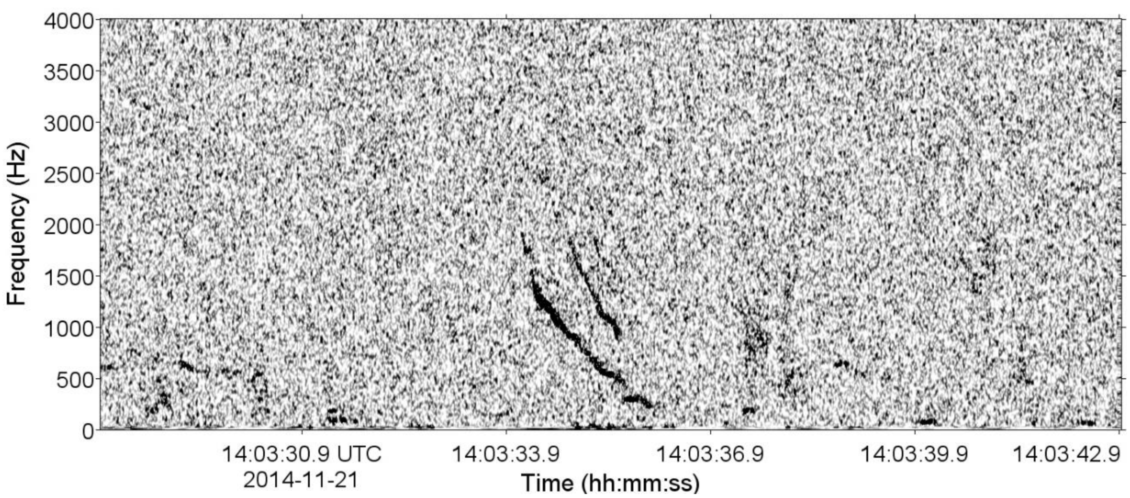


Figure 46. Spectrogram of ribbon seal calls recorded 21 Nov 2014 at Station CL5. Frequency resolution: 1 Hz; Frame size: 0.06 s; Time step: 0.006 s; Hamming window.

3.4.11.2. Summer 2015 Recording Period

Ribbon seal calls were not detected in summer 2015 data.

3.4.12. Ringed Seal Call Detections

3.4.12.1. Winter 2014–2015 Recording Period

Ringed seal calls were detected at all stations during the winter 2014–2015 deployment. The number of days with detections ranged from 2 days at PLN40, where recordings ended prematurely, to 112 days at CL5 (Table C–11). Stations CL5 and PL50 had similar temporal detection patterns with detections occurring sporadically at low levels in November, December, and January. Calls were detected almost daily, in a few files, in February and March. Detections increased in April and peaked in May before stopping abruptly at the end of May. This pattern was similar at WN40 and W10 except that detections were essentially absent before April (W10) and May (W50) (Figure 47).

In previous years, we showed that the detection probability for ringed seal barks (Figure 48) and yelps using a 5% manual data analysis protocol was low (22%; see Appendix A in Delarue et al. 2013b). Including thumps (see Delarue et al. 2014) in the set of targeted calls definitely raised the detection probability although we did not quantify the associated increase. The current results better represent the true acoustic occurrence of ringed seals in the Chukchi Sea.

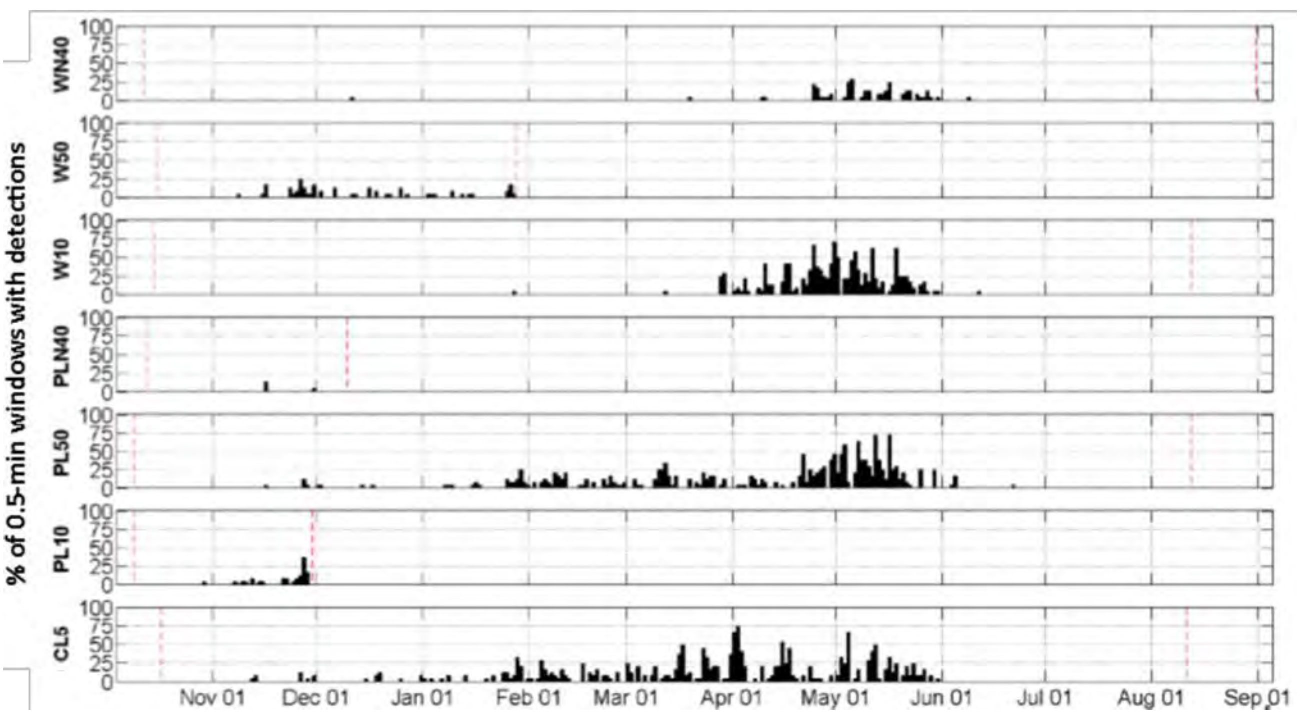


Figure 47. Winter 2014–2015 daily ringed seal call detections: Daily proportion of sound files with call detections based on the manual analysis of 5% of the acoustic data recorded early October 2014 through late August 2015 in the northeastern Chukchi Sea for each station. Forty-eight sound files lasting 5 min were recorded each day every 30 min. Stations are ordered from (top) northeast to (bottom) southwest. The red dashed lines indicate the record start and end dates.

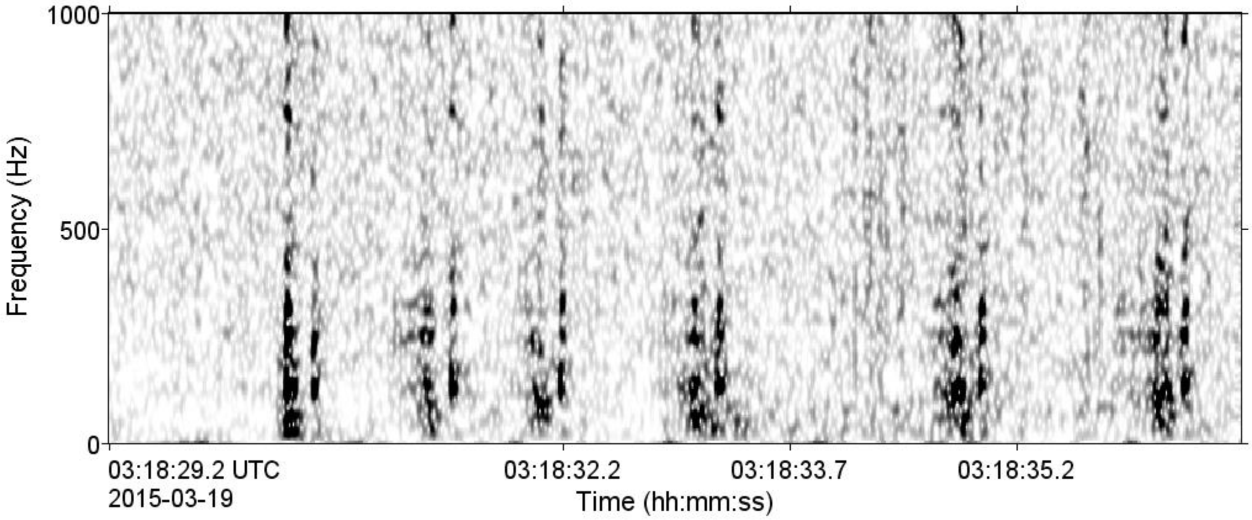


Figure 48. Spectrogram of ringed seal calls recorded 19 Mar 2015 at Station WN40. Frequency resolution: 1 Hz; Frame size: 0.06 s; Time step: 0.006 s; Hamming window.

3.4.12.2. Summer 2015 Recording Period

Ringed seal calls were detected at seven stations during summer 2015. Calls were recorded from 1 to 16 days per station (Table C–12). Detections were sporadic throughout the study area. At B30 and B15 stations, most detections occurred from 17 Sep to 4 Oct. No clear temporal or spatial patterns were observed (Figure 49).

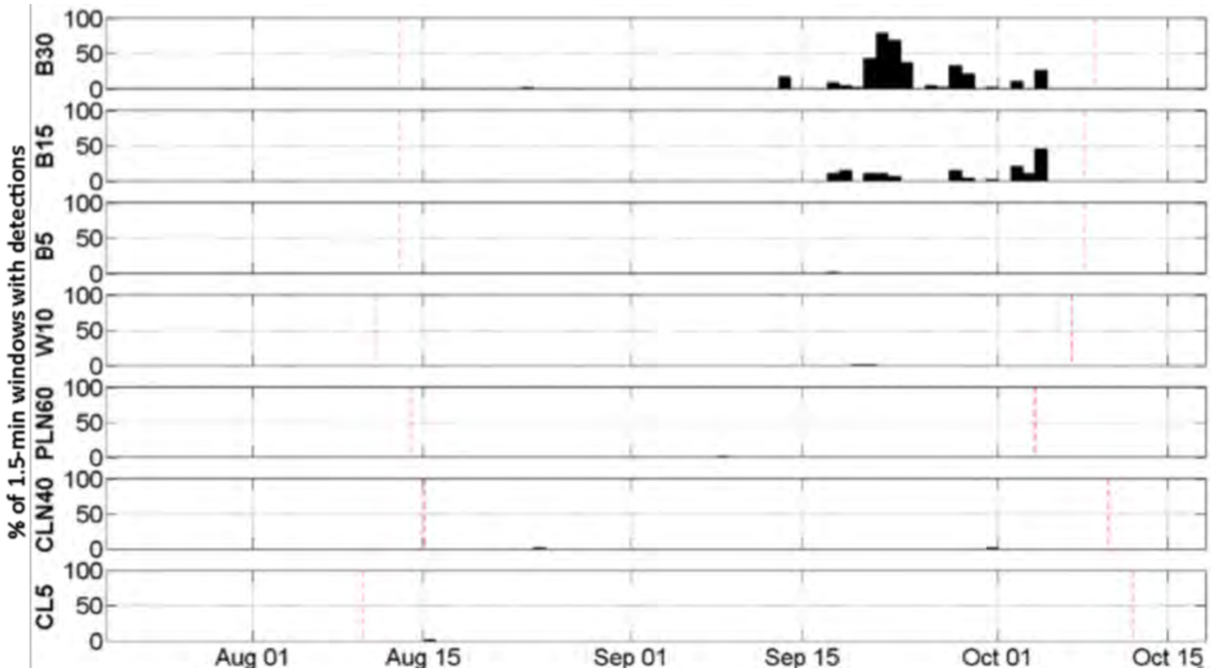


Figure 49. Summer 2015 daily ringed seal call detections: Daily proportion of sound files with call detections based on the manual analysis of 5% of the acoustic data recorded late July through early October 2015. Forty-eight sound files were recorded each day. Red dashed lines indicate record start and end. Stations are ordered from (top) northeast to (bottom) southwest. Stations without call detections were omitted.

3.4.13. Spotted Seal Call Detections

Spotted seals were not manually or automatically detected in the winter 2014–2015 or summer 2015 datasets, likely because we do not have a good representation of their call types. Spotted seals are regularly seen in the program area in summer (e.g., Aerts et al. 2013). It would be worthwhile to document their calls to improve this analysis. One way to do that would be to place recorders near known spotted seal summer haul-outs (e.g., in Kasegaluk Lagoon passes; Frost et al. 1993).

4. Discussion: 2007–2015 Trends

4.1. Received Ocean Noise

The total received sound in the ocean consists of sounds produced by wind, waves, ice-cracking events, geological seismic events, biological sources, and human activities. Marine mammals are the primary biological sources in the Chukchi Sea, but fish and crustaceans also contribute.

Because the natural soundscape has been part of the environment in which marine life has evolved, it is appropriate to assume that marine animals have adapted to this noise. Nevertheless, this assumption does not mean that ambient noise does not constitute a cost for marine animals while they forage, socialize, and find mates. Anthropogenic noise is a much more recent addition to the underwater soundscape, especially in remote regions like the Chukchi Sea. Marine fauna are likely less well adapted to deal with anthropogenic sounds that differ in temporal and spectral character from natural sounds. One of the goals of this study is to characterize natural and anthropogenic sounds in the Chukchi Sea environment and to determine when and where it exceeds the natural ambient noise.

In this section, we compare the sound levels measured at Station PLN40 throughout the summer and the winter deployments from seasons 2007 through 2015. Sound levels at four recorders along an east-west line of the Chukchi in summer 2015 are also discussed. Measured and predicted sound levels based on source levels measured during the sound source verification program and the known activity locations are compared. Finally, we summarize the measured sound levels throughout the Chukchi Acoustic Monitoring Program and introduce the acoustic continuity index as a means of describing the nature of the measured sounds.

The list below summarizes the hydrocarbon exploration activities in the Chukchi Sea for 2007–2015 to provide context for interpreting the results:

- 2007: 3-D seismic survey in Shell lease areas
- 2008: 3-D seismic survey in Shell and ConocoPhillips Alaska, Inc. (CPAI) lease areas
- 2009: Shallow hazards survey in Shell and CPAI lease areas
- 2010: 3-D seismic survey in Statoil lease areas and a geotechnical program in Shell lease areas
- 2011: Shallow hazards program in Statoil lease areas
- 2012: First Burger drill campaign
- 2013: Wide area seismic survey (TGS) from 29 Aug to 29 Oct; shallow hazards seismic survey in Shell lease areas from 18 Jul to 28 Sep.
- 2014: No major activity
- 2015: Second Burger drill campaign.

4.1.1. Station PLN40 Multi-Year Analysis

The 2007–2015 summer total sound measurements were consistent with each other and with previous years' measurements of this program. Local variations were correlated with weather, marine mammal acoustic activity, vessel activity, and seismic exploration. The 50th percentile (median) power spectral density (PSD) levels are presented in Figure 50 from Station PLN40 for summer recording periods from 2007 to 2015. Station KL11 was substituted for summer 2009 because PLN40 was not deployed that year. Winter session PSDs from 2007 to 2014 are plotted in Figure 54. Station W50 was substituted for winter 2013-2014 because the recorder at Station PLN40 was not retrieved. The recorder at Station PLN40 stopped early in winter 2014–2015, so PL50 was substituted. Spectrograms for the summer and winter periods are separately displayed because their spectral characteristics differ (Figures 52, 53, and 55).

The 2013–2014, winter dataset was the first one monitored using AMARs; all prior winter measurements were made with AURALs. The AMAR has a lower noise floor than the AURAL and thus this type of recorder captured true ambient levels above 1500 Hz that were obscured by AURAL self-noise (Figure 54). At 8 kHz, the AMAR showed a median PSD of approximately 35 dB re $\mu Pa^2/Hz$, approximately 15 dB lower than measured by the AURALs. While this is a low level, it is still well above the corresponding lower Wenz curve range of 20 dB re $\mu Pa^2/Hz$.

Summer 2015 noise levels at PLN40 were higher than any previous year. The decade-band levels were the highest in each of the decade-bands (Table 14). The highest levels occurred from 40 to 300 Hz, which correspond to vessel noise. There were 1.3 vessels detected per day at PLN40 compared with 0.2 per day in summer 2014 (Figure 51).

Summer 2014 noise levels at PLN40 were similar to previous years' but spectral levels from 300 Hz to 4 kHz were above previous years. These elevated levels are attributed to noise produced a relatively large number of weather events this year.

Summer 2013 noise spectral levels in the 30 to 400 Hz band were higher than all but two years. This difference can be attributed to more seismic survey activity in 2013 near Station PLN40. The spectral levels above 400 Hz are similar to other years.

In summer 2012, ambient noise levels below 1 kHz increased in mid-September (Figure 52). That increase was likely due to higher wind speeds during that time. Tonals from distant shipping were present in recordings between mid-August and early September 2012.

In summer 2011, two periods of increased broadband noise in mid-August and mid-September were attributed to wind and wave-break noise and partially to water movement against the hydrophone. Tonal noise, present from early August to mid-September, was associated with the shallow-hazards geotechnical vessel operating near the Statoil lease area. (Figure 50).

In summer 2010 the 3-D seismic survey and the Shell geo-technical program resulted in the highest spectral levels below 150 Hz of all years. Sound levels at higher frequencies were among the lowest of the multi-year measurements, which could have been due to calmer weather conditions.

The summer 2009 spectral levels were similar to those in other years. There was a restricted period of shallow hazards seismic activity captured in this recording but it did not significantly affect the median time-averaged levels. The elevated levels above 3 kHz in these data are likely due to recorder self-noise in the early generation of AMAR recorder.

The summer 2008 recording period showed spectral levels were slightly elevated relative to other years. Even though this recording period was much shorter than other years, it began later and thus extended later in the season when wind and weather conditions were worse.

During summer 2007, the PLN40 recorder was deployed only until 14 Sep. Because August and early September had mild weather, the spectral levels are low relative to other years, despite an extensive seismic survey program that occurred in September.

The spectral density percentiles (Figure 50) and spectrograms (Figure 52 and Figure 53) both indicate that sound levels are higher at lower frequencies (< 1 kHz) than at higher frequencies. When integrated over decade-bands, however, the in-band SPLs show that the total sound levels from 10–100 Hz are 7–12 dB lower than those in the 100–1000 and 1000–8000 Hz bands in most years (Table 14). Generally, sound levels in the 100–1000 Hz band are the highest, which indicates that wind-generated surface noise is the dominant noise source in the Chukchi summer.

Table 14. Median decade-band sound pressure levels (dB re 1 μPa) for summers 2009 through 2015 at Station PLN40.

Year	10–100 Hz	100 Hz to 1 kHz	1–8 kHz
2015	97.8	105.4	98.3
2014	92.0	100.3	95.2
2013	92.1	100.2	95.7
2012	86.4	98.0	94.2
2011	88.2	99.5	97.0
2010	95.8	96.2	92.6
2009	88.2	97.1	98.4

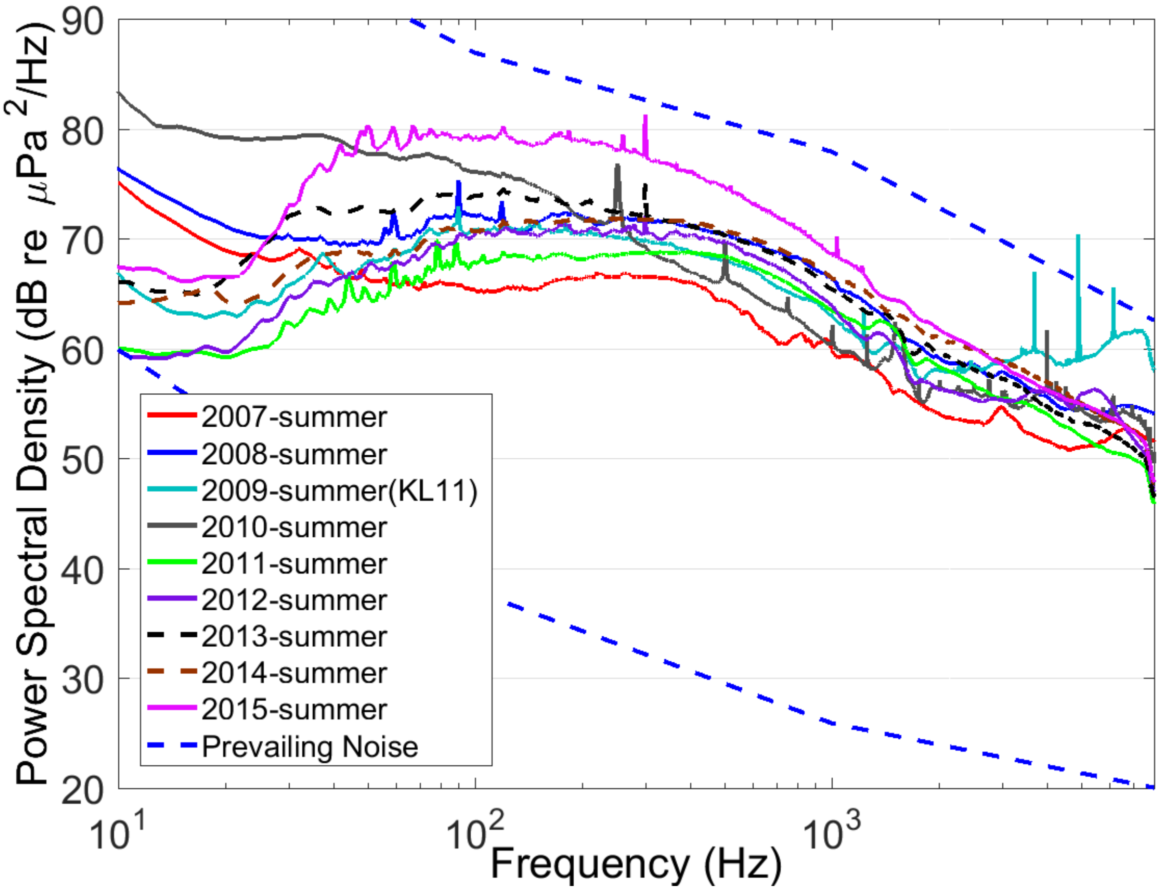


Figure 50. Percentile 1-min power spectral density levels at PLN40, for the recording periods from summer 2007 through 2015. Station KL11 results are shown for summer 2009 because PLN40 data are unavailable for that year.

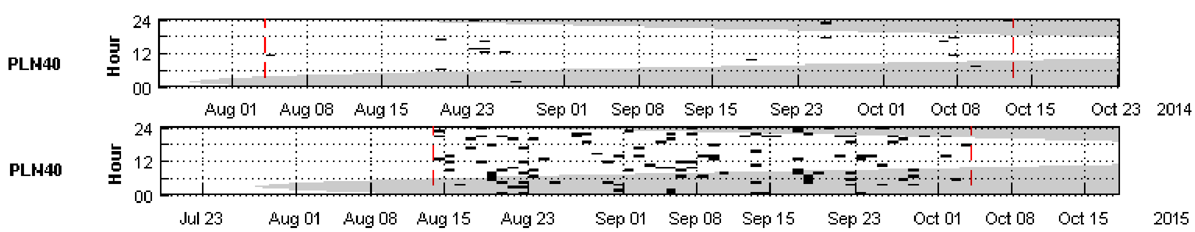


Figure 51. Vessel detections each hour (vertical axis) versus date (horizontal axis) at PLN40 for (top) summer 2014 and (bottom) summer 2015. The grey areas indicate hours of darkness. Vertical dashed lines indicate AMAR deployment and retrieval.

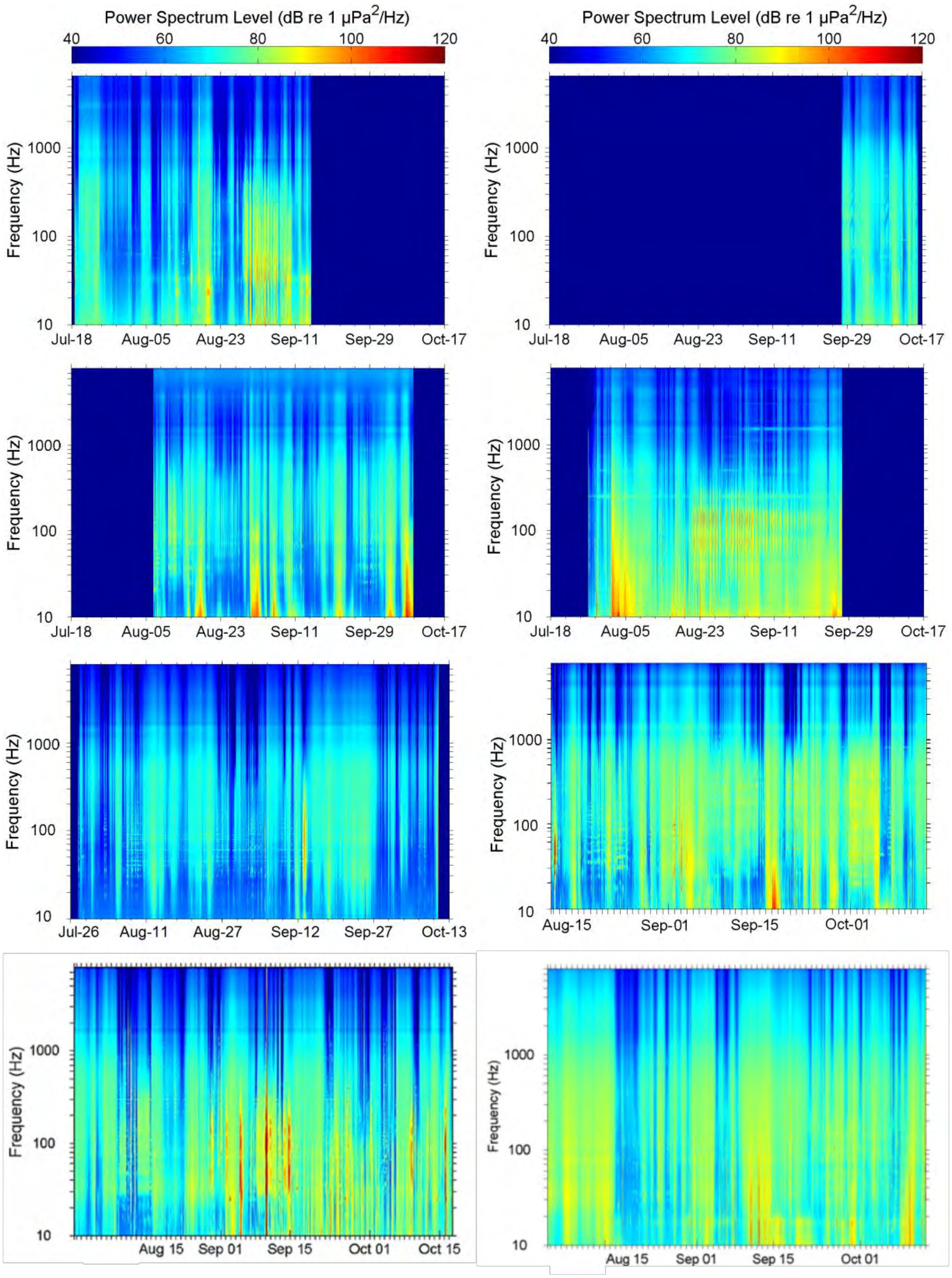


Figure 52. Spectrogram of underwater sound at Station PLN40 for summer deployments (top left) 2007, (top right) 2008, (upper middle left) 2009, (upper middle right) 2010, (lower middle left) 2011, (lower middle right) 2012, (bottom left) 2013, and (bottom right) 2014. Dark blue areas correspond to periods with no data.

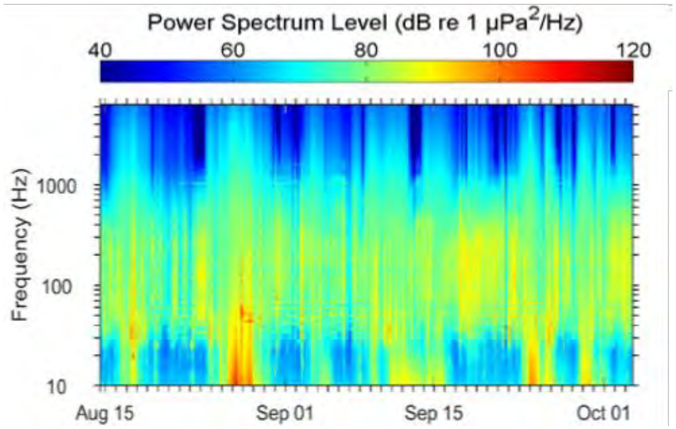


Figure 53. Spectrogram of underwater sound at Station PLN40 for summer 2015 deployment.

Power spectral density levels from the 2007 to 2010 winter periods decrease linearly over the frequency range 40 Hz to 2 kHz. The winter 2011 recording period was much quieter than the other recording periods; winter 2012 was louder than the others (Figures 54 and 55). Starting in fall 2013, AMARs were used in all winter deployments instead of AURALs. Due to the lower noise floor of the AMAR, the winter 2013 median data are lower for frequencies above 2 kHz. Below 2 kHz, PSD levels are similar to previous years, with the exception of a small increase between 400 and 700 Hz, which was likely caused by bearded seals that were more prominent at W50 than PLN40. The winter 2014 median data at PL50 show a similar profile to the winter 2013 median data at W50. Below 200 Hz, however, the median noise level is much lower than all other years. We speculate this may be the result of PL50 lying outside the main flow area of the Central Channel current that moves northeast between Herald and Hanna Shoals. PLN40 lies much closer to the area of highest flow associated with that current. Flow noise contribution is indeed greatest below 100–200 Hz, which would explain the observed differences at these frequencies. The loudest periods correspond with ice formation and break up. In general, the relatively high spectral levels below 100 Hz are attributed to wind noise propagating through the ice, which wave noise could also be contributing to.

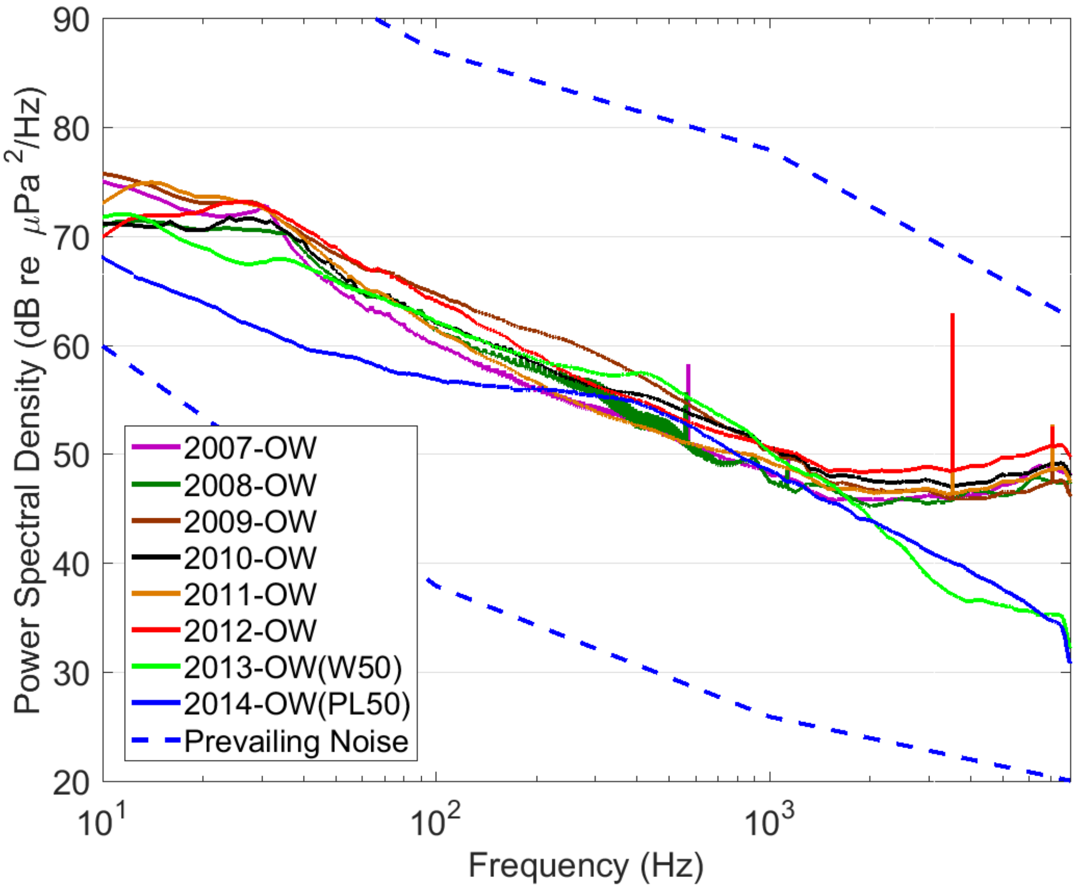


Figure 54. Percentile 1-min power spectral density levels at PLN40, for the recording periods from winter 2007 through 2014. Station W50 results are shown for winter 2013 because PLN40 was not retrieved. Station PL50 results are shown for winter 2014 because PLN40 stopped recording early.

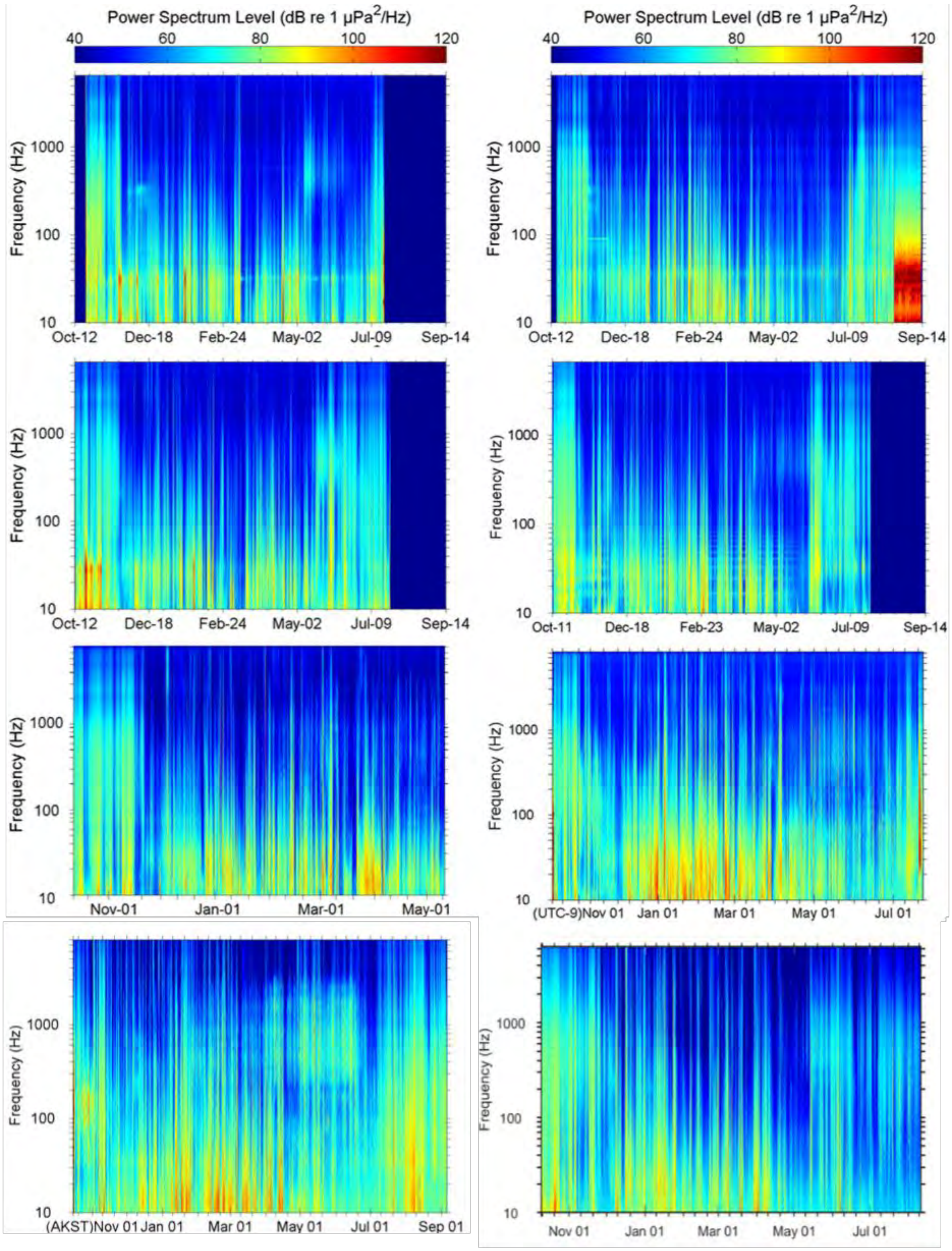


Figure 55. Spectrogram of underwater sound at Station PLN40 for the winter programs for (top left) 2007–2008, (top right) 2008–2009, (upper middle left) 2009–2010, (upper middle right) 2010–2011, (lower middle left) 2011–2012, (lower middle right) 2012–2013, (bottom left) 2013–2014, and (bottom right) 2014–2015. Station W50 results are shown for winter 2013–2014 and Station PL50 results are shown for winter 2014–2015.

4.1.2. Summer 2015 Recording Period

The 50th percentile power spectral density levels from the summer 2015 recordings are plotted for stations along a line roughly going east to west (Figure 56); the corresponding spectrograms for the recordings are shown in Figure 57. Sound levels below 1 kHz at Stations PLN60 and W50 were higher than other stations due to their proximity to the Burger drill site, and the associated vessel traffic. An anthropogenic source—likely a motor of some type—near B5 operated from 16 Aug through 6 Sep (Figure 57) with fundamental frequency at 12 Hz. In addition to the motor sound, a lot of small boat traffic around B5 increases the median sound level. The small vessels tend to emit higher frequencies than the vessels associated with the drilling operations, so the sound at B5 extends almost to 1 kHz, whereas noise levels at PLN60 and W50 begin to decrease at around 300–400 Hz.

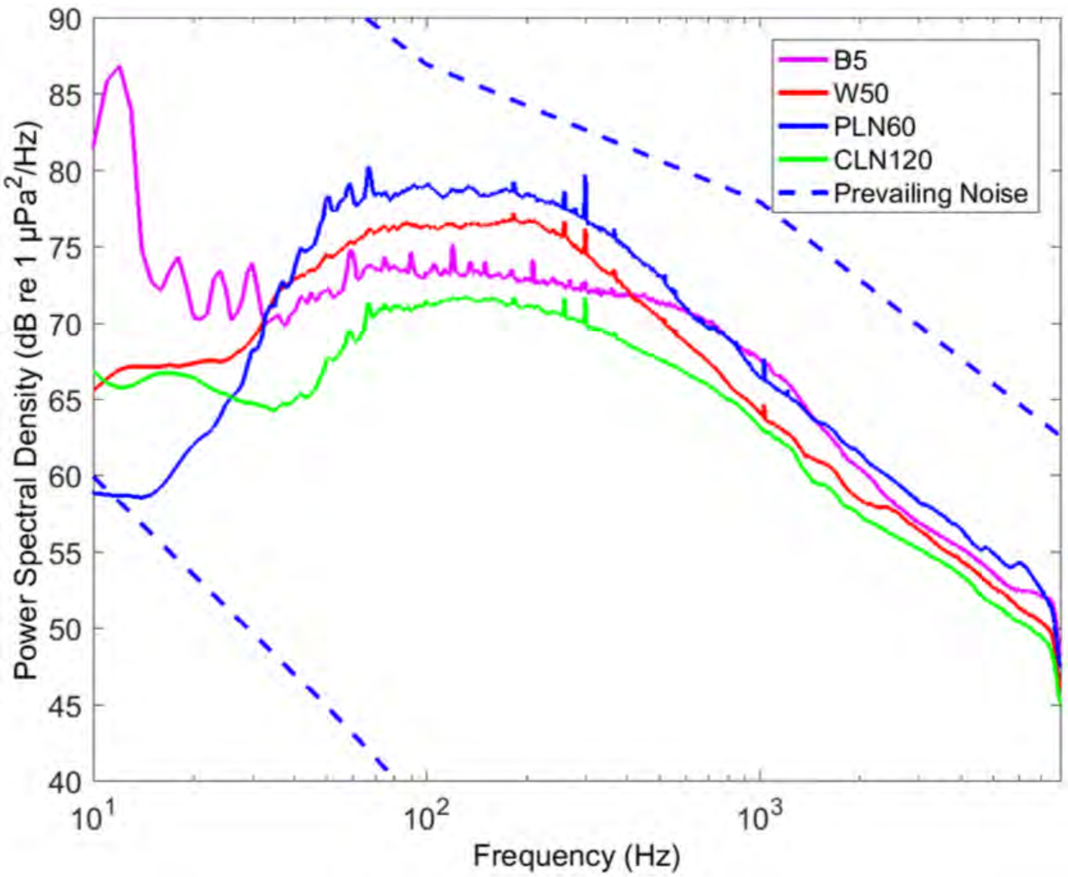


Figure 56. 50th percentile (median) 1-min power spectral density levels at stations along a roughly east-west line across the Chukchi Sea for summer 2015.

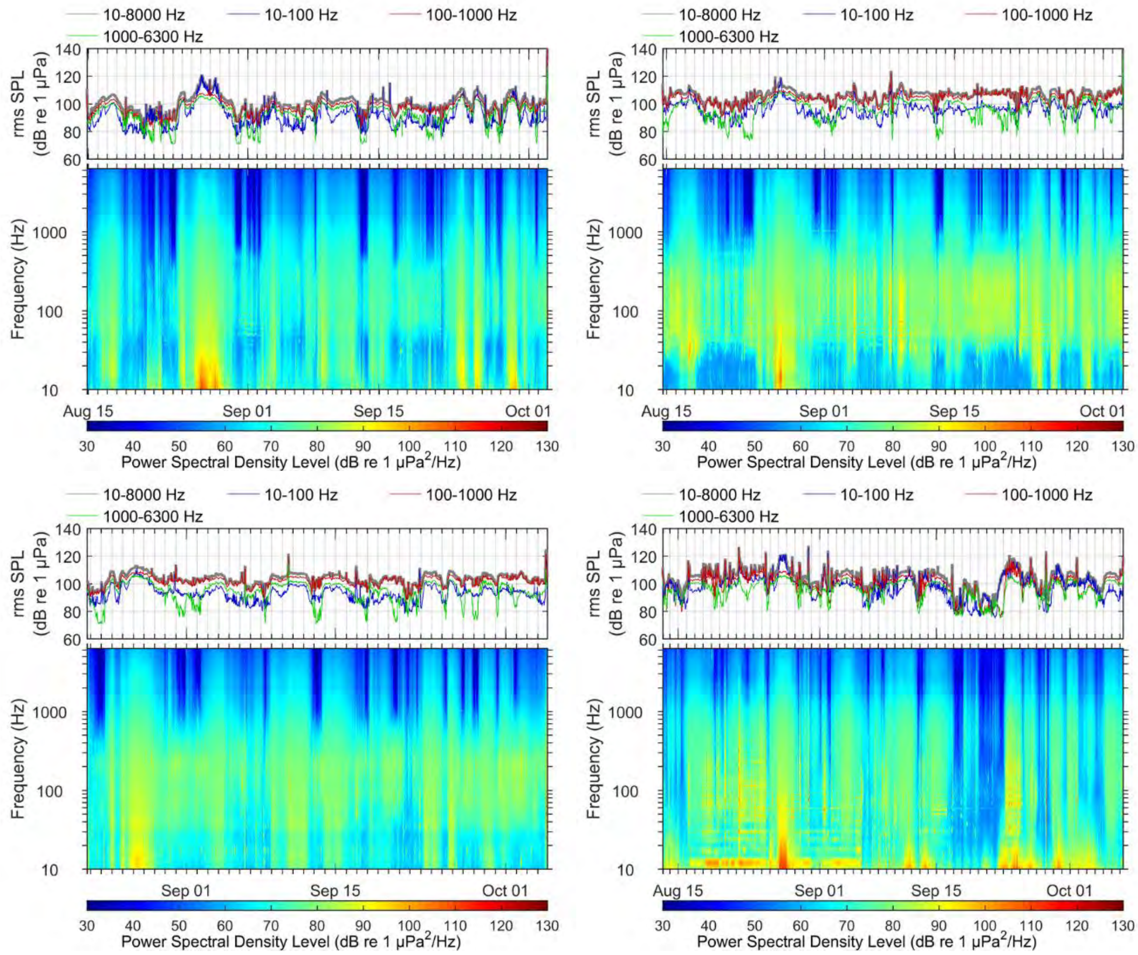


Figure 57. Spectrogram of underwater sound for the summer 2015 program at (top left) CLN120, (top right) PLN60, (bottom left) W50, and (bottom right) B5. Electronic noise was present when W50 was first deployed.

4.1.3. Comparison with Model

The measurements performed in the Vessel SSV and Drilling SSC (see Section 2.1.3) allowed us to characterize sound sources for multiple vessels and drilling activities that took place in summer 2015. Activities from each source were separated into ambient, drilling, and vessel noise. See Ref: Comprehensive report Chapter 4 for details of the source measurements, activity classification, and model specifications. In addition to the anthropogenic activity, non-acoustic data relating to vessel position, bathymetry, geoacoustics, sound speed profiles, and wind speed were used as inputs to JASCO’s Marine Operations Noise Model (MONM) to produce Figure 58.

The measured and modeled results are quite similar for most of the recording period at Station PLN40. Exceptions are spikes in the measured data at the start and end of the recorded data, where noise from the vessel during deployment and retrieval dominates immediately at the receiver. Figure 58 shows that vessel noise is the dominant noise source at PLN40 and displays the large contribution from wind-driven ambient noise from the storm that passed through around 27 Aug (Figure 53). Noise from drilling activities is not significant at PLN40 since it is more than 40 km from the drill site.

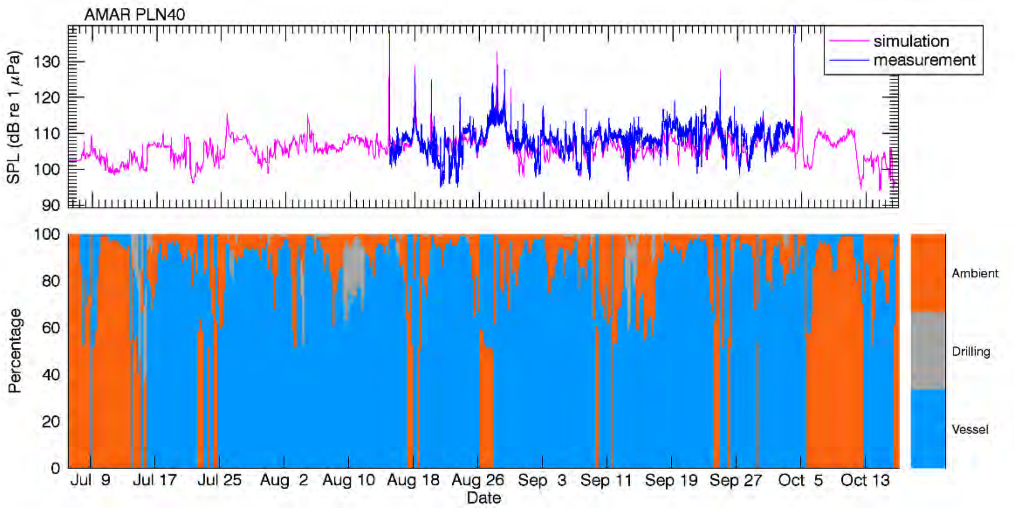


Figure 58. (Top) Measured versus simulated hourly SPL for Station PLN40. (Bottom) Modeled relative contribution (as a percentage) for the ambient, drilling, and vessel noise.

4.1.4. Summary of Total Sounds Levels

Mean monthly sound pressure levels (L_{eq}) for all months with at least one week of recorded data (Figure 59) were summarized to create total sound levels. Mean monthly sound pressure levels were computed in four frequency bands that were selected to represent known biological, natural, and anthropogenic sound sources (Table 15). The monthly averages and standard deviations are shown in Table 16. October had the highest sound levels of all months, with contributions from increasing storm activity, ice formation, and the end of the seismic surveys. During the open water months (July–early November) the 200–2000 Hz band had the highest sound levels, primarily due to wind driven noise. During the ice-covered months, the 10–40 Hz band had the highest levels.

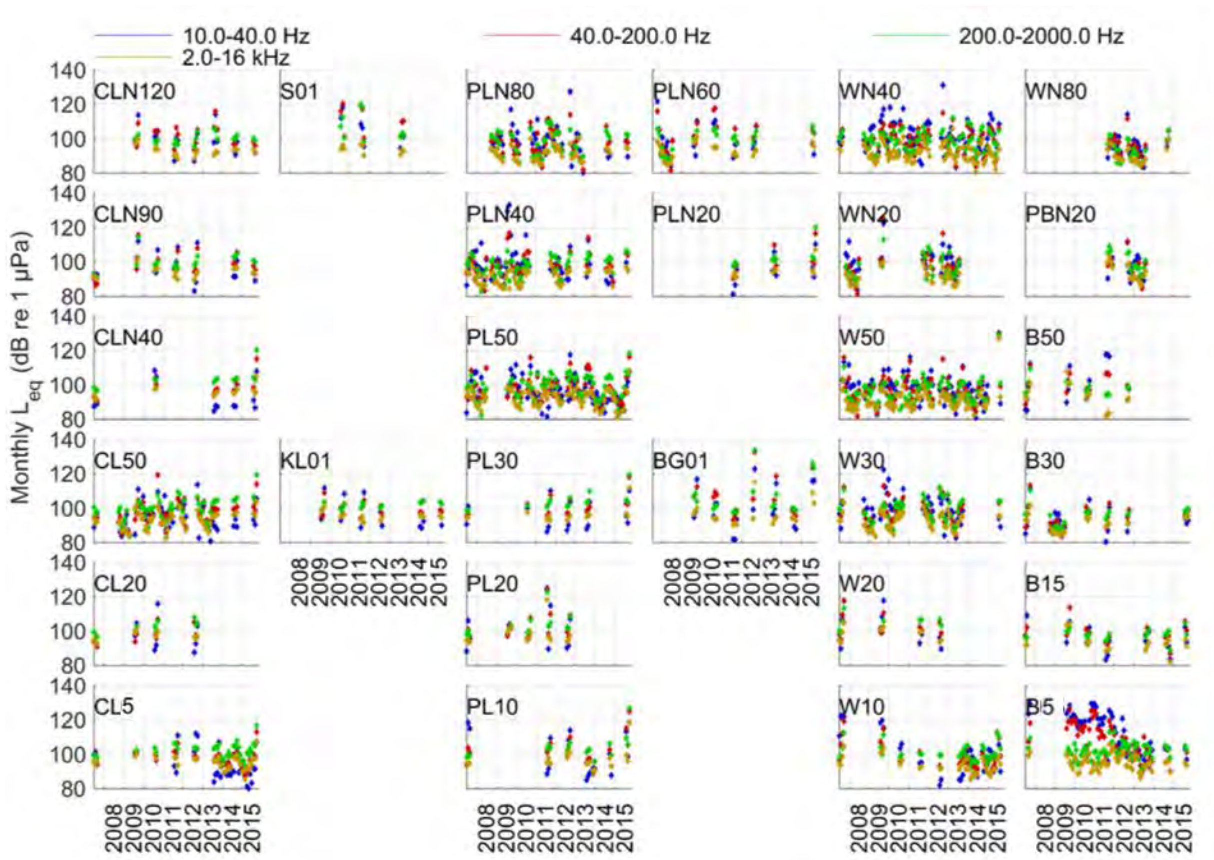


Figure 59. Monthly average sound levels (L_{eq}) throughout the 2007–2015 Chukchi Sea Acoustic Monitoring Program. The stations in the figure are organized approximately in the same north-south and east-west order as the geographic locations of the recorders. Color represents the frequency band. The Stations PL10 and W10 combine the PL05 and PL10 recorders or W05 and W10 recorders, respectively. Similarly, Station W30 combines W30 and W35, and PL30 combines PL30 and PL35. BG01 combines BG01 and BGF data sets, as they were very close in location between years.

Table 15. Frequency bands used for summary analysis.

Frequency Band (Hz)	Biological sources	Anthropogenic sources	Geological sources	Pseudo-noise
10–40	Fin whales, gray whales, walruses	Seismic surveys	Seismic	Flow noise, strum,
40–200	Bowhead whales, seals, walruses	Seismic surveys, larger vessels	ice	Flow noise, strum
200–2000	Bowhead whales, seals, walruses, belugas	Vessels, seismic surveys	Wind & wave action, ice	
2000–8000	Bowhead song, belugas, bearded seal trills.	Chains	Sediment movement	

Table 16. Monthly mean sound levels in dB re 1 μPa followed by standard deviation, for 2007–2015.

Monthly Mean L_{eq}					
Frequency Band (Hz)	10–8000	10–40	40–200	200–2000	2000–8000
Jan	106.1 (6.6)	102.7 (7.4)	99.5 (6.8)	97.1 (5.7)	91.3 (3.7)
Feb	105.6 (6.5)	102.4 (7.1)	99.2 (6.6)	96.8 (5.4)	90.2 (3.7)
Mar	103.1 (5.9)	100.2 (6.3)	96.3 (5.8)	94.3 (5.8)	88.9 (4.3)
Apr	102.1 (6.2)	98.9 (7.4)	94.9 (6.2)	92.6 (6.3)	87.6 (4.1)
May	98.9 (6.8)	93.0 (9.5)	91.2 (7.7)	93.0 (5.7)	88.1 (3.6)
Jun	99.4 (7.7)	91.6 (9.4)	92.4 (8.7)	94.7 (6.1)	89.2 (4.9)
Jul	104.1 (7.0)	96.4 (9.8)	98.4 (6.9)	98.2 (4.8)	91.6 (3.6)
Aug	107.1 (6.5)	96.6 (9.7)	101.3 (7.0)	102.4 (5.6)	95.3 (4.9)
Sep	107.2 (6.3)	96.9 (9.7)	101.3 (7.0)	102.0 (4.9)	95.4 (3.4)
Oct	111.0 (6.7)	103.9 (10.2)	104.9 (7.0)	104.0 (5.0)	96.8 (4.5)
Nov	104.7 (6.9)	97.1 (9.4)	97.8 (6.9)	99.4 (5.4)	93.6 (4.2)
Dec	102.4 (6.3)	98.7 (7.5)	95.0 (6.5)	93.7 (4.6)	91.1 (3.5)

4.1.5. Acoustic Continuity Index

The Acoustic Continuity Index results for the Chukchi (Figure 60) show that in the absence of significant anthropogenic or biological activity, the values in all frequency bands remain close to zero, such as the CL-line of recorders in the summers of 2012, 2014, and 2015. Seismic surveys create regular pulse trains of transients, which generate large positive ACI values in all bands, but especially in the 10–40 Hz and 40–200 Hz bands. The continuous presence of shipping at a location resulted in negative ACI values, as expected, for example at BG01 in 2012 and 2015, W30 in 2012 which was the staging area for vessels, and most years at B5 that appears to have either a large amount of vessel traffic or from shore-based power generator noise entering the water. Biological sounds also are present in the ACI, especially bearded seal calls on the offshore stations in May and June and walrus vocalizations at Point Lay (PL) in August and September.

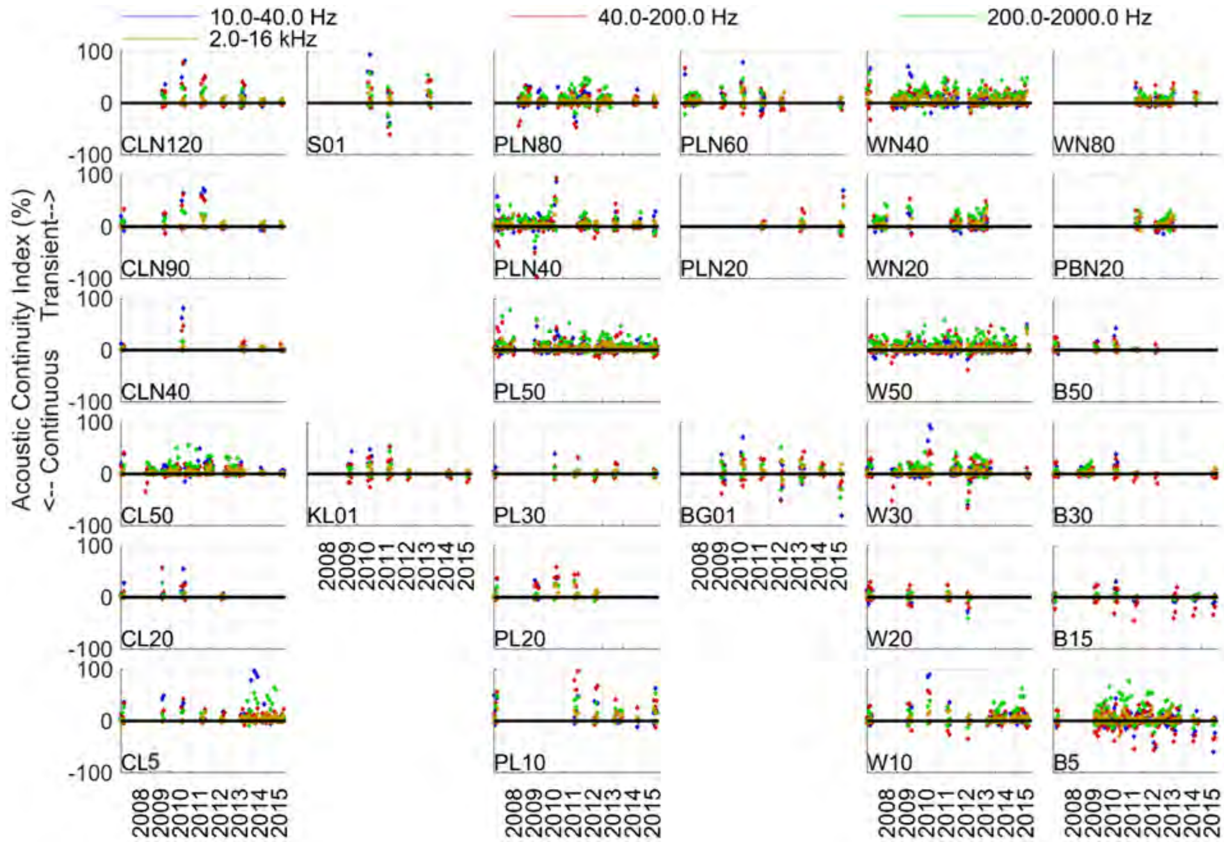


Figure 60. Acoustic Continuity Index data for recordings from the Chukchi Sea Acoustic Monitoring Program 2007–2015.

4.2. Marine Mammal Call Detections

The deployment of acoustic recorders at the same or similar locations each year since 2007 allows comparing data collected over multiple years. This discussion does not include the 2008 summer data that were acquired with just five recorders late in the season (26 Sep to 16 Oct 2008). The datasets for the first deployment in summer 2007 and winter 2007–2008 were not analyzed using the standardized protocol described in this report and first applied to the winter 2008–2009 data. Because these initial datasets are not directly comparable to later ones, they are omitted from this discussion. The sections below compare 2015 results to prior recording periods.

4.2.1. Bowhead Whale Call Detections

4.2.1.1. Comparison of Winter Acoustic Recording Periods

Bowhead whale detections during fall 2014 extended later than in any previous years of the Acoustic Monitoring Program. In contrast, the fall 2012 data revealed the earliest complete departure on record since the winter recording program began in 2007. In the central part of the study area (W50–PL50), detections usually stop in the last week of November. December detections are generally restricted to stations off Cape Lisburne. Detections lasted until early December 2014 at Station W50 and until early January 2015 at PL50. Detections at CL5 lasted until 23 Jan 2015, with the last detection associated with the fall migration.

The increase in call counts from October to December is mostly due to an increase in vocal activity associated with the onset of singing (e.g., Delarue et al. 2009). Bowhead whales were not detected at WN40. The lowest call counts occurred at Stations W10 and W50. Low call counts inshore (W10) and far offshore (WN40) correspond with collected acoustic data issued from the Acoustic Monitoring Program that indicates in the fall bowheads migrate offshore along a trajectory centered near the 71st parallel; however, the low call counts at W50 contrast with previous years' results. W50 and PLN40 generally have similar detection time series and call counts. The fall 2014 results could indicate that the main migration path was located somewhere between W10 and W50, or that whales came to the Point Lay recorders from the north. The high call counts at CL5 are attributed to the extended detection period at this station. A longer recording period means that ice concentrations would have decreased, so bowheads could remain in the area longer.

The spring migration in 2015 occurred generally at the same time as previous years, starting in late March and lasting until early June. The only station near the lease areas (PL50) that was still active during the spring migration recorded marginal numbers of detections. 1The farthest offshore station (WN40) did not detect any bowheads. In contrast, there were many consistent detections at the two inshore active stations (CL5 and W10) for 6 to 7 weeks. Although this year's acoustic monitoring of the Chukchi Sea was more limited than in previous years because three recorders stopped before spring migration began (W50, PLN40, and PL10), these findings confirm that bowheads prefer to migrate along the coast in the spring (Braham et al. 1984).

4.2.1.2. Comparison of Summer Acoustic Recording Periods

Summer detections in 2015 differed markedly from previous years in terms of call counts. The 2015 Chukchi-wide mean daily call counts were about 90% lower than the 2009–2014 average and only comparable to 2011, which also had low call counts. This trend was true for individual stations (Figure 63). As in previous years, there were more detections measured from Barrow recorders and they were more consistent than other stations. The inshore Wainwright recorders (W10 and W30) have also typically yielded many detections, but in 2015 few bowhead calls were detected there. Similarly, bowheads have generally transited through the Burger lease area in the fall, but in 2015 they were only detected on 3 days at one of the analyzed Burger stations (BG03). Other areas of higher call counts in 2015 included northern Point Lay (PLN60 and PLN80) and Cape Lisburne (CLN120). While this is consistent with historical data, detections in these areas extended farther south than in previous years.

Most years, including 2015, bowhead detections off Barrow start in late August/early September (Figure 64); however, their calls have not generally been detected at Burger and stations farther west before the third week of September. In 2015, the first pulse of detections at PLN80 and CLN120 occurred in the first week of September, followed by another in the third week. Because the recorders were retrieved a maximum of 10 days earlier in 2015, it is unclear whether these pulses correspond to late summer waves of early migrants, which have been observed in recent years, or were part of the true fall migration, which based on previous years, did not usually start until late September culminating in the first or second weeks of October. The two pulses of detections observed off Barrow in late September/early October suggest that some bowhead whales had yet to migrate across the Chukchi Sea. Nevertheless, the detections in 2015 occurred early compared to previous years.

Although the low call counts observed in 2015 could be explained by a reducing the recording period during the fall migration, they were more likely driven by the high noise levels associated with Shell's drilling activities; there were a lot fewer bowhead whale detections around Burger (Appendix D, Estimating the Detection Range of Bowhead Moans). Indeed, in-band and broadband noise levels were higher in 2015 than in any previous years in the Acoustic Monitoring Program, which resulted in fewer bowhead whale detection ranges compared to previous years at stations PLN20, PLN40, and PLN60 (Appendix D, Estimating the Detection Range of Bowhead Moans). The migration corridor, as defined by acoustic detections, also appeared to shift north in 2015 compared to previous years. While higher noise levels along the typical migration path could be contributing to this northern shift, our findings are consistent with visual sightings recorded during the ASAMM (Figure 61).

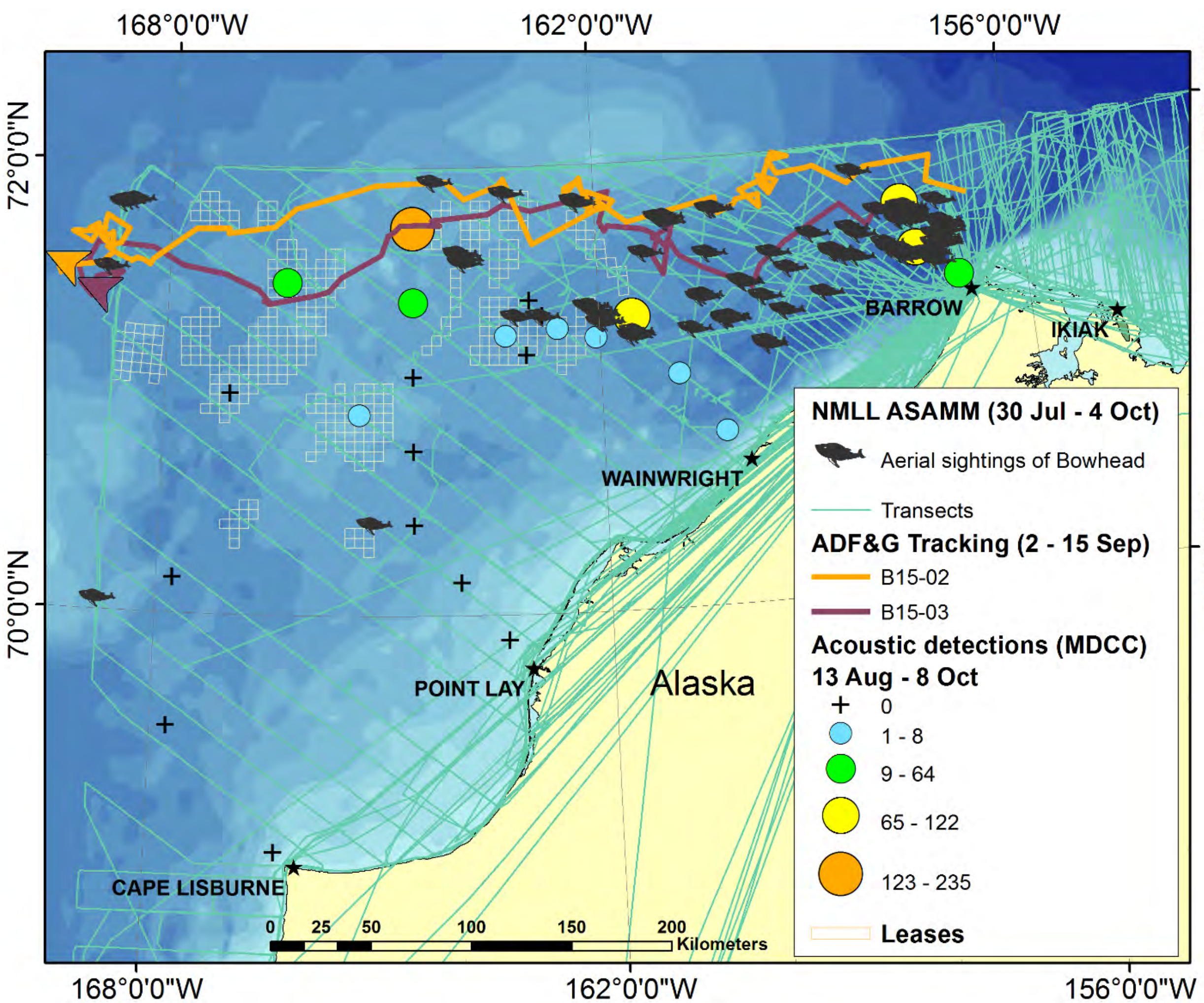


Figure 61. Acoustic detections and visual sightings of bowhead whales during summer 2015 in the study area. Sighting survey data were provided by National Marine Mammal Laboratory–Aerial Surveys of Arctic Marine Mammals (NMML ASAMM). Bowhead tracking data were provided by Alaska Department of Fish and Game.

Figure 62 shows the annual average of mean daily bowhead whale call counts from 2009 to 2015. These results show that, on average, few bowhead whales occur south of a line running west from Wainwright. Stations to the south of that line had consistently low detections (low standard deviation) while those to the north recorded more calls and experienced more inter-annual variability in the daily number of detected calls, particularly off Wainwright and Barrow. The higher variability in the number of detected calls in areas of greater acoustic presence could be associated with the use of these areas. Depending on the abundance of prey, whales differentially exploit foraging areas, such as Barrow Canyon. Productivity in these areas is driven by oceanographic conditions, which vary annually to some extent. Figure 63 shows that inter-annual variations in mean daily call counts are greatest off Barrow and Wainwright and lowest at Burger and PLN60, suggesting a more predictable occurrence associated with the annual migration of bowhead whales near stations in the western half of the study area.

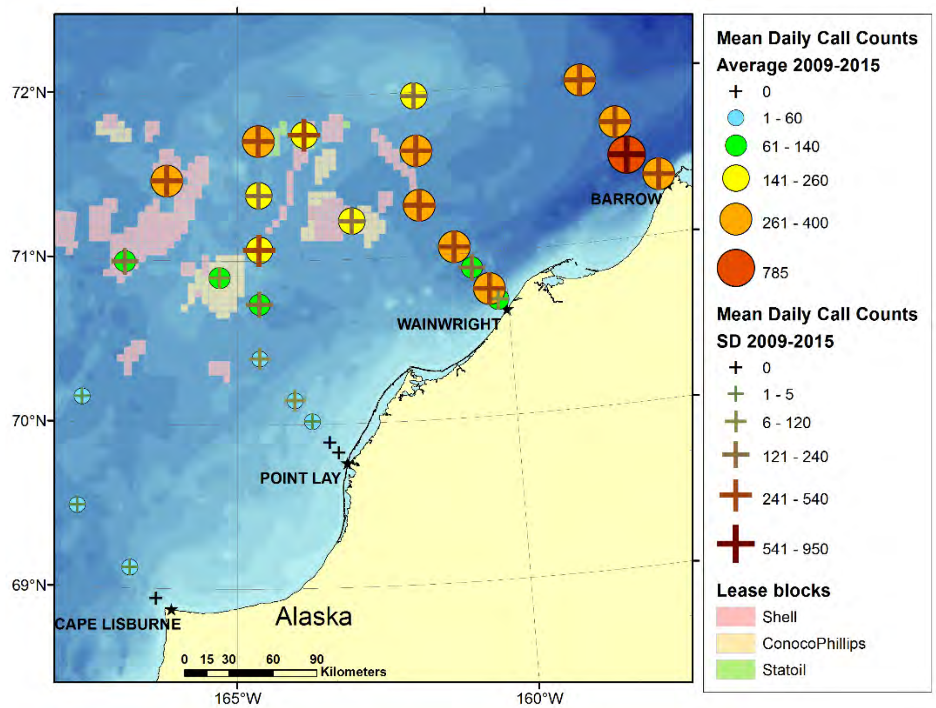


Figure 62. Annual average and standard deviation (SD) of mean daily bowhead whale call counts calculated as the sum of automated call detections in all files with manual detections divided by the number of active recording days from 2009 to 2015 at all summer stations deployed at least twice in the northeastern Chukchi Sea.

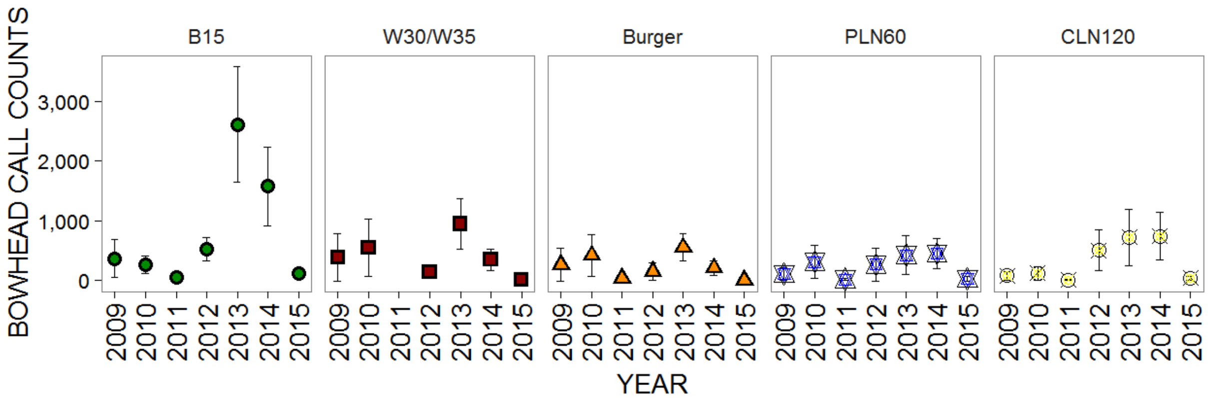


Figure 63. The mean daily bowhead whale call count and 95% confidence intervals from 2009 to 2015 at five stations.

Figure 64 shows the number of years bowhead whale calls were detected during the summer programs (~1 Aug to ~15 Oct) between 2009 and 2015 for five representative stations. All stations recorded calls that began between September 8 and 20 each day in at least half the years depending on the location. Figure 64 also shows peaks in detections associated with the onset of the fall migration in the study area that occur on the same day or the same week every year. The latter usually started in early Sep of Barrow and Wainwright, around mid-Sep near Burger and in the last week of Sep farther west.

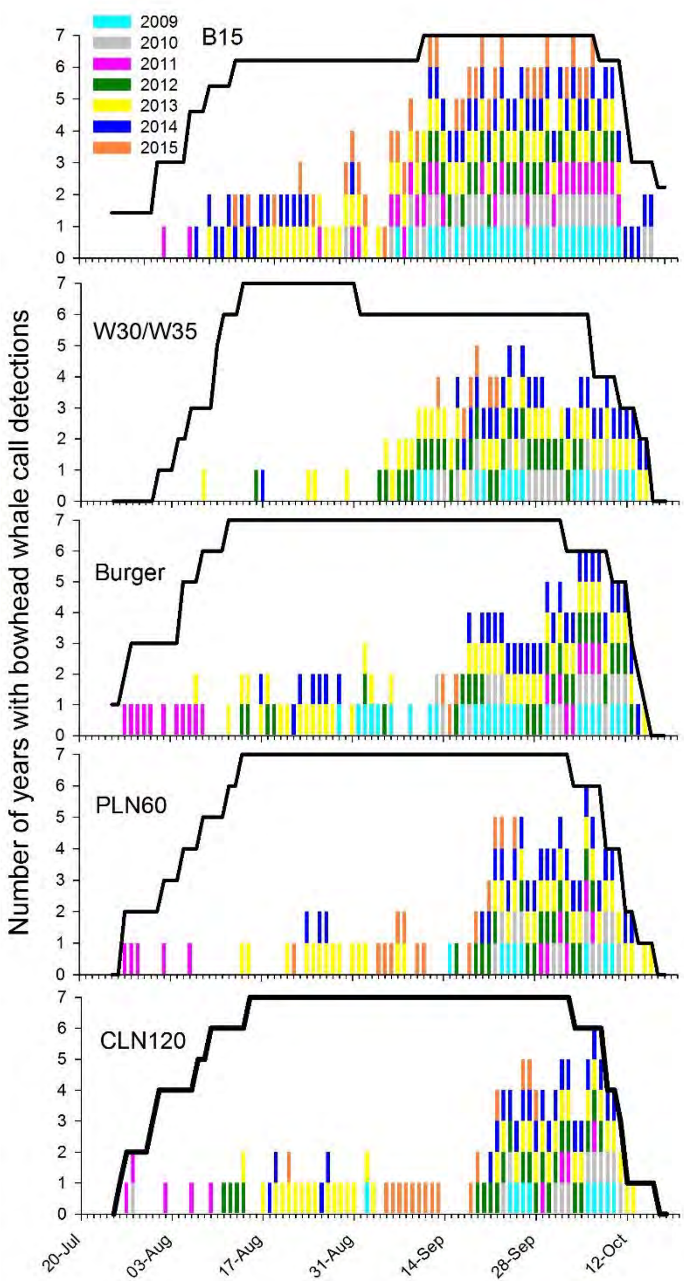


Figure 64. Number of years with daily bowhead whale call detections between late July and mid-October (maximum duration of summer Acoustic Monitoring Programs) at five representative stations. The black lines show the number of years in which data was recorded for each day.

4.2.2. Walrus Call Detections

4.2.2.1. Comparison of Winter Acoustic Recording Periods

Walrus detections during the winter programs are noticeable because of their regularity. Although they vary more in the fall, they are consistently low and few detections occur after October. In the spring, walruses are almost systematically detected for the first time in the first week of June, although in 2015, an isolated detection event occurred on 1 May at W10. Calls are progressively detected farther northeast until walruses reach stations at or near Hanna Shoal. Detections at stations in the southwestern part of the study area only last 2–3 weeks, but persist near Hanna Shoal once they start, confirming that this is the final migration destination for walruses.

4.2.2.2. Comparison of Summer Acoustic Recording Periods

Walrus summer detections occur consistently in the same place and time. Seven years of data indicate that the nearshore Point Lay stations consistently recorded the most walruses. This observation can be explained by the formation of large coastal haul-outs, which occurred for the first time in 2007 and in most years since then as a result of sea ice on or near of the foraging grounds disappearing. 2008 and 2012, when sufficient sea ice allowed walruses to remain offshore, are the only exceptions. Our data show that walruses were present every day past mid-August near Point Lay in most years (Figure 65). The Hanna Shoal area (W50–WN40), and to a lesser extent Burger, also consistently have many call detections (Figure 66). Except for CL5 and the inshore Wainwright stations, the rest of the stations are characterized by low call counts. The regularity with which walruses use the Hanna Shoal and Burger areas highlights their strong affiliation to these areas for foraging. These areas also tend to be the last ones covered with sea ice in summer.

Walruses are the most commonly acoustically detected species in the northeastern Chukchi Sea. Most stations within the core of walrus habitat had detections each day from 1 Aug to 15 Oct on at least one, and often multiple, study years (Figure 65). Mean daily call counts were quite stable at most stations except WN20 and off Point Lay (Figure 67). Inter-annual variations in call counts at Point Lay are likely driven by differences in the residency time at the haul out sites, the proximity of these sites to the recorders, and the number of walruses present.

Mean daily call counts throughout the Chukchi in 2015 were about 30% lower than the 2009–2014 average. Areas that traditionally yielded high call counts such as the Burger lease areas, had comparatively fewer call detections in 2015. Because of the consistency with which walruses have occurred in such areas over time, call masking associated with the elevated noise levels measured in 2015 is believed to be at least partly responsible for this trend.

The high density and biomass of benthic organisms in the Burger and Hanna Shoal areas (Blanchard and Knowlton 2013) best explains the high detection rates of walrus calls in these areas. The highly consistent distribution of walrus call detections in summers across years could be due to two factors: their benthic prey's distribution does not vary much over the years, and/or there are many suitable haul out sites near Point Lay.

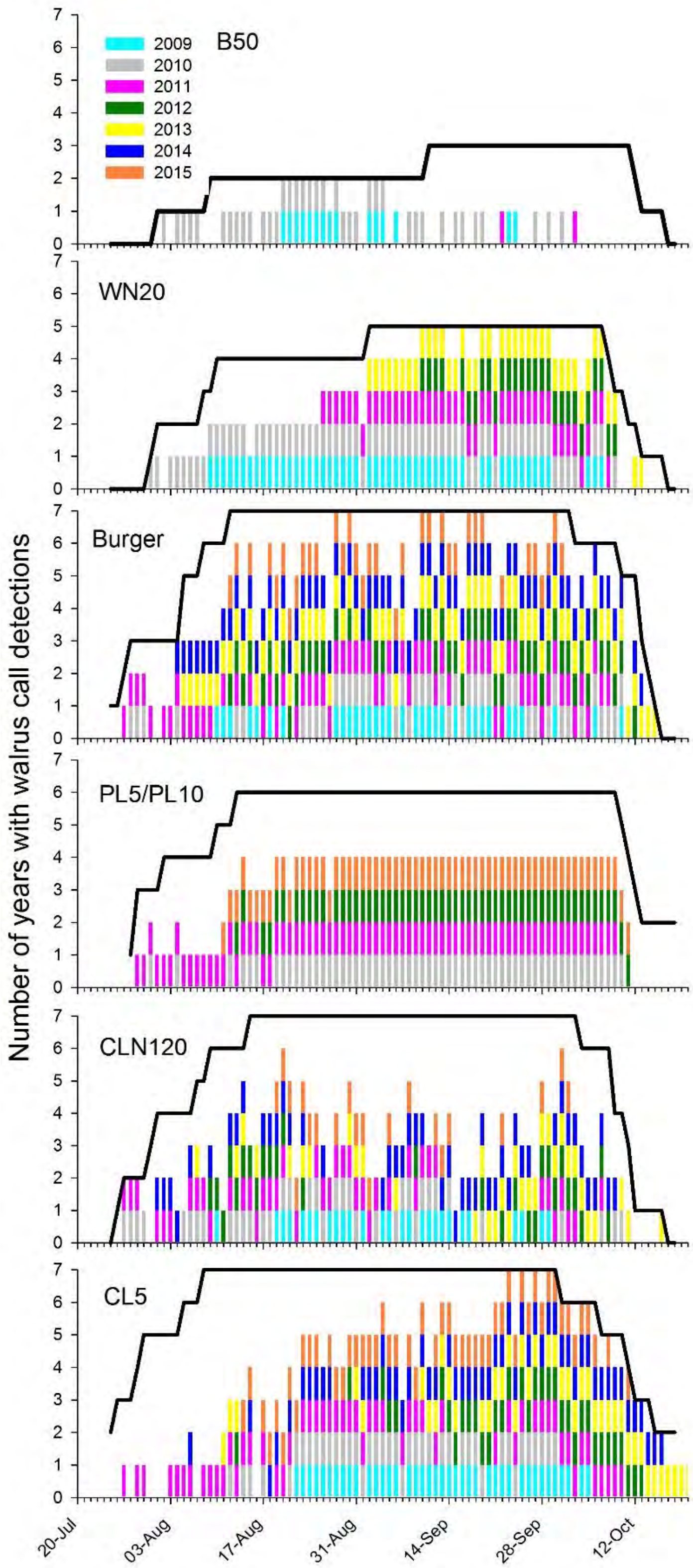


Figure 65. Number of years with daily walrus call detections between late July and mid-October (maximum duration of summer Acoustic Monitoring Programs) at six representative stations. The black lines show the number of years in which data was recorded for each day.

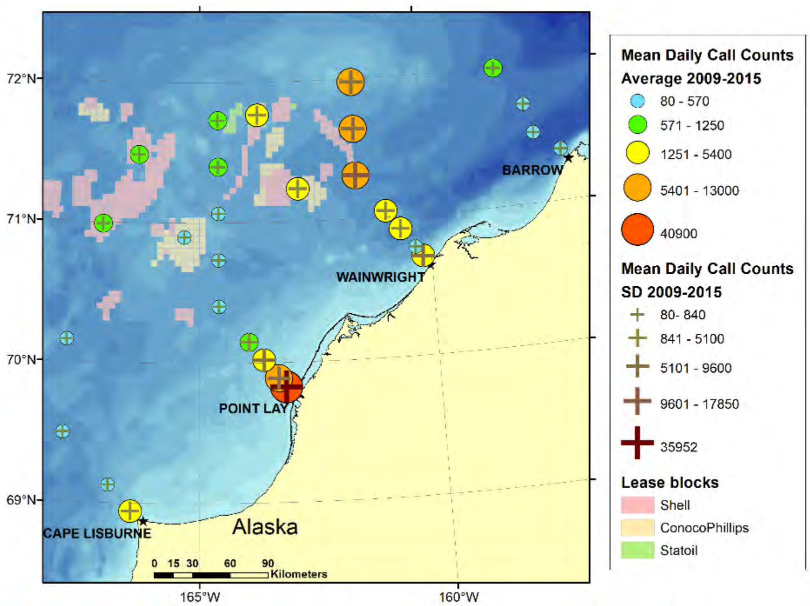


Figure 66. Annual average and standard deviation (SD) of mean daily walrus call counts (calculated as the sum of automated call detections in all files with manual detections divided by the number of active recording days) from 2009 to 2015 at all summer stations deployed at least twice throughout the recording program in the northeastern Chukchi Sea.

Figure 67. Whisker plot of the mean daily walrus call count and 95% confidence interval from 2009 to 2015 at stations B50, WN20, Burger, PL05/PL10, CLN120, and CL5.

4.2.3. Beluga Whale Call Detections

4.2.3.1. Comparison of Winter Acoustic Recording Periods

The spatial and temporal distribution of beluga whale call detections during winter 2014–2015 was generally consistent with the trends observed in previous years within the main part of the study area. Previous years have demonstrated that B5, near Barrow, had the most consistent and predictable rate of detections during the fall, presumably because belugas transit via Barrow canyon on their way back from the northern Chukchi and Beaufort Seas. Stations farther west had fewer detections and those were separated more in time, possibly because belugas spread out over a larger area after leaving Barrow canyon. Although we previously speculated that the low number of detections in the fall could be due to belugas migrating inshore where recorders were not deployed in earlier years, neither the lack of detections at PL10 nor the few detections at CL5 support this hypothesis. The discrepancy in the number of detections between fall (low) and spring (high) seems best explained by the fact that only eastern Chukchi Sea belugas, which are far fewer in number than eastern Beaufort Sea belugas, migrate past our recorders in the fall, yielding fewer detections.

The number and distribution of spring detections were similar to those from previous years. Beluga call counts were higher inshore than offshore. The main period of detection was shifted by about two weeks as beluga progressed along the migration path from CL5 to W10. This detection period is likely attributable to migrating eastern Beaufort Sea belugas, which usually reach the Amundsen Gulf by mid to late May (Fraker 1979). Because the eastern Chukchi Sea beluga population aggregates in coastal lagoons, such as Kasegaluk Lagoon, in July, this group is likely responsible for the differences measured between when the main detection period ended and the sporadic detections in June/July at W10 and PL50. Nevertheless, both populations mixing over the spring detection period cannot be ruled out. Satellite telemetry data are needed to conclusively assess the potential migratory segregation between both beluga stocks.

4.2.3.2. Comparison of Summer Acoustic Recording Periods

The acoustic detections from summer 2015, when detections occurred at few stations and were generally concentrated in mid-September, were lower to those from summer 2014. Belugas were detected off Barrow only at the end of the deployment period. In 2014, detections occurred at most stations and were generally concentrated in early October. Before 2014, detections had always been concentrated in or near Barrow canyon in August where Eastern Chukchi belugas are known to forage before heading north into the northern Chukchi and Beaufort Seas (Suydam et al. 2005, Delarue et al. 2011b), and at the end of the recording period as they start migrating back toward the Bering Sea (Figure 68). As discussed for walruses and bowhead whales, the significant decrease in beluga call detections in 2015 compared to previous years is at least partly linked to elevated noise levels inducing call masking. However, other factors such as area avoidance and differences in migration timing cannot be ruled out.

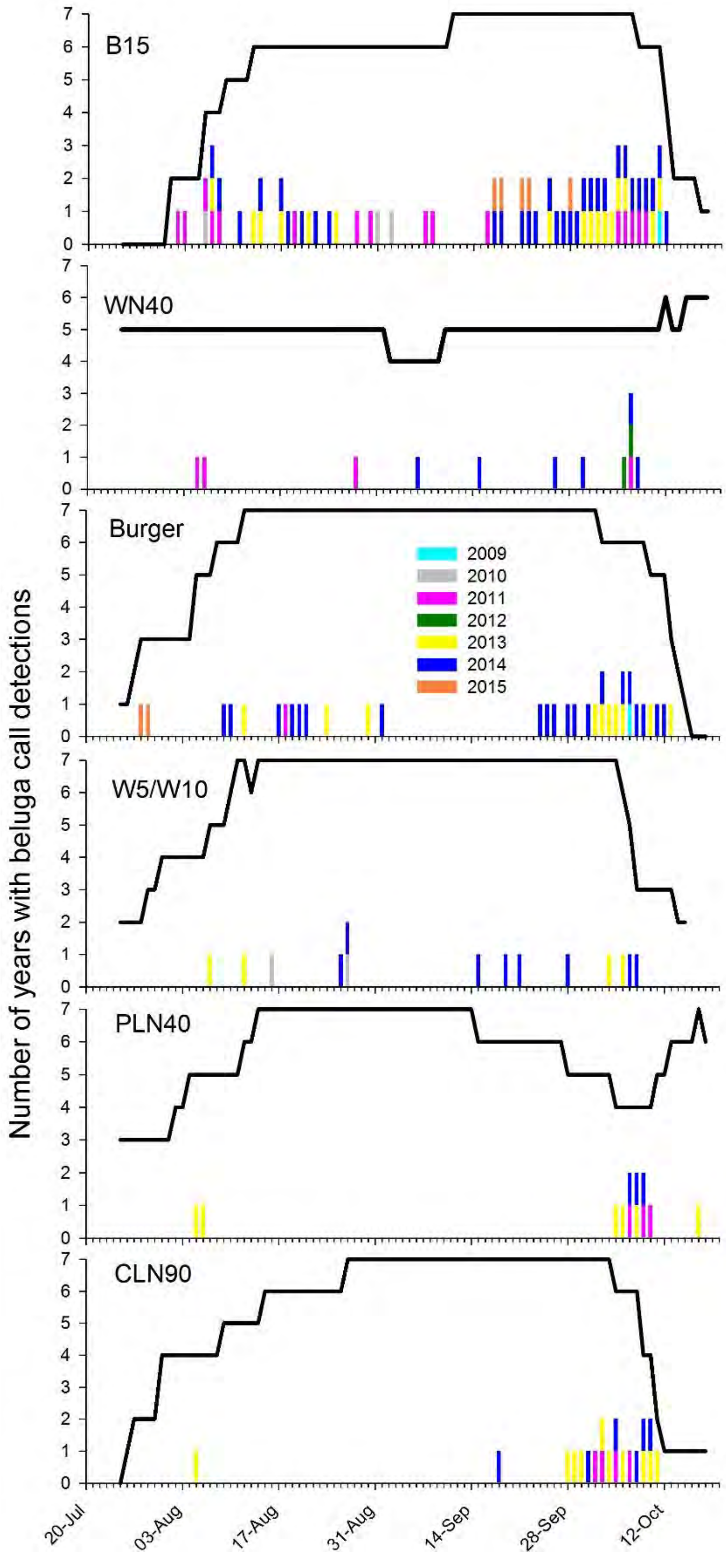


Figure 68. Number of years with daily beluga whale call detections between late July and mid-October (maximum duration of summer Acoustic Monitoring Programs) at six representative stations. The black lines show the number of years in which data was recorded for each day.

4.2.4. Bearded Seal Call Detections

4.2.4.1. Comparison of Winter Acoustic Recording Periods

Bearded seal call presence during winter 2014–2015 was similar to that of previous years. The recordings made from 2011–2012 showed that most bearded seals in the northeastern Chukchi Sea were concentrated in the north of the study area, near stations PLN80 and PLN100. In 2012–2013, the area near PLN100 was also rife with acoustic activity, as was an area between W35 and WN20. In 2014–2015, CL5 and W10 had the most call counts. Because winter 2014-2015 recorders were not deployed in the offshore areas (PLN80 and PLN100) that have so far been associated with the highest call counts, any conclusions about shifts in distribution during the 2014–2015 winter recording period are not possible.

As in previous years, the overall increase in call detections throughout the winter and early spring occurred in steps. Call detections became continuous at various time across the area. The onset of the continuous detection period associated with the peak of the breeding season occurred earlier at stations located farther southwest and inshore. As in previous years, detections stopped over a few days in June at all stations, but this occurred up to two weeks earlier at stations in the southwestern part of the study area.

4.2.4.2. Comparison of Summer Acoustic Recording Periods

Summer detections typically consist of a few sporadic calls in late July and August. Acoustic activity steadily increases into September, and peaks in October (Figure 69). Bearded seal calls are detected at some stations throughout the summer, but the likelihood of a call occurring on any given day increases after the beginning of September. Calls were generally absent off Barrow and near WN40 before the end of August.

The steady increase in bearded seal calling rates from September to May is the result of seasonal changes in vocal behavior, which complicates estimates and comparisons of abundance throughout the year. This behavioral change results in a low number of detections in July and August, which does not indicate the seals are not in the area because they are regularly sighted in summer in the Chukchi Sea.

Because seasonal changes in calling behavior generally occur at the same rate across the area, acoustic detections can be used to assess the relative occurrence of bearded seals between stations. Detections over the 2009–2015 summers were highest at the northernmost stations and off Wainwright and lowest west of Wainwright and south of 71° N (Figure 70). Call counts in 2015 were much lower than in previous years; the y call detection hotspots during 2015 summer were the inshore Wainwright recorder and PLN80.

Inter-annual variations in mean daily call counts (Figure 71) occurred at all stations. We noted previously that the location and magnitude of detection peaks varied annually. This might be related to the diverse diet of bearded seals, which means they can forage where it is most energetically rewarding instead of being tied to productive, yet geographically restricted, patches of prey as are walruses who prey on benthic bivalves in the Chukchi Sea. In 2015, call masking due to elevated noise levels associated with Shell's drilling activities was likely a factor in the low call counts recorded.

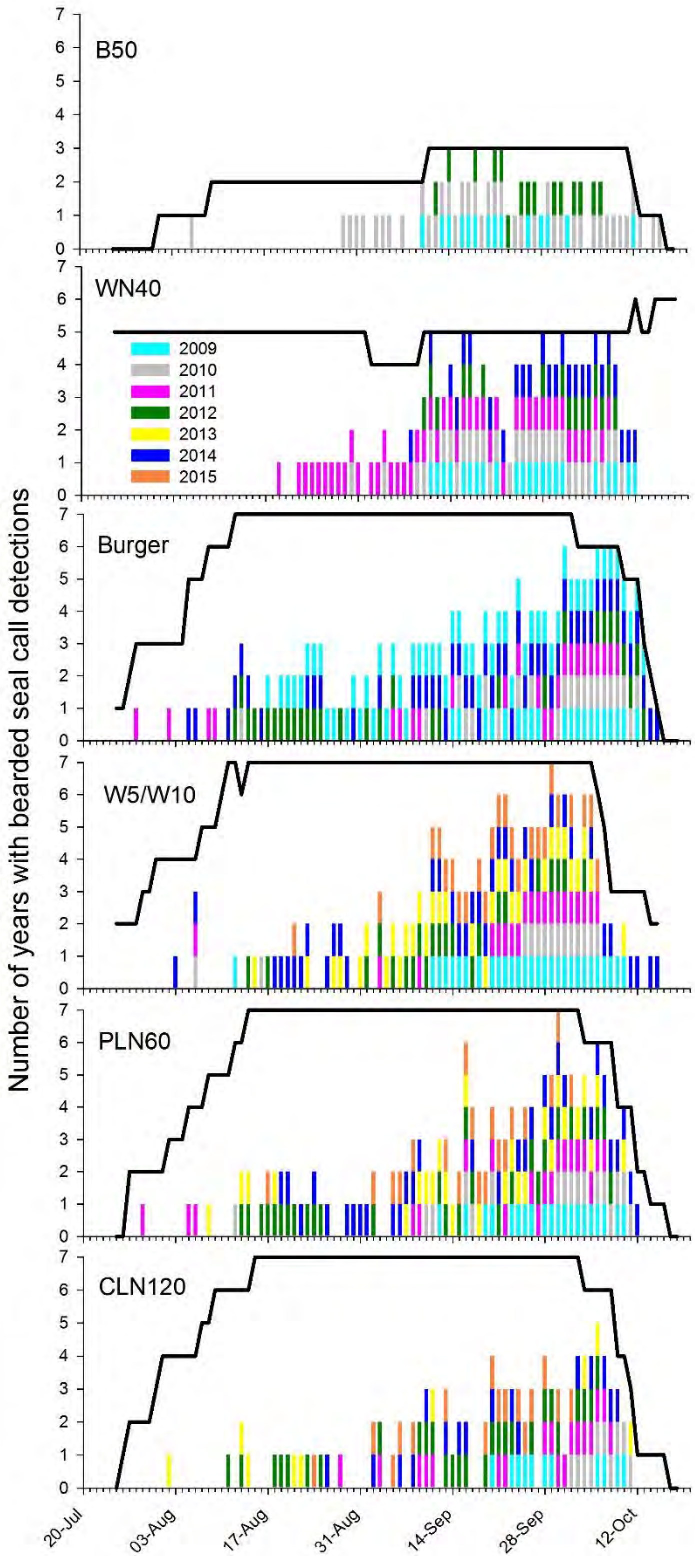


Figure 69. Number of years with daily bearded seal call detections between late July and mid-October (maximum duration of summer Acoustic Monitoring Programs) at five representative stations. The black lines show the number of years in which data was recorded for each day.

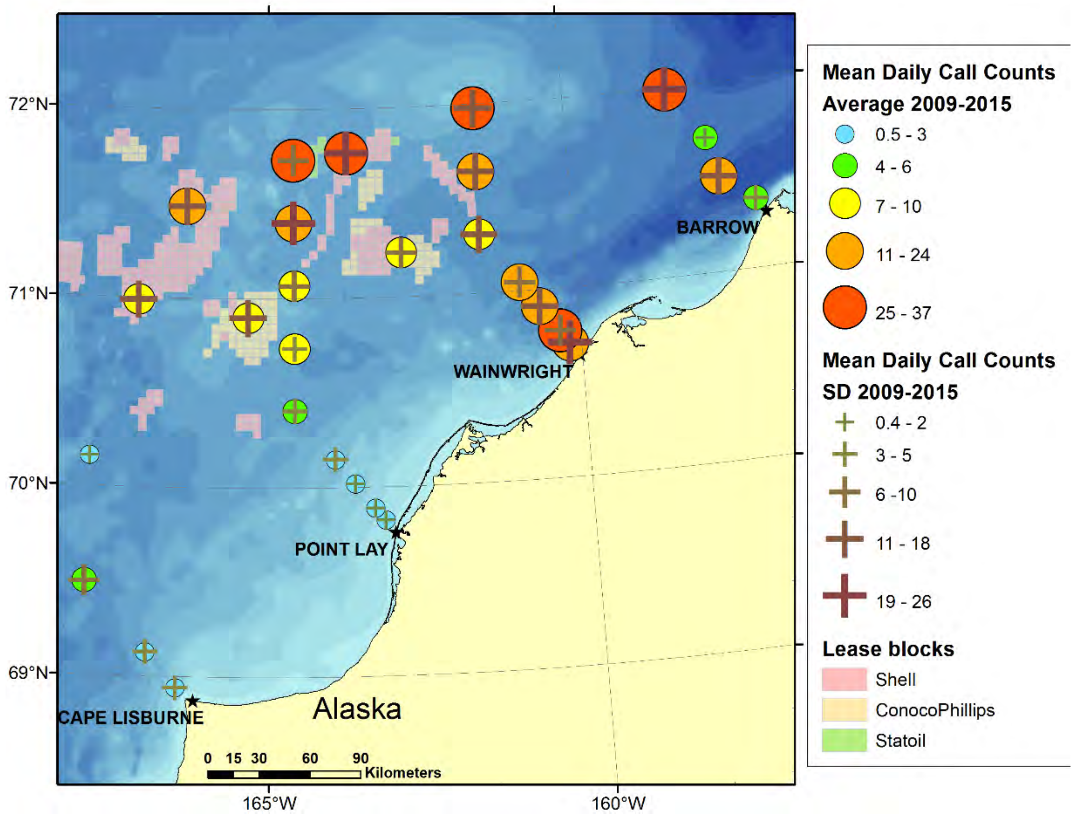


Figure 70. Annual average and standard deviation (SD) of mean daily bearded seal call counts calculated as the sum of automated call detections in all files with manual detections divided by the number of active recording days from 2009 to 2015 at all summer stations deployed at least twice in the northeastern Chukchi Sea.

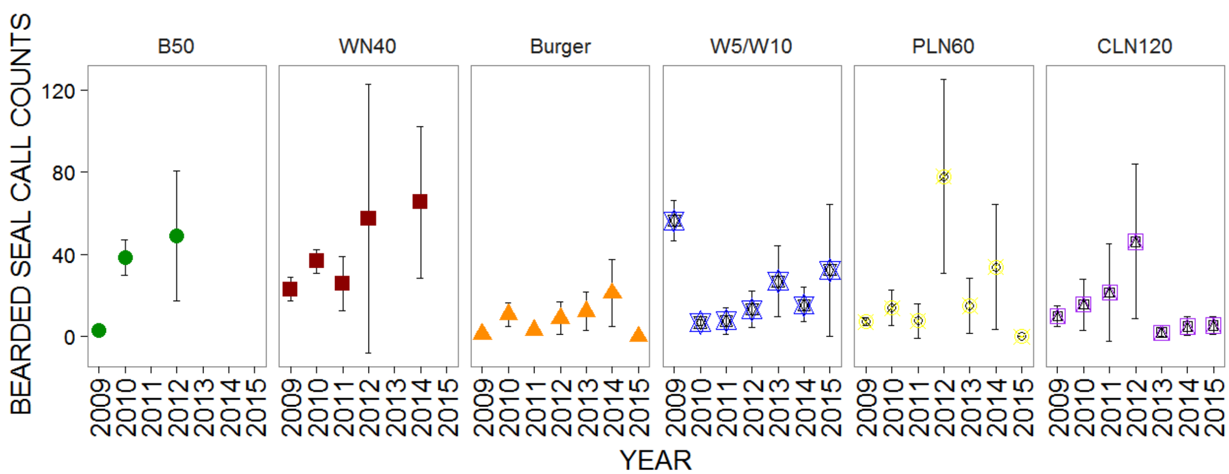


Figure 71. Mean daily bearded seal call count and 95% confidence interval from 2009 to 2015 at six stations.

4.2.5. Fin Whale Call Detections

Fin whale calls were first recorded in 2007 (Delarue et al. 2013a) and since 2009 were detected in all years except 2012. All these detections occurred at the offshore Cape Lisburne stations and Station PL50. The number of detections decreased sharply between 2007, a year with an unusually high number of detections, and 2009. Detections have remained low thereafter, indicating that fin whale visits to the northeastern Chukchi Sea are still a rare occurrence. This is consistent with the lack of visual sightings there in 2015, although fin whales were regularly sighted southwest of Cape Lisburne during the Aerial Surveys for Arctic Marine Mammals.

4.2.6. Gray Whale Call Detections

Gray whales have an affinity for the waters off Wainwright, particularly in August. They occur sporadically in other areas throughout the summer (Figure 72). These detections coincide with gray whale distribution patterns established via aerial surveys (Clarke and Ferguson 2010). The 2013 sightings from both the ASAMM (Clarke et al. 2014) and CSESP (Aerts et al. 2014) were also concentrated inshore, mainly between Barrow and Wainwright, with a slight offshore extension off Wainwright. There were few shipboard visual sightings in 2014 (Christman et al. 2015). In 2015, acoustic detections off Wainwright occurred more commonly offshore (near W50), which was corroborated by aerial observations (Figure 73). Data from winter deployments have shown that gray whales arrive as early as late June off Wainwright.

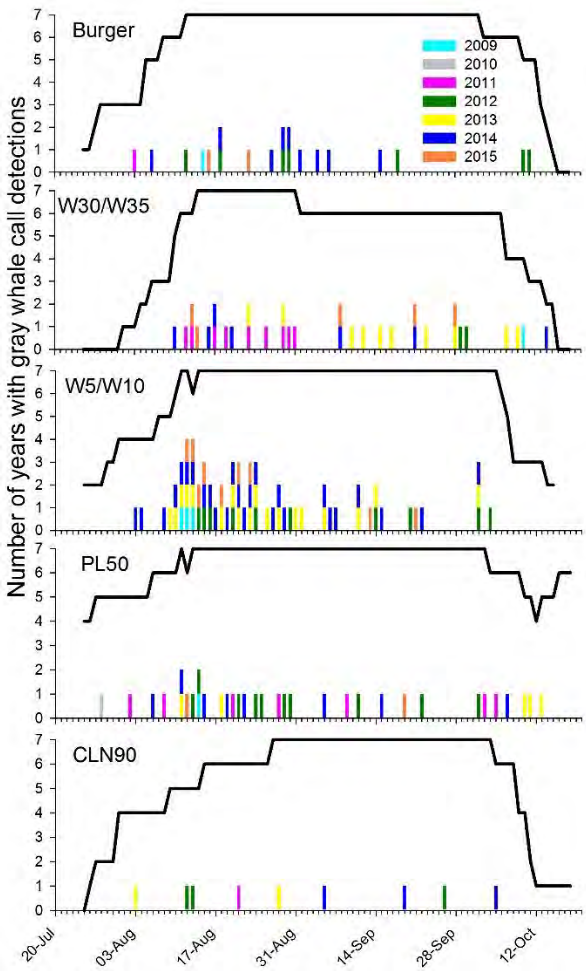


Figure 72. Number of years with daily gray whale call detections between late July and mid-October (maximum duration of summer Acoustic Monitoring Programs) at five representative stations. The black lines show the number of years in which data was recorded for each day.

An analysis of the detection probability of gray whale calls in 2012 showed that the currently applied analysis protocol underestimates the acoustic occurrence of gray whales. Assuming that the vocal repertoire of gray whales is similar across the study area, the spatial distribution is likely correctly depicted by the current analysis protocol while the occurrence (i.e., proportion of hours with detections) of gray whales at each station might be underestimated.

Gray whales' preference for the area off Wainwright is linked to the area's high amphipod density (Blanchard and Knowlton 2013). The densest amphipod beds are 20 to 30 mi offshore, which is where call detections were highest over the course of the study.

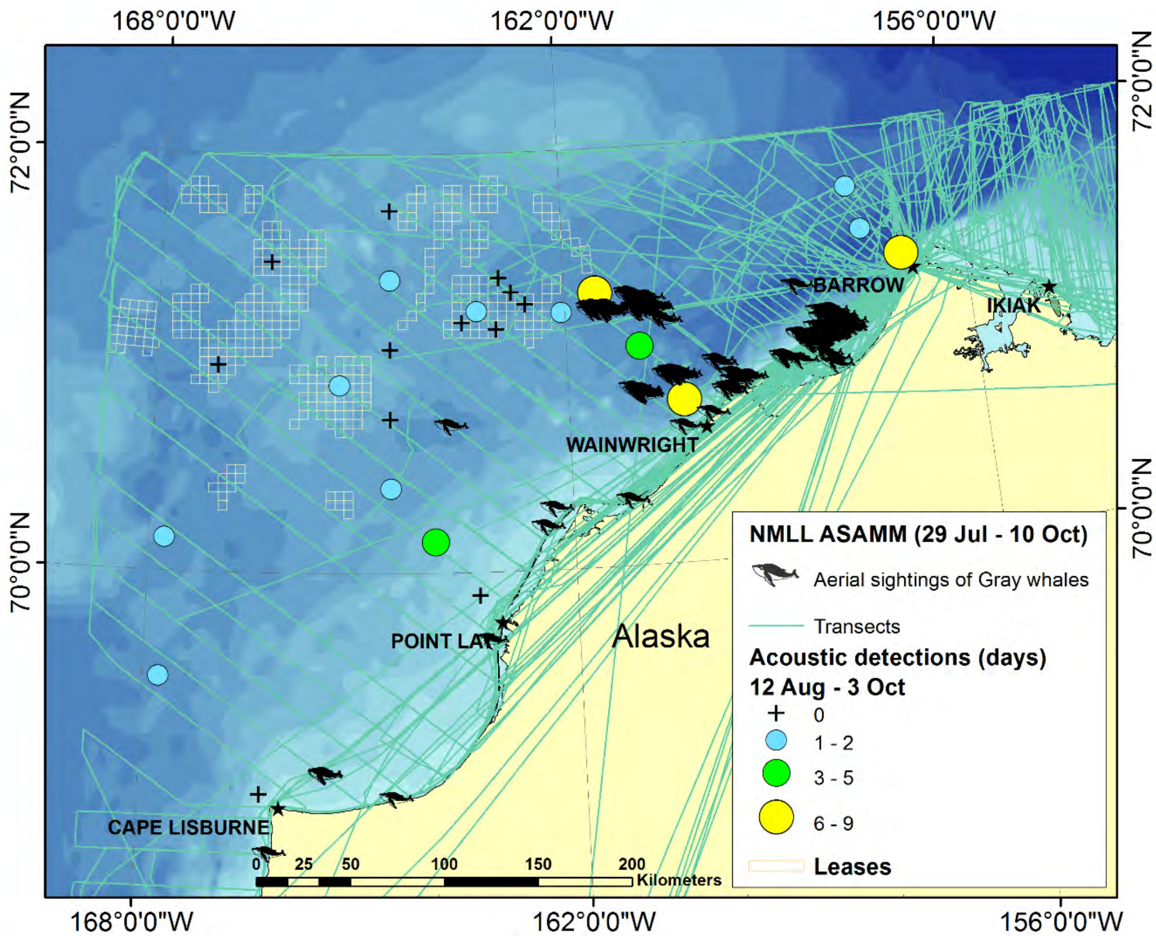


Figure 73. Acoustic detections and visual sightings of gray whales during summer 2015 in the study area. Sighting survey data were provided by National Marine Mammal Laboratory–Aerial Surveys of Arctic Marine Mammals (NMML ASAMM).

4.2.7. Humpback Whale Call Detections

Humpback whales were first detected in summer 2010 and calls have been recorded every year since. Humpback whale calls were only detected twice in 2015, which indicates this species only occurs at low densities in the northeastern Chukchi Sea, or that they do not actively vocalize.

4.2.8. Killer Whale Call Detections

Killer whales were first recorded in 2007 (Delarue et al. 2010b) and acoustically detected in all summers from 2009–2015. Further analysis of the 2007 data revealed mammal-eating killer whales were the sources of the detected calls (Delarue et al. 2010b). This is consistent with visual observations of killer whale predation on marine mammals in the Chukchi Sea (George and Suydam 1998).

Because of the quiet nature of mammal-eating killer whales (Deecke et al. 2005), it is likely that the results underestimate the true occurrence of this killer whale ecotype, even though they are in line with the limited number of visual observations. In 2015, the cluster of detections at W50 in late September coincided with the gray whale detection cluster at the same station. Killer whales were not sighted during the ASAMM in 2015.

Killer whales can occur throughout the study area any time during the summer, even though detections were more concentrated from mid-August to mid-September; within any year their presence has been infrequent (Figure 74).

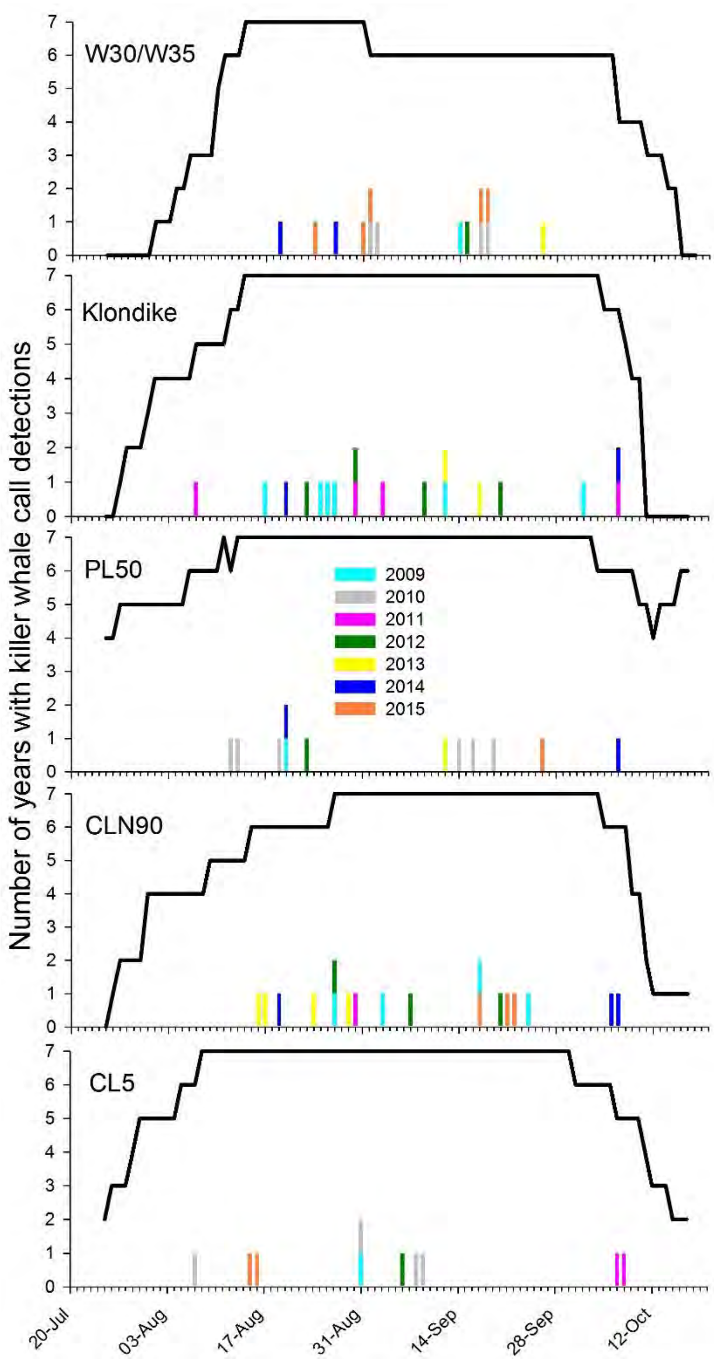


Figure 74. Number of years with daily killer whale call detections for each day between late July and mid-October (maximum duration of summer Acoustic Monitoring Programs) at five stations. The black lines show the number of years in which data was recorded for each day.

4.2.9. Minke Whale Call Detections

Minke whales were not detected during the winter 2014–2015 but were detected at CL50 in September 2015. They have been detected at that station in all years of the Acoustic Monitoring Program in late October/November. This species was also detected in the summer recordings from 2011 onward, with detections concentrated off Cape Lisburne and Point Lay. Visual observations in 2013 (one minke whale sighting northeast of Wainwright, Aerts et al. 2014) and five ASAMM sightings along the shore between Cape Lisburne and Icy Cape (Clarke et al. 2014) confirmed the presence of this species. Most sightings occurred in July and August while most acoustic detections occurred from mid-September onward, suggesting that minke whales in this region may be less vocally active during summer.

The increase in minke whale calling rate in fall is consistent with the increase in vocal activity of other baleen whale species over this period, which is associated with the onset of their reproductive cycle (e.g. Stafford et al. 2007, Stafford et al. 2012). The lack of detections in summer therefore does not mean minke whales are absent.

4.2.10. Ringed Seal Call Detections

4.2.10.1. Comparison of Winter Acoustic Recording Periods

Starting in winter 2012–2013, a new call type was included in the set of target calls, thereby increasing the detection probability of ringed seals compared to previous winters. The peak in detections occurring in April and May coincides with this species' breeding period. This is consistent with the acoustic behavior of other pinnipeds, such as bearded seals, whose calling activity also peaks around the breeding season. Detections were most common around 50 nmi from shore.

These results show unequivocally that some ringed seals winter in the Chukchi Sea and presumably mate there in the spring.

4.2.10.2. Comparison of Summer Acoustic Recording Periods

The summer 2015 detections were similar to previous years. They were distributed throughout the study area and occurred sporadically at most of the stations. In 2015, ringed seals were most acoustically active at Barrow stations (B15 and B30). Low calling rates combined with the analysis protocol likely underestimates the true occurrence of ringed seals.

5. Conclusions

5.1. Winter 2014–2015

- The bowhead whale 2014 fall migration extended later than in previous years, particularly in the central part of the study area. The spring 2015 migration was well defined between early April and early June.
- Walrus 2014 fall detections were rare; spring 2015 detections were highly consistent with previous years, i.e., starting in the first or second week of June and progressively moving toward Hanna Shoal.
- Beluga calls were detected sporadically in the fall of 2014. Spring detections started in early April 2015 with the main wave lasting until late May. Only sporadic detections occurred after May.
- Bearded seal calls were received intermittently and in low numbers through the fall and winter. They increased slowly from January to mid-March, when they increased rapidly, and continued strongly in May before dropping off rapidly at the end of breeding season, in early June.
- Ringed seals were detected from late October 2014 through June 2015, with a peak in April and May, corresponding to their breeding season. As with bearded seals, detections were almost completely absent after mating.
- Gray whales were first detected in late June 2014 off Point Lay. They were detected almost daily off Wainwright in July.

5.2. Summer 2015

- The 2015 summer acoustic data were characterized by few acoustic detections for all species. This can partly be explained by the highest ambient noise levels ever recorded throughout most of the Chukchi, associated with Shell's drilling operations, but lower summer call detections are normal for all species other than walrus.
- Bowhead whale detections started in late August off Barrow. These were followed immediately by detections in the central part of the study area, suggesting early westward movements across the Chukchi Sea in 2015. Calls of migrating bowhead whales were once again concentrated north of 71° N.
- Similar to other years, walruses were the most commonly detected species overall. Hanna Shoal and just off Point Lay were their core areas with detections generally rare in other areas.
- Beluga detections were common off Barrow in September with only a few detections at other stations.
- Ringed seals were detected sporadically throughout the summer with higher acoustic occurrence off Barrow.

- Bearded seal call detections increased at the end of the recording period (late September 2015) and were more common offshore, except for nearshore waters off Wainwright and Barrow.
- Humpback, fin, and Minke whales were each detected twice in summer 2015, consistent with their sporadic acoustic occurrence in the northeastern Chukchi Sea.
- Ambient noise levels at PLN40 were higher than in previous years. Sound levels were approximately 10 dB higher in 2015 than 2012 (the last year drilling operations occurred) in the 40–200 Hz band, the dominant sound emissions frequency band of large vessel traffic.

6. Acknowledgements

We acknowledge Emily Maxner, Katie Kowarski, Eric Lumsden and Craig Evans for their contribution to the manual analysis. We thank Jorge Quijano for his efforts comparing measured and modeled sound levels. We also thank the crew of the Fennica for their help deploying and retrieving the acoustic recorders. Final thanks to Katherine Williams for editing this report. The Aerial Surveys for Arctic Marine Mammals sightings were provided by Janet Clarke and Megan Ferguson. Funding for the ASAMM was provided by the National Marine Mammal Laboratory (NMML) and the Bureau of Ocean and Energy Management (BOEM).

7. Abbreviations & Glossary

90% rms	root-mean-square pressure within the time window containing the center 90% (from 5% to 95%) of the pulse energy
AMAR	Autonomous Multichannel Acoustic Recorder
ASAMM	Aerial Surveys for Arctic Marine Mammals
AURAL	Autonomous Underwater Recorder for Acoustic Listening Model 2 (by Multi-Electronique)
BG*XX*	the Burger lease station
B*XX*	regional array recorder Station *XX* statute mi from Barrow
CL*XX*	regional array recorder Station *XX* statute mi from Cape Lisburne
CLN*XX*	regional array recorder Station *XX* statute mi north of Station CL50
CPAI	ConocoPhillips Alaska, Inc.
CSESP	Chukchi Sea Environmental Studies Program
E	event
$\overline{E}$	non-event
FFT	fast Fourier transform
FM	frequency-modulated
FN	false negative
FP	false positive
h	hour
KL*XX*	the Klondike lease recorder Station
M/V	motor vessel
mi	statute mile
nmi	nautical mile
min	minute
P	precision
PL*XX*	regional array recorder Station, *XX* mi from Point Lay
PLN*XX*	regional array recorder Station, *XX* mi north of Station PL50
R	recall
rms	root-mean-square
SEL	sound exposure level (dB re 1 $\mu Pa^2 \cdot s$)
SEL 24 h	24 h sound exposure level
SNR	signal-to-noise ratio
SPL	sound pressure level (dB re 1 µPa)

TB terabyte (1TB = 10244 bytes)

UTC Coordinated Universal Time

W*XX* regional recorder Station *XX* mi from Wainwright

WN*XX* regional recorder Station *XX* mi north of Station W50

8. Literature Cited

Aerts, L.A.M., W. Hetrick, S. Sitkiewicz, C. Schudel, D. Snyder, and R. Gumtow. 2013. *Marine mammal distribution and abundance in the northeastern Chukchi Sea during summer and Early fall, 2008-2012*. Final Report prepared by LAMA Ecological for ConocoPhillips Company, Shell Exploration and Production Company and Statoil USA E&P, Inc.

Aerts, L.A.M., C.L. Christman, C. Schudel, W. Hetrick, and D. Snyder. 2014. *Marine mammal distribution and abundance in the northeastern Chukchi Sea during summer and early fall, 2008-2013*. LAMA Ecological, ConocoPhillips Company, Shell Exploration and Production Company and Statoil USA E&P, Inc. 81 pp.

Allen, B.M. and R.P. Angliss. 2013. Alaska marine mammal stock assessments, 2012. *NOAA Technical Memorandum* NMFS-AFSC-245: 282.

Arveson, P.T. and D.J. Vendittis. 2000. Radiated noise characteristics of a modern cargo ship. *Journal of the Acoustical Society of America* 107(1): 118-129.

Austin, M. and Z. Li. 2016. Underwater Sound Measurements. (Chapter 3) *In* Ireland, D.S. and L.N. Bisson (eds.). *Marine mammal monitoring and mitigation during exploratory drilling by Shell in the Alaskan Chukchi Sea, July–October 2015: Draft 90-Day Report*. LGL Rep. P1363D. Report from LGL Alaska Research Associates Inc., LGL Ltd., and JASCO Applied Sciences Ltd. For Shell Gulf of Mexico Inc, National Marine Fisheries Service, and U.S. Fish and Wildlife Service. 188 pp + appendices.

Belikov, R. and V. Bel'kovich. 2006. High-pitched tonal signals of beluga whales (*Delphinapterus leucas*) in a summer assemblage off Solovetskii Island in the White Sea. *Acoustical Physics* 52(2): 125-131.

Belikov, R.A. and V.M. Bel'kovich. 2008. Communicative pulsed signals of beluga whales in the reproductive gathering off Solovetskii Island in the White Sea. *Acoustical Physics* 54(1): 115-123. http://dx.doi.org/10.1134/S1063771008010168.

Blanchard, A.L. and A.L. Knowlton. 2013. *Chukchi Sea Environmental Studies Program 2008-2012: Benthic Ecology of the Chukchi Sea*. ConocoPhillips Company, Shell Exploration and Production Company and Statoil USA E & P, Inc.

Braham, H.W., B.D. Krogman, and G.M. Carroll. 1984. Bowhead and white whale migration, distribution, and abundance in the Bering, Chukchi, and Beaufort seas, 1975-78. *NOAA Technical Report. NMFS SSRF-778*. http://aquaticcommons.org/2054/1/NOAA_Tech_Rpt_NMFS_SSRF_778.pdf.

Christman, C.L., L.A.M. Aerts, and D. Snyder. 2015. *Marine mammal distribution and abundance in the northeastern Chukchi Sea from shipboard surveys during summer and early fall 2014*. CLC Research and LAMA Ecological, ConocoPhillips Company, Shell Exploration and Production Company and Statoil USA E&P, Inc. 36 pp.

Clark, C.W. and J.H. Johnson. 1984. The sounds of the bowhead whale, *Balaena mysticetus*, during the spring migrations of 1979 and 1980. *Canadian Journal of Zoology* 62: 1436-1441.

Clarke, J.T. and M.C. Ferguson. 2010. Aerial surveys of large whales in the northeastern Chukchi Sea, 2008-2009, with review of 1982-1991 data. *IWC Scientific Committee*. Volume SC/62/BRG13. 1-18 pp.

Clarke, J.T., A.A. Brower, C.L. Christman, and M.C. Ferguson. 2014. *Distribution and Relative Abundance of Marine Mammals in the Northeastern Chukchi and Western Beaufort Seas, 2013*.

Annual Report, OCS Study BOEM 2014-018. National Marine Mammal Laboratory, Alaska Fisheries Science Center, NMFS, NOAA, 7600 Sand Point Way NE, F/AKC3, Seattle, WA 98115-6349.

Crane, N.L. and K. Lashkari. 1996. Sound production of gray whales, *Eschrichtius robustus*, along their migration route: A new approach to signal analysis. *Journal of the Acoustical Society of America* 100(3): 1878-1886.

Deecke, V.B., J.K.B. Ford, and P.J.B. Slater. 2005. The vocal behaviour of mammal-eating killer whales: Communicating with costly calls. *Animal Behaviour* 69: 395-405. http://www.abdn.ac.uk/lighthouse/documents/Deecke_et_al_Vocal_behaviour_2011.pdf.

Delarue, J., M. Laurinolli, and B. Martin. 2009. Bowhead whale (*Balaena mysticetus*) songs in the Chukchi Sea between October 2007 and May 2008. *Journal of the Acoustical Society of America* 126(6): 3319-3328. http://link.aip.org/link/?JAS/126/3319/1.

Delarue, J., B. Martin, X. Mouy, J. MacDonnell, D. Hannay, N. Chorney, and J. Vallarta. 2010a. *Northeastern Chukchi Sea Joint Acoustic Monitoring Program 2008-2009*. Technical report for ConocoPhillips Company, Shell Exploration & Production Company, and Statoil USA E&P, Inc. by JASCO Applied Sciences Ltd. 156 pp plus appendices (85 pp).

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

Delarue, J., M. Laurinolli, and B. Martin. 2011a. Acoustic detections of beluga whales in the Northeastern Chukchi Sea, July 2007 to July 2008. *Arctic* 64(1): 15-24.

Delarue, J., B. Martin, X. Mouy, J. MacDonnell, J. Vallarta, and N. Chorney. 2011b. *Northeastern Chukchi Sea Joint Acoustic Monitoring Program 2009-2010*. *In*: Hannay, D. (ed.). Technical report for ConocoPhillips Company, Shell Exploration & Production Company, and Statoil USA E&P, Inc. by JASCO Applied Sciences. 156 pp plus appendices (85 pp), Dartmouth, NS. https://www.chukchiscience.com/Portals/0/Public/Science/AcousticMoorings/2010_CSESP_Acoustics_Final_Report.pdf and https://www.chukchiscience.com/Portals/0/Public/Science/AcousticMoorings/2010_CSESP_Acoustics_Final_Report_Appendices.pdf.

Delarue, J., B. Martin, D. Hannay, and C.L. Berchok. 2013a. Acoustic occurrence and affiliation of fin whales detected in the Northeastern Chukchi Sea, July to October 2007–10. *Arctic* 66(2): 159-172. http://www.jstor.org/stable/23594680?seq=1#page_scan_tab_contents.

Delarue, J., J. Vallarta, H. Frouin-Mouy, J. Wladichuk, B. Martin, X. Mouy, and D.H. Hannay. 2013b. *Northeastern Chukchi Sea Joint Acoustic Monitoring Program 2011-2012*. Document Number 00533 Version 3.0. Technical report for ConocoPhillips Company, Shell Exploration & Production Company, and Statoil USA E&P, Inc. by JASCO Applied Sciences.

Delarue, J., J. MacDonnell, B. Martin, X. Mouy, and D.H. Hannay. 2014. *Northeastern Chukchi Sea Joint Acoustic Monitoring Program 2012-2013*. Document Number 00808. Technical report for ConocoPhillips Company, Shell Exploration & Production Company, and Statoil USA E&P, Inc. by JASCO Applied Sciences.

Delarue, J., J. MacDonnell, K. Kowarski, B. Martin, X. Mouy, and D.H. Hannay. 2015. *Northeastern Chukchi Sea Joint Acoustic Monitoring Program 2013-2014*. Document Number 01023. Technical report for ConocoPhillips Company and Shell Exploration & Production Company by JASCO Applied Sciences.
https://www.chukchiscience.com/portals/0/Public/Science/AcousticMoorings/2013-

2014_Report_Northeastern_Chukchi_Sea_Joint_Acoustic_Monitoring.pdf and https://www.chukchiscience.com/portals/0/Public/Science/AcousticMoorings/2013-2014_Northeastern_Chukchi_Sea_Joint_Acoustic_Monitoring_Program_Appendices.pdf.

[ESA] Endangered Species Act of 1973 as Amended through the 108th Congress. 2002. United States Pub. L. No. 93–205, 87 Stat. 884, 16 U.S.C. 1531 (Dec 28, 1973) as amended by Pub. L. No. 107–136 (Jan 24, 2002). http://www.fws.gov/endangered/esa-library/pdf/ESAall.pdf.

Desjonquères, C., F. Rybak, M. Depraetere, A. Gasc, I. Le Viol, S. Pavoine, and J. Sueur. 2015. First description of underwater acoustic diversity in three temperate ponds. *PeerJ* 3: e1393.

Diachok, O.I. 1976. Effects of sea-ice ridges on sound propagation in the Arctic Ocean. *Journal of the Acoustical Society of America* 59(5): 1110-1120.

Ford, J.K.B. 1989. Acoustic behavior of resident killer whales (*Orcinus orca*) off Vancouver Island, British Columbia. *Canadian Journal of Zoology* 67(3): 727-745.

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

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

Frouin-Mouy, H., X. Mouy, B. Martin, and D. Hannay. 2016. Underwater acoustic behavior of bearded seals (*Erignathus barbatus*) in the northeastern Chukchi Sea, 2007–2010. *Marine Mammal Science* 32(1): 141-160. http://onlinelibrary.wiley.com/doi/10.1111/mms.12246/full.

George, J.C. and R. Suydam. 1998. Observations of killer whale (*Orcinus orca*) predation in the Northeastern Chukchi and Western Beaufort Seas. *Marine Mammal Science* 14(2): 330-332.

Greene, C.R. and B.M. Buck. 1964. Arctic ocean ambient noise. *Journal of the Acoustical Society of America* 36(6): 1218-1220. http://scitation.aip.org/content/asa/journal/jasa/36/6/10.1121/1.1919192.

Hauser, D.D., K.L. Laidre, R.S. Suydam, and P.R. Richard. 2014. Population-specific home ranges and migration timing of Pacific Arctic beluga whales (*Delphinapterus leucas*). *Polar Biology* 37(8): 1171-1183.

Jay, C.V., A.S. Fischbach, and A.A. Kochnev. 2012. Walrus areas of use in the Chukchi Sea during sparse sea ice cover. *Marine Ecology Progress Series* 468: 1-13.

Karlsen, J., A. Bisther, C. Lydersen, T. Haug, and K. Kovacs. 2002. Summer vocalisations of adult male white whales (*Delphinapterus leucas*) in Svalbard, Norway. *Polar Biology* 25(11): 808-817. http://link.springer.com/article/10.1007/s00300-002-0415-6.

Ljungblad, D.K., P.O. Thompson, and S.E. Moore. 1982. Underwater sounds recorded from migrating bowhead whales, *Balaena mysticetus*, in 1979. *Journal of the Acoustical Society of America* 71(2): 477-482.

Ma, B.B. and J.A. Nystuen. 2005. Passive acoustic detection and measurement of rainfall at sea. *Journal of Atmospheric and Oceanic Technology* 22(8): 1225-1248.

Martin, B., D. Hannay, M. Laurinolli, C. Whitt, X. Mouy, and R. Bohan. 2009. Chukchi Sea Acoustic Monitoring Program. (Chapter 5) *In* Ireland, D.S., D.W. Funk, R. Rodrigues, and W.R. Koski (eds.). *Joint Monitoring Program in the Chukchi and Beaufort Seas, open water seasons, 2006-*

2007. LGL Alaska Report P971-2. Report from LGL Alaska Research Associates Inc., LGL Ltd., JASCO Research Ltd., and Greeneridge Sciences Inc. for Shell Offshore Inc., ConocoPhillips Alaska Inc., National Marine Fisheries Service (US), and US Fish and Wildlife Service. 485 plus appendices.

Martin, B., D. Hannay, C. Whitt, X. Mouy, and R. Bohan. 2010. Chukchi Sea Acoustic Monitoring Program. (Chapter 5) *In* Funk, D.W., D.S. Ireland, R. Rodrigues, and W.R. Koski (eds.). *Joint Monitoring Program in the Chukchi and Beaufort Seas, open water seasons, 2006–2008*. LGL Alaska Report P1050-2. Report from LGL Alaska Research Associates, Inc., LGL Ltd., Greeneridge Sciences, Inc., and JASCO Research Ltd., for Shell Offshore, Inc., other industry contributors, National Marine Fisheries Service (US), and US Fish and Wildlife Service. 506 pp plus appendices.

Mellinger, D.K., S.W. Martin, R.P. Morrissey, L. Thomas, and J.J. Yosco. 2011. A method for detecting whistles, moans, and other frequency contour sounds. *Journal of the Acoustical Society of America* 129(6): 4055-4061.

Quakenbush, L.T., J.J. Citta, J.C. George, R.J. Small, and M.P. Heide-Jørgensen. 2010. Fall and winter movements of bowhead whales (*Balaena mysticetus*) in the Chukchi Sea and within a potential petroleum development area. *Arctic* 63(3): 289–307. http://www.jstor.org/stable/20799597?seq=1#page_scan_tab_contents.

Rankin, S. and J. Barlow. 2005. Source of the North Pacific “boing” sound attributed to minke whales. *Journal of the Acoustical Society of America* 118(5): 3346-3351.

Roth, E.H., J.A. Hildebrand, and S.M. Wiggins. 2012. Underwater ambient noise on the Chukchi Sea continental slope from 2006-2009. *Journal of the Acoustical Society of America* 131(1): 104-110.

Schusterman, R.J. and C. Reichmuth. 2008. Novel sound production through contingency learning in the Pacific walrus (*Odobenus rosmarus divergens*). *Animal Cognition* 11(2): 319-27.

Stafford, K.M., D.K. Mellinger, S.E. Moore, and C.G. Fox. 2007. Seasonal variability and detection range modeling of baleen whale calls in the Gulf of Alaska, 1999–2002. *Journal of the Acoustical Society of America* 122(6): 3378-3390.

Stafford, K.M., S.E. Moore, C.L. Berchok, O. Wiig, C. Lydersen, E. Hansen, D. Kalmbach, and K.M. Kovacs. 2012. Spitsbergen’s endangered bowhead whales sing through the polar night. *Endangered Species Research* 18: 95-103.

Stirling, I., W. Calvert, and H. Cleator. 1983. Underwater vocalizations as a tool for studying the distribution and relative abundance of wintering pinnipeds in the high Arctic. *Arctic* 36(3): 262-274. http://arctic.journalhosting.ucalgary.ca/arctic/index.php/arctic/article/view/2275.

Stirling, I., W. Calvert, and C. Spencer. 1987. Evidence of stereotyped underwater vocalizations of male Atlantic walruses (*Odobenus rosmarus rosmarus*). *Canadian Journal of Zoology* 65(9): 2311-2321.

Suydam, R.S., L.F. Lowry, and K.J. Frost. 2005. *Distribution and movements of beluga whales from the eastern Chukchi Sea stock during summer and early autumn*. OCS Study MMS2005-035.

Thompson, P.O., W.C. Cummings, and S.J. Ha. 1986. Sounds, source levels, and associated behavior of humpback whales, southeast Alaska. *Journal of the Acoustical Society of America* 80(3): 735-740.

Watkins, W.A. and G.C. Ray. 1977. Underwater sounds from ribbon seal, *Phoca (Histriophoca) fasciata*. *Fishery Bulletin* 75: 450-453. https://darchive.mblwhoilibrary.org/bitstream/handle/1912/6185/Watkins_Ray_1977%20ribbon%20seal%20vocalizations.pdf?sequence=1.

Wenz, G.M. 1962. Acoustic ambient noise in the ocean: Spectra and sources. *Journal of the Acoustical Society of America* 34(12): 1936-1956.