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Cooperative Acoustic Monitoring of North Pacific Right Whales

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Table of Contents

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Executive Summary

We used autonomous High-Frequency Acoustic Recording Packages (HARPs) to provide long-term recordings of critically endangered North Pacific right whales and other whales in the South East Bering Sea (SEBS). With support from ADFG, we deployed HARPs at two sites on the Bering Sea middle-shelf, in collaboration with the NOAA Pacific Marine Environmental Laboratory, which is conducting oceanographic moorings in this region. Long-term, passive acoustic recorders are an efficient method for monitoring marine mammals, providing ecological, geographical, and behavioral information. The acoustic data provided by these instruments revealed information on North Pacific right whale population abundance, important habitats, and spatial and temporal geographic distribution. Based on North Pacific right whale call patterns, we discern that the SEBS middle-shelf is an important habitat for right whales from May through December, and that right whales pass through the SEBS middle-shelf study area most frequently and remain for longer durations in July-October. Calling behavior on daily timescales may be related to other behaviors such as foraging, traveling, and social interaction. The mean calling rate during darkness was significantly higher than during all other time periods.

Background

The North Pacific right whale (*Eubalaena japonica*), which is found in the Bering Sea, Aleutian Islands, and Gulf of Alaska, is one of the most endangered species of large whale in the world. Thousands of North Pacific right whales were killed in the Gulf of Alaska and the Bering Sea during commercial whaling in the 1800s (Scarff, 2001), and by the middle of the 20th century, only a small population remained (Shelden *et al.*, 2005). Illegal takes of right whales by the Soviet Union in the 1960s reduced the population to near extinction (Brownell *et al.*, 2001). Sightings of right whales are now extremely rare in the entire eastern North Pacific (Shelden *et al.*, 2005). There are no reliable estimates of abundance for the eastern North Pacific right whale but most biologists believe the current population is unlikely to exceed a hundred animals, and may be significantly smaller.

Long-term, passive acoustic recorders are useful tools for monitoring marine mammal populations (Mellinger et al., 2004; Siciliano and de Oliveira Santos, 2003; Sirovic et al., 2004; Thompson and Friedl, 1982). Used as a method for monitoring marine mammals, underwater acoustic recordings have provided ecological, geographical, and behavioral information on a variety of species. For example, recorded calling patterns have given clues to whales' daily calling behavior and seasonal presence (Sirovic *et al*., 2004; Wiggins *et al*., 2005). Also, acoustic monitoring can aid in studying behavioral responses of calling animals to acoustic events, either anthropogenic or natural.

Objectives

The objective of this project was to monitor North Pacific right whales, and other marine mammal species, using High-frequency Acoustic Recording Packages (HARPs). The acoustic data provided by these instruments reveal information on population abundance and trend, important habitats, and spatial and temporal geographic distribution of the North Pacific right whale. The project data also reveal information on other cetaceans, including humpback, fin, and killer whales. The project increased the spatial extent of an acoustic monitoring program conducted in collaboration with the NOAA Pacific Marine Environmental Laboratory, designed to cover the historical summer range of the right whale. These acoustic data were analyzed to better understand right whale seasonality in the Bering Sea, and to better understand their behavior.

Technical Approach

Advancements in low-power and high-data-capacity consumer computer technology during the past decade recently have been adapted to autonomously record sounds from marine mammals over long periods. Acoustic monitoring has advantages over traditional visual surveys including greater detection ranges, continuous long-term monitoring in remote locations under various weather conditions and independent of daylight, and lower cost. The need for a broad-band, high-data-capacity system capable of autonomously recording the full range of marine mammal species for long periods has prompted the development of a High-frequency Acoustic Recording Package (HARP) capable of sample rates up to 200 kHz and deployment durations of many months.

The HARP design is described in this report, along with data analysis strategies for locating marine mammal calls in broad-band large-volume recorded data. Currently, HARPs accumulate data at a rate of almost 2 TB per instrument deployment which creates challenges for processing these large data sets. One method we employ to address some of these challenges is a spectral averaging algorithm in which the data are compressed and viewed as long duration spectrograms. These spectrograms provide the ability to view large amounts of data quickly for events of interest, and they provide a link for quickly accessing the short time-scale data for more detailed analysis.

Project Accomplishments

(1) Deployment of High_Frequency Acoustic Recording Packages in the Bering Sea

With support from ADFG, we deployed HARPs at two sites in the Bering Sea, in collaboration with the NOAA Pacific Marine Environmental Laboratory which is conducting oceanographic moorings in this region. This portion of the report documents these moorings, the HARP instruments, the acoustic data that they recorded, and methods for processing these data.

Deployment Cruises and Moorings

Table 1 lists the NOAA cruises/vessels used to deploy HARPS in the Bering Sea. Table 2 gives details of the HARP instruments and moorings including location, sample rate, duration of recording, and total storage capacity.

NOAA Vessel	Cruise Name	Begin Date	End Date	SIO Personnel
Miller Freeman	MF-04-04	4/24/04	5/7/04	Kevin Hardy Lisa Munger
Miller Freeman	MF-04-11	9/24/04	10/4/04	Kevin Hardy
Miller Freeman	MF-05-06	4/18/05	5/7/05	Chris Garsha Lisa Munger
Miller Freeman	MF-05-13	9/21/05	10/4/05	Allan Sauter

Table 1 NOAA vessels and cruises with HARP deployments in the Bering Sea

The moorings we used for HARP deployment are located in the Southeastern Bering Sea middle-shelf region, at water depths of about 70m (Figure 1 shows mooring locations: M-2 latitude 56º 51.60’ N longitude 164º 03.60’ W depth 72 m; and M-4 latitude 57º 51.18’ N longitude 168º 52.20’ W depth 70 m). The moorings generally consisted of a 300 kHz ADCP, a 28” syntactic float, the HARP, and an EGG acoustic release (Figure 2). The HARP was located near the bottom of the mooring, about 4 m above the seafloor.

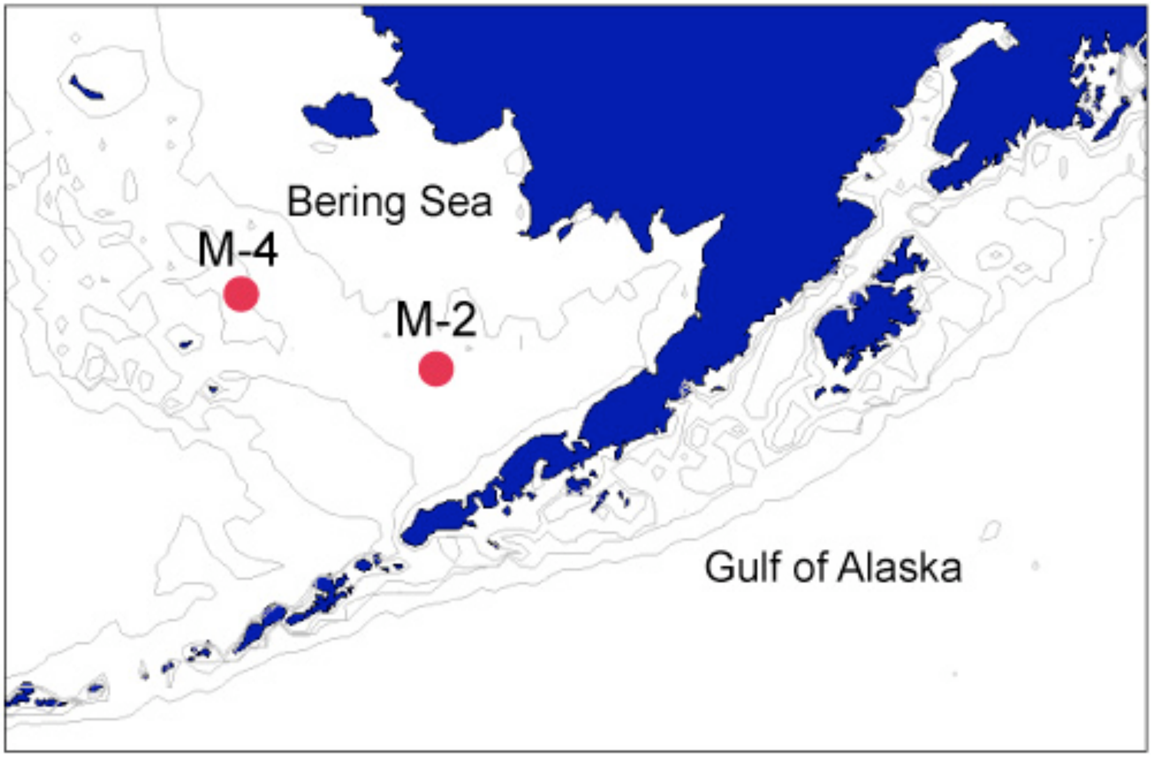


Figure 1. HARP deployment locations on NOAA Moorings M-2 and M-4 in the Southeast Bering Sea. The coordinates are: M-2 lat 56º 51.60' N lon 164º 03.60' W depth 72 m; and M-4 lat 57º 51.18' N lon 168º 52.20' W depth 70 m

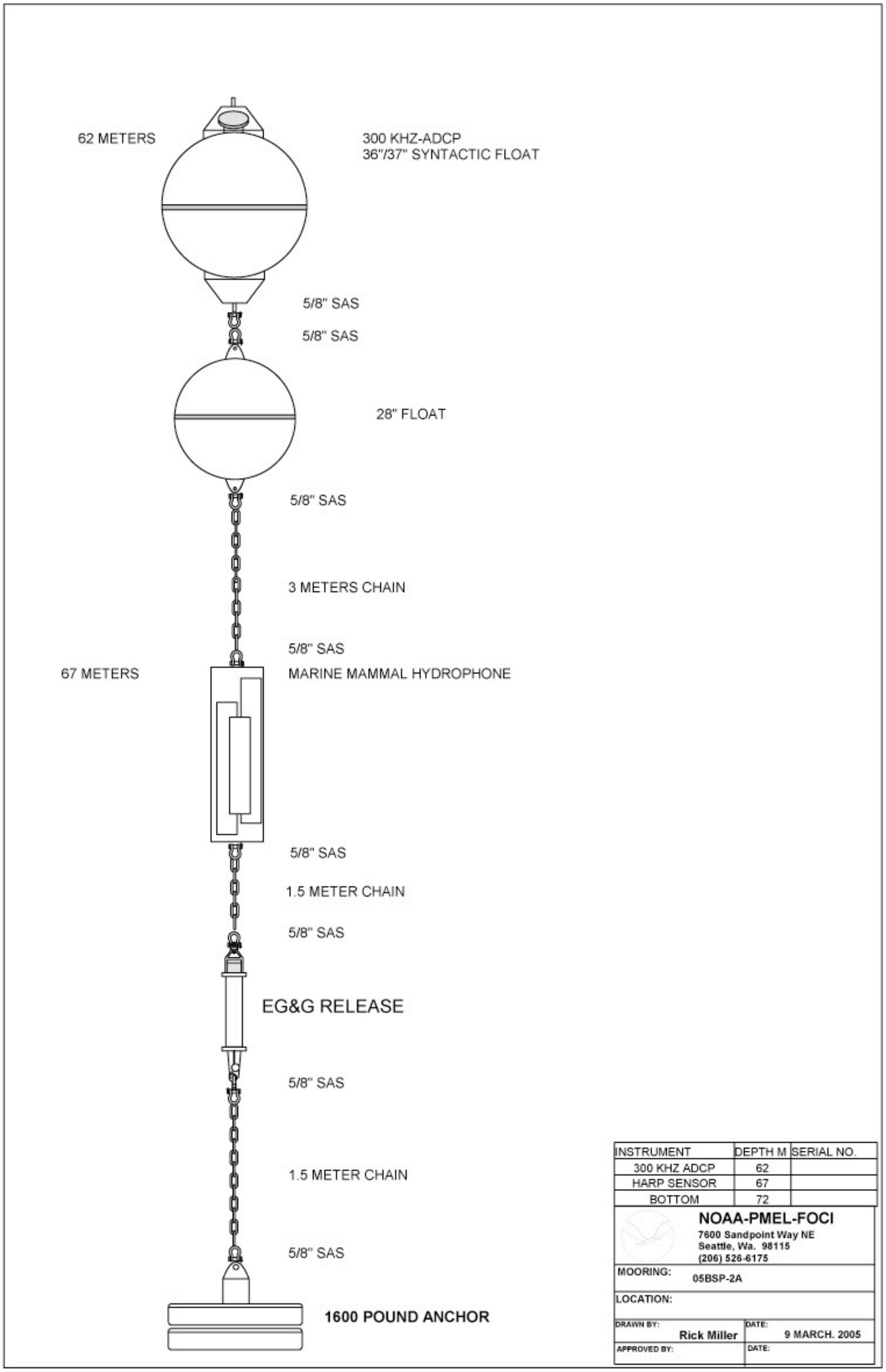
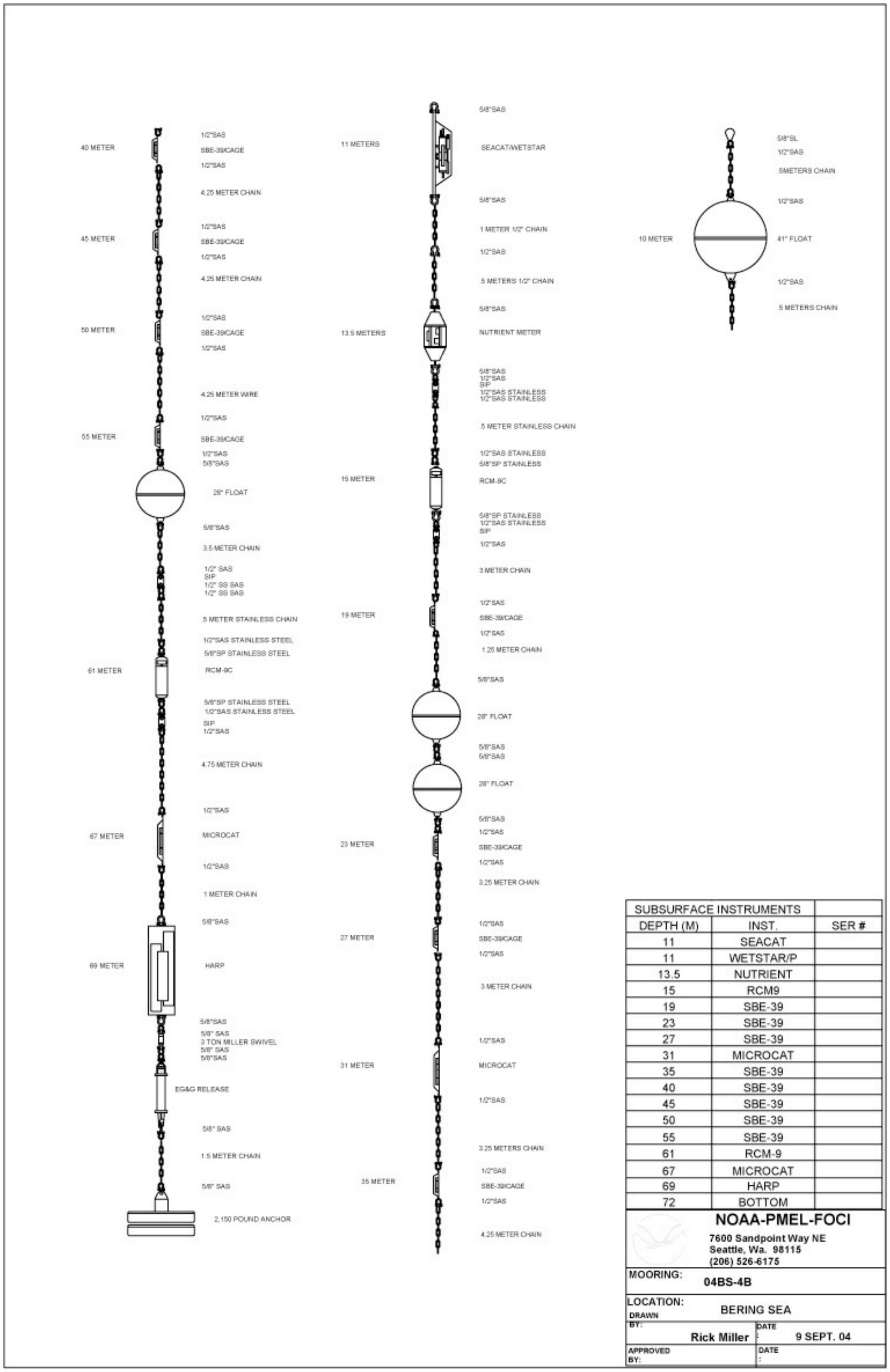


Figure 2. Mooring configuration for subsurface moorings containing HARPs at all Bering Sea deployments except for 04BS-4B (see Figure 3).



SUBSURFACE INSTRUMENTS		
DEPTH (M)	INST.	SER #
11	SEACAT	
11	WETSTAR/P	
13.5	NUTRIENT	
15	RCM9	
19	SBE-39	
23	SBE-39	
27	SBE-39	
31	MICROCAT	
35	SBE-39	
40	SBE-39	
45	SBE-39	
50	SBE-39	
55	SBE-39	
61	RCM-9	
67	MICROCAT	
69	HARP	
72	BOTTOM	

Figure 3. Mooring configuration for 04BS-4B, the HARP deployed during MF-04-11 at site M-4.

Site Name	Mooring Name	Begin Data Date	End Data Date	Sample Rate (kHz)	Total Data Storage Capacity	Hydophone Depth (m)
M-2	04BSP-2A	04/26/04	07/28/04	80	16x60Gb	67
M-2	04BSP-2B	09/28/04	12/05/04	32	16x80Gb	67
M-4	04BSP-4B	10/3/04	12/23/04	32	16x80Gb	69
M-2	05BSP-2A	04/23/05	09/23/05	40	16x80Gb	67
M-2	05BSP-2B	09/24/05	01/16/06	32	16x80Gb	67
M-4	05BSP-4B	09/25/05	01/25/06	32	16x80Gb	69

Table 2. HARPS deployments on NOAA Moorings M-2 and M-4 in the Bering Sea.

HARP Design

To provide long-term acoustic records of marine mammal calls from an autonomous instrument, there are three main requirements for the data acquisition electronics: low-power, high-speed digitizing, and high-capacity data storage. Low-power components are essential for long duration deployments. High-speed digitizing is needed to record broad-band marine mammal calls and to provide enough bandwidth for call differentiation. High-speed digitizing coupled with long duration recordings requires high-capacity data storage. Laptop computer disks were chosen for data storage because of their widespread use in the consumer electronics market. Furthermore, their design provides a rugged, small form factor (high capacity density), and most importantly, low-power device; all desired characteristics which will likely continue to improve.

We use 16 integrated drive electronics (IDE) laptop disk drives (2.5" form-factor) for our high-capacity data storage. The disks are arranged in a block and are addressed sequentially (Figure 4), with only one disk powered at a time. To allow for efficient instrument refurbishment, the block of 16 full disks can be easily removed and replaced with a new block of disks upon instrument recovery. The removed disk block then can be connected to a computer and the data can be uploaded to large capacity desktop computer disk drives for data backup and analysis. In the spring of 2004, 60 GB disks were used for a total of 960 Gb of data capacity and for later deployments we used 80 Gb disks for a total capacity of 1280 Gb (Table 2).

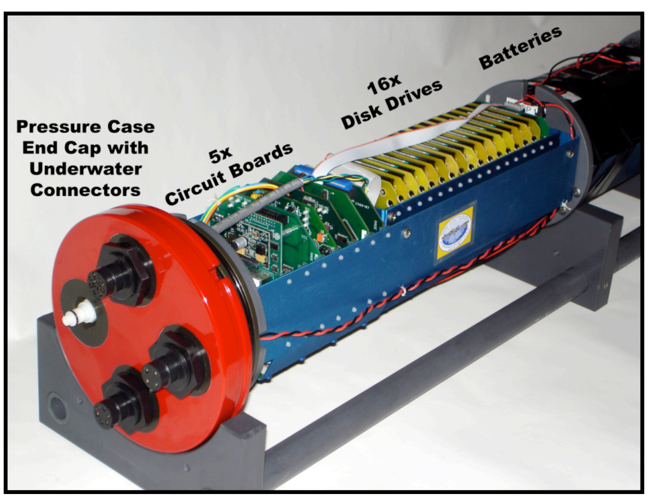


Figure 4 HARP data logger electronics attached to a pressure case endcap.

The HARP data logger includes five printed circuit boards: the central processing unit (CPU), analog-to-digital converter (ADC), static random access memory (SRAM) buffer, Ethernet/IDE communication, and clock cards. For converting the analog sensor signal into digital data, a low-power, low-noise analog-to-digital converter was chosen that provides 16-bit resolution and up to 250,000 samples/second sample rate. Also included on the ADC card are 4-pole anti-alias filter for the analog signal that can be easily modified for various sampling frequencies. The SRAM card consists of 32 MB of data buffer space. After digitizing, the data are temporarily stored in the SRAM buffer before being written to a disk drive. The disk writing process requires about one minute to offload the data from the SRAM. The Ethernet/IDE card provides 10BaseT file transfer protocol (FTP), telnet connectivity, and IDE communication between the data logger and the disk drives. The FTP functionality can be used to upload individual files from the data logger disks (i.e., individual SRAM buffer flushed disk writes) without connecting the disk block directly to a computer. Uploading these files through the data logger housing allows the data acquisition system to be evaluated and tested prior to deployment and allows the data quality recorded on the seafloor to be evaluated immediately after recovery without opening the housing. The clock card is populated with a temperature compensating phase-lock circuit and a low-power Seascan clock oscillator module which provides low, long-term clock drifts on the order of 1 part in 10^{-8}. Precise clocks are needed for maintaining accurate timing information over long instrument deployments, and for tracking calling whales with multiple instruments deployed in an array configuration.

Data storage capacity dictates monitoring duration and sample rate. The 1280 GBb data storage capacity allows for approximately 230 days of continuous sampling at 32 kHz. For all Bering Sea HARP deployments the acoustic data were continuously sampled to provide the best chance of detecting marine mammal calls.

Batteries are required to operate HARPs autonomously, and the longer the deployment and the higher the sample rate, the larger the number of batteries that are needed to accomplish the mission. To a large extent, batteries drive the design of an autonomous instrument packaging, for instance, pressure cases are often used to house the batteries and additional instrument flotation is required to buoy the weight of the batteries during instrument recovery. In the current HARP seafloor instrument configuration, a total of 192 D size alkaline cells (140g each) are arranged in four sub-packs. For this configuration an estimated 330 Amp-hours are available per deployment.

The HARP acoustic sensor is a broad-band (10 Hz - 100,000 Hz), low-power (50 mW), high-sensitivity (more than -120 dB re 1V/μPa) hydrophone which includes a transducer, signal conditioning preamplifier, pre-whitening filter and anti-alias filter electronics. The hydrophone uses a spherical omni-directional transducer (ITC-1042, www.itc-transducers.com) which is constructed from lead zirconate titanate ceramic and has an approximately flat (+/- 2 dB) sensitivity response of about -200 dB re 1Vrms / μPa from 1 Hz to 100 kHz. The signal from the transducers are fed into a preamplifier with approximately 40 dB of gain at low frequency, and about 60 dB for the high frequencies. This is a frequency response similar to the reciprocal of the ocean ambient noise as a function of frequency (i.e., ocean ambient noise decreases as frequency increases). The pre-whitening filter flattens the response of the hydrophone system in the presence of ocean ambient noise, adding more gain at higher frequencies where ambient noise levels are lower and sound attenuation is higher. After pre-amplifying and pre-whitening, a 4-pole low-pass filter is used to reduce high-frequency aliasing effects. Line drivers send the signals through a 10m cable to a differential receiver in the data logger which receives the signals, and another 4-pole low-pass filter with a -3 dB point at the Nyquest frequency (one-half the sampling rate) is included in the data logger to further reduce high frequency aliasing effects.

The transducer and signal conditioning electronics are packaged in a soft, oil-filled polyurethane tube to provide good acoustic coupling with the seawater. The signal conditioning surface mount electronics are populated onto a 2 cm x 8 cm, two-sided printed circuit board which is mounted on a bulkhead connector to allow easy electronics changing based on experimental requirements (i.e., different sample rates require different anti-alias and pre-whitening filters).

Data are uploaded from the 16 raw laptop disks in the disk block to a smaller number of higher capacity disks to make data handling more manageable. The larger disks are also more cost effective than the laptop disks, do not need to be low-power, and typically operate at faster rates. During the uploading process, the data are copied from the HARP specialized file system to a standard file system so that the data can be read by a desktop computer. Each raw HARP disk is copied to a single file (e.g., 120 GB) to provide a complete backup of the original disk. The backup files are then parsed into smaller (~1 GB) processing files using MATLAB (www.mathworks.com). We found this size to be a good optimization of the tradeoff between having the fewest number of files per instrument-deployment to manage and file sizes small enough to easily process. The 1 GB processing files are generated in a format we call XWAV which is similar to a WAV formatted file but which include additional information in an expanded header. For example, the XWAV header includes data timing information (i.e., start and stop times), latitude, longitude and depth of instrument deployment, and other experiment specific information. The raw data are evaluated for timing accuracies before including in the XWAV file header. XWAV files can be viewed and played with standard audio software that can read WAV files. The XWAV header also can be modified to adjust the gain and speed at which the file is played in standard audio software, but still retain the original amplitude and sample rate for processing with XWAV-capable software.

Each instrument deployment results in about 2000 XWAV time series files, and viewing and analyzing each one of these files in a non-automated way is not practical, so we use a means of file compression for data overview based on long-term spectral averages (LTSA). Spectral-averaging is a method of searching for acoustic events such as whale calls in long-term data sets. Instead of inspecting short duration spectrograms for individual calls, successive spectra are calculated and averaged together. These averaged-spectra are arranged sequentially to provide a time series of the spectra. The averaging time determines the resolution of the resulting plot and the data compression factor. Essentially, spectral-averaging is a spectrogram over long time periods and provides a map or table of contents to groups of events in the finer time scale XWAV data. Depending on number of samples used for the spectra and the averaging time used, data compression factors of 4000 or more are possible while still providing enough resolution to observe short-term events above the ambient noise.

LTSA data representing a 2 hour period of acoustic data from the Bering Sea are shown in Fig. 5. These spectra reveal periods of enhanced energy in the 100 – 160 Hz band (see arrow in Figure 5), which is the result of right whale calling. Note that a large portion (70% – 90%) of time these spectra do not contain calls, but with the LTSA technique, the quiet times can be passed over during initial analysis.

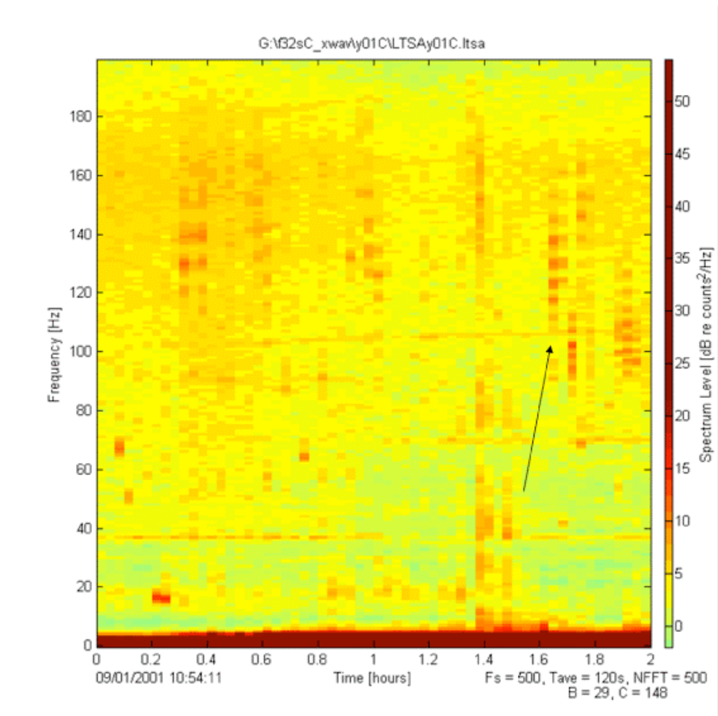


Figure 5. Two hour long-term spectral average (LTSA) from the Bering Sea HARP at mooring M-2. The arrow points to a time of enhanced energy at 100-160 Hz which is the result of right whale calling.

The corresponding short time-scale spectrogram containing these right whale calls is shown in Fig. 6. Matching the characteristics of the short term spectra back to the LTSA plot shows most of the energy from the right whale up-sweep calls is clustered between 100 – 160 Hz.

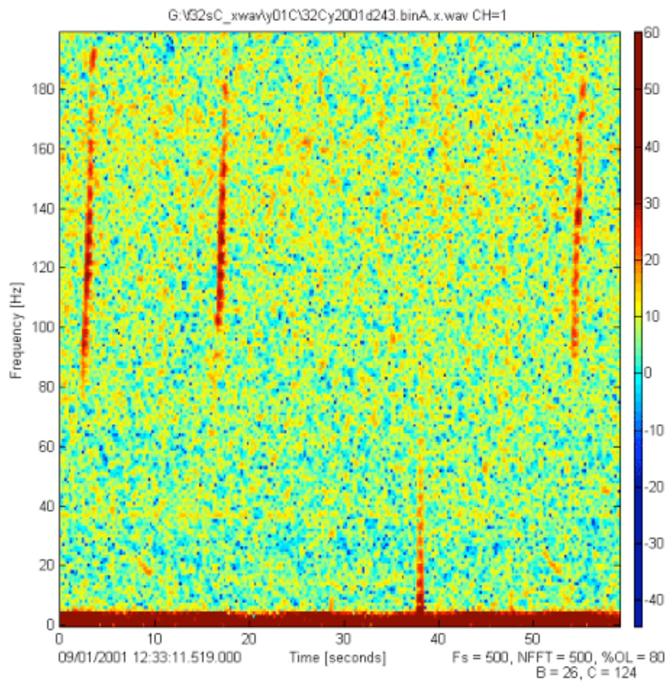


Figure 6. Short time-scale spectrogram corresponding to time period of arrow from Figure 5. Three up-swept right whale calls are seen at 100-160 Hz.

(2) Analysis of North Pacific right whale seasonal and diel calling patterns

Eastern North Pacific right whales appear to migrate seasonally, with recent and historic sightings indicating a northward movement in spring to high-latitude summer feeding grounds, and a southward movement in autumn (Brownell et al., 2001; Clapham et al., 2004; Shelden et al., 2005; Townsend, 1935). Data from 1835-1852, during peak whaling for North Pacific right whales, suggest that right whales occurred in the eastern Bering Sea as early as April and were abundant there by May (Scarff, 1991). The southeastern Bering Sea (SEBS) and western Gulf of Alaska (GoA) historically supported high concentrations of right whales from June through September; the western GoA was known to whalers in the 19th century as the lucrative 'Northwest Ground' or 'Kodiak Ground'. Small numbers of right whales have been seen in most summers since 1996 in the SEBS (Goddard and Rugh, 1998 ; LeDuc, 2004 ; LeDuc et al., 2001; Moore et al., 2000; Tynan et al., 2001; Wade et al., 2006), with occasional recent sightings in the western GoA (Waite et al., 2003). The latest seasonal right whale sighting in the SEBS was reported in October 1999 (Brownell *et al*. 2001). North Pacific right whales have rarely been seen in winter, either historically or recently, and winter sightings in the eastern North Pacific have been geographically scattered and usually are comprised of single animals (Brownell *et al.* 2001). In a 2004 satellite-transmitter tag study of two North Pacific right whales, the whales traveled around the SEBS middle and outer shelf regions, but did not leave the Bering Sea during 40 days of monitoring in August-September (Wade *et al*. 2006).

Most of our current knowledge of eastern North Pacific right whales is based on visual surveys, which are conducted primarily in summer months in the Bering Sea and Gulf of Alaska (*e.g*., LeDuc *et al*. 2001; LeDuc 2004), and when weather and light conditions are favorable for vessels and aircraft. During the 19th and 20th centuries, the majority of right whale sightings in the Bering Sea were reported in June through September, the months with highest search effort (Scarff 1991; Brownell *et al*. 2001; Shelden *et al.* 2005). Recently designated critical habitat areas in the southeast Bering Sea and western Gulf of Alaska are based on visual sightings of right whales since 1970 (Register, 2006). Traditional cetacean visual surveys provide photographic, genetic, and observational data (*e.g*., (LeDuc et al., 2001; McDonald and Moore, 2002), but are constrained to operate in good weather and daylight, and limited to usually a few to several weeks in duration by vessel, aircraft or personnel expense and schedules. Because of these constraints in visual sighting data, it is unclear whether right whales are consistently present in the SEBS throughout the summer, and whether they are present at other times of year.

We present results from the first long-term acoustic monitoring study of critically endangered North Pacific right whales in the southeast Bering Sea. The use of autonomous acoustic moorings allowed us to conduct almost year-round monitoring. We show that right whale calling in the SEBS exhibits seasonal and diel patterns, and provide evidence that right whales were present at times of year and locations where they have not recently been known to occur.

Methods

We analyzed data from the ADFG supported deployment of HARPs on NOAA moorings, and integrated these data with ARP data from several other locations in the Bering Sea, as well as one site southeast of Kodiak Island in the western GoA (Figure 7). Site names, locations, recording dates, sampling rates and number of call detections are summarized in Table 3. HARPs have been shown to have a right whale recording range of up to at least 60 km on the Bering Sea shelf (Wiggins et al., 2004), several times greater than visual sighting range.

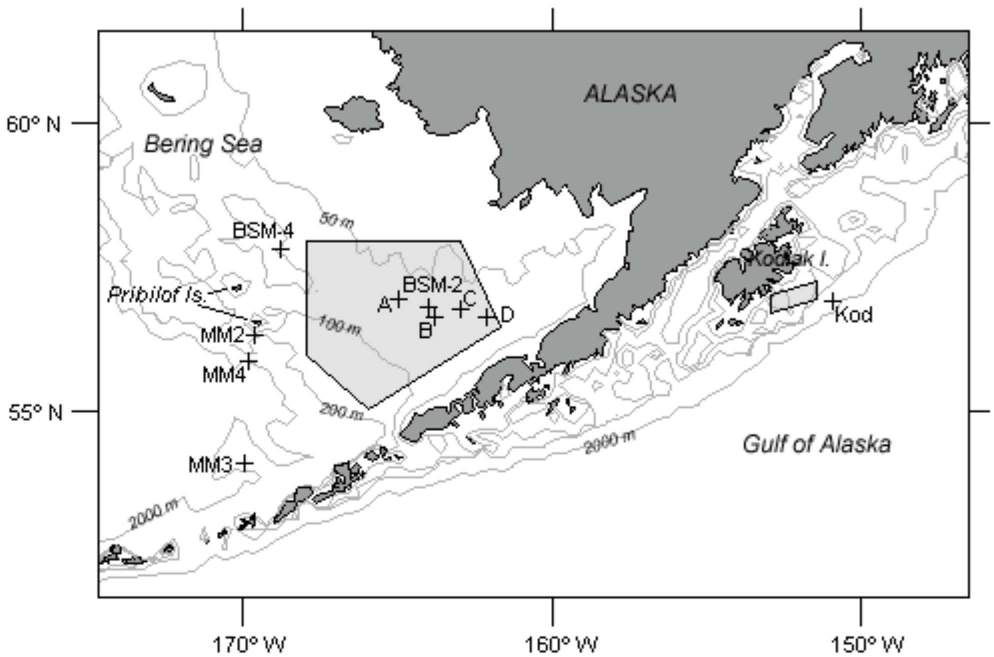


Figure 7. Study area where '+' symbols represent long-term acoustic recorder deployments, 2000-2006 (see Table 3). Shaded polygons are federally designated right whale critical habitat, (Federal Register 07/06/2006).

Site	Sampling rate (kHz)	Deployment Location	Depth (m)	Recording Begin	Recording End	Right whale call detections 'good'	'fair'	'poor'
A	0.5	57° 00.00' N 164° 59.97' W	70	10/01/00	05/08/01	109	178	395
B	0.5	56° 40.37' N 163° 50.74' W	70	10/02/00	12/13/00	127	133	219
C	0.5	56° 49.89' N 163° 00.48' W	70	10/02/00 08/31/01	05/03/01 07/28/02	70 1116	0 438	173 670
D	0.5	56° 40.05' N 162° 10.80' W	70	10/02/00	05/07/01	54	19	57
Kod	1	56° 57.02' N 150° 59.81' W	802	04/19/03	08/31/03	0	0	0
MM2	1	56° 21.48' N 169° 39.74' W	125	05/01/04	06/09/04	0	0	0
MM3	1	54° 0.00' N 170° 0.00' W	1880	05/03/04	12/27/04	0	31	234
BSM-2	80 32 40	56° 51.60' N 164° 03.60' W	72	04/26/04 9/28/04 04/23/05	7/28/04 12/05/04 01/16/06	99 0 1313	96 0 416	221 0 797
BSM-4	32 40	57° 51.18' N 168° 52.20' W	70	10/3/04 9/24/05	12/23/04 1/25/06	0 790	31 285	234 511
MM4	0.5	55° 54.07' N 169° 52.01' W	1590	4/30/05	08/02/05	7	2	4

Table 3. ARP site names, sampling rates, locations & depth, recording dates, and number of right whale calls detected.

Right whale calls in the Bering Sea were first recorded in 1999 using directional frequency analysis and recording (DIFAR) sonobuoys deployed from a ship (McDonald and Moore 2002). During the 1999 survey and subsequent surveys in 2002 and 2004, DIFAR sonobuoys were used to localize calls from right whales that were confirmed by visual sightings (McDonald and Moore 2002; Wade *et al*. 2006). Over eighty percent of right whale calls recorded during these surveys were frequency-modulated 'up-calls' (Figure 8), with variable frequency and sweep rate characteristics on average from 90-150 Hz and about 0.7 s in duration (*e.g*. McDonald and Moore 2002). Other call types, such as down-swept calls and constant-tonal 'moans', also were produced and were usually interspersed with up-calls. Therefore, we used up-calls in this study as a reliable indication of right whale presence.

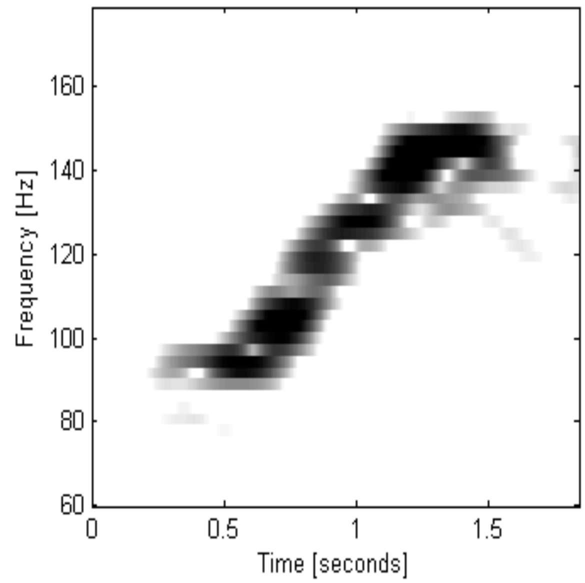


Figure 8. Spectrogram of single right whale up-call. Sampling rate = 500 Hz, 180-point FFT and same length Hanning window for 0.36 s window length, 99% overlap

We detected potential right whale up-calls in long-term recordings using two methods. The first was to compute "long-term spectral averages" (LTSAs) of acoustic recordings by computing Fast Fourier Transforms (FFTs) and then averaging successive FFTs into a single spectral average and displaying successive spectral averages as spectrograms (Wiggins and Hildebrand, 2007). To compute the FFTs we applied a Hanning window, 0% overlap, and 1 Hz frequency bins; successive FFTs were averaged over 120 seconds. High-bandwidth (>1 kHz) recordings were decimated to a sampling rate of 1 kHz using an 8^{th} order lowpass Chebyshev type I forward and backward filter prior to calculating LTSAs. Displaying data in the LTSA format allowed the analyst (LMM) to quickly visually scan through years of recordings, note times of potential right whale calling, and easily open the detailed data files for additional evaluation of calls. The second technique used for call detection was automatic spectrogram correlation using the software program *Ishmael* (Mellinger, 2001). We cross-correlated spectrogram data from the acoustic recorders with a synthetic spectrogram kernel based on the North Pacific right whale up-call (Munger et al., 2005). Automatic detections were saved as individual sound files.

Potential right whale calls detected by either of the above techniques were reviewed using *Triton*, a Matlab-based acoustic data display & analysis software program (Wiggins 2003) or using *Ishmael*. We analyzed positive call detections aurally and visually to identify right whale calls and searched for additional calls for at least one day before and one day after call detection times. Data were scanned until no calls were found for 24 h. All potential right whale calls were analyzed to distinguish them from similar-appearing humpback whale (*Megaptera novaeangliae*) calls (Figure 9). The main differences used to distinguish the two species are in their frequency range and temporal patterns. Most North Pacific right whale calls are less than 250 Hz (Figure 9a) and, like those of other right whale species (*Eubalaena* sp.), occur in non-repetitive clusters with variable silent intervals up to several hours in length (Matthews et al., 2001 ; McDonald and Moore, 2002; Vanderlaan et al., 2003), whereas humpback whales produce songs that are characterized by consistently structured ‘phrases’ and the cyclical repetition of phrases over long (minutes to hours) periods (Payne and McVay, 1971). Humpback singing has been reported primarily in low-latitude winter breeding grounds, but has also been recorded on higher-latitude summer feeding grounds (Clark and Clapham, 2004; Mattila et al., 1987; McSweeney et al., 1989). In the Bering Sea, humpback whales produce song fragments containing frequencies < 250 Hz (Figure 9b), which appear similar to low-frequency components of humpback whale songs in other areas in the North Pacific (*e.g*.,(Cerchio et al., 2001; Fristrup et al., 2003).

Potential right whale call times (Coordinated Universal Time, UTC) were picked by cursor in a spectrogram display to within ± 0.5 s and each call was rated ‘good’, ‘fair’, or ‘poor’, in order of decreasing certainty that the call was made by a right whale. ‘Good’ right whale calls were up-calls or ‘down-up’ calls similar to those recorded in the presence of right whales during prior surveys (*e.g*. McDonald and Moore 2002; Munger unpub. data) and had a relatively high signal-to-noise ratio (SNR). ‘Fair’ right whale calls were either non-upswept right whale call types co-occurring with up-calls, or were more difficult to identify due to lower SNR or nearby detections of humpback whale calls. ‘Poor’ right whale calls may have resembled right whale calls or portions of right whale calls, but were either too difficult to distinguish from humpback whale calls or had low SNR such that the analyst was not confident of the calling species. We did not include ‘fair’ and ‘poor’ right whale calls (19% and 38% of total detections; Table 1) in the results presented in this paper. Therefore the total numbers of true right whale calls may be underestimated, but seasonal and daily patterns were not affected by excluding lower-rated calls as they were interspersed with ‘good’ calls.

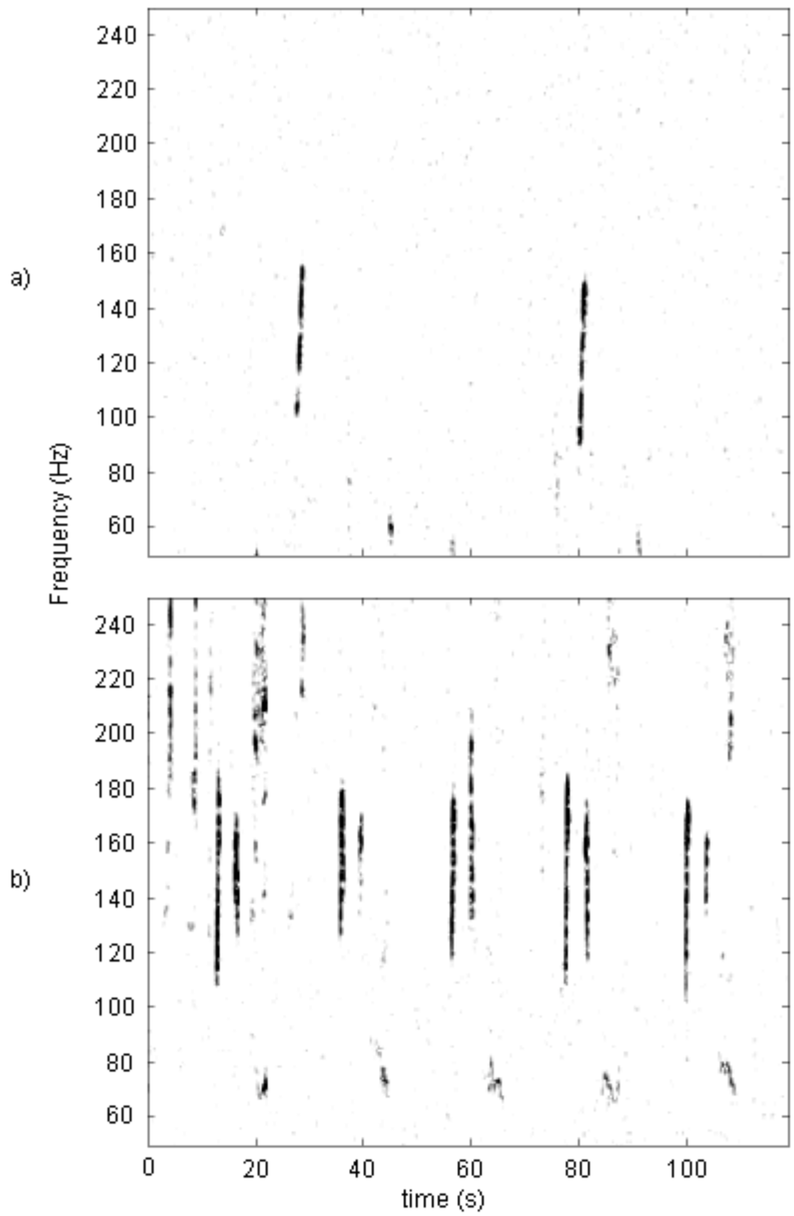


Figure 9. a) Right whale 'up' calls recorded by ARP at site C, August 2001. Spectrogram generated using Hanning window, FFT and frame size=600 points, 90% overlap. Original sampling rate = 500 Hz. b) Humpback song components recorded by ARP at site 'B', October 2000. Same sampling rate and spectrogram parameters as (a).

Diel patterns in right whale calling were analyzed using SEBS middle-shelf recordings. For each day with calls, we obtained the time (UTC) of sunrise, sun transit (maximum altitude of sun relative to horizon), sunset, and start & end of nautical twilight (-12º sun altitude relative to horizon) at the instrument site using data from the U.S. Naval Observatory website (http://aa.usno.navy.mil). Calls were categorized as occurring during 'dawn' (sun altitude between -12º and 0º prior to rise), 'morning' (sun altitude increasing from 0º to transit), 'afternoon' (sun altitude decreasing from transit to 0º), 'dusk' (0º to -12º following sunset), and 'dark' (sun below -12º to horizon). To obtain calling rates in calls/hour, we normalized the number of calls within each category to the corresponding duration of that period on the day on which calls were sampled. We then subtracted the overall calling rate (calls/hour) for that day to obtain a mean-adjusted calling rate, in order to correct for variation in the total number of calls recorded each day. We used a Kruskal-Wallis test (Zar, 1999) to rank and compare mean-adjusted calling rates among diel periods, and a Tukey-Kramer multiple comparison test to determine which, if any of the diel periods showed significant difference in mean rank of mean-adjusted right whale calling rates.

Results

A total of 3685 'good' right whale calls were detected, nearly all within the SEBS middle-shelf at ~ 70 m depth. Only seven right whale calls were recorded at MM4 (1590 m depth) south of the Pribilof Islands on 14 June 2005, and no right whale calls of any quality rating were detected on two other SEBS outer shelf/slope instruments (MM2, 125 m and MM3, 1880 m) in May- December 2004 or off Kodiak Island (802 m) in April-August 2003 (Table 3).

The number of right whale calls per day and sampling effort are shown for the SEBS middle-shelf instruments in Figure 10. The overall seasonal occurrence of right whale calls is shown in figure 10(a), with calls per day plotted from the instrument with the maximum calling rate for that day across recording years. The earliest SEBS middle-shelf right whale calls of any year were recorded on 23 May 2004, and the latest right whale calls of any year were recorded on 15 December 2005. The highest calling rates (> 300 calls/day) were in August, September and December.

Calls per day and recording effort for each year at SEBS middle-shelf sites are shown in figure 10(b). In 2000 and early 2001, maximum calls/day are plotted for a single instrument to avoid duplicating counts of calls recorded by more than one instrument. Effort in January 2006 at sites BSM-2 and BSM-4 is not shown because no right whale calls were detected during this time. The longest continuous deployments were August 2001 - July 2002 (site C) and April 2005 – January 2006 (site BSM-2); peak calling rates in these recordings occurred during August and September. Right whale calls were not detected in January through April in 2001, 2002, and 2005. Right whale calling was episodic throughout the season, with typical durations of 1-3 consecutive days and up to 5 days. The longest consecutive periods of right whale calling were in late summer and early autumn. Intervals between days with calls ranged from 2 to 49 days, with a median value of 6.5 days.

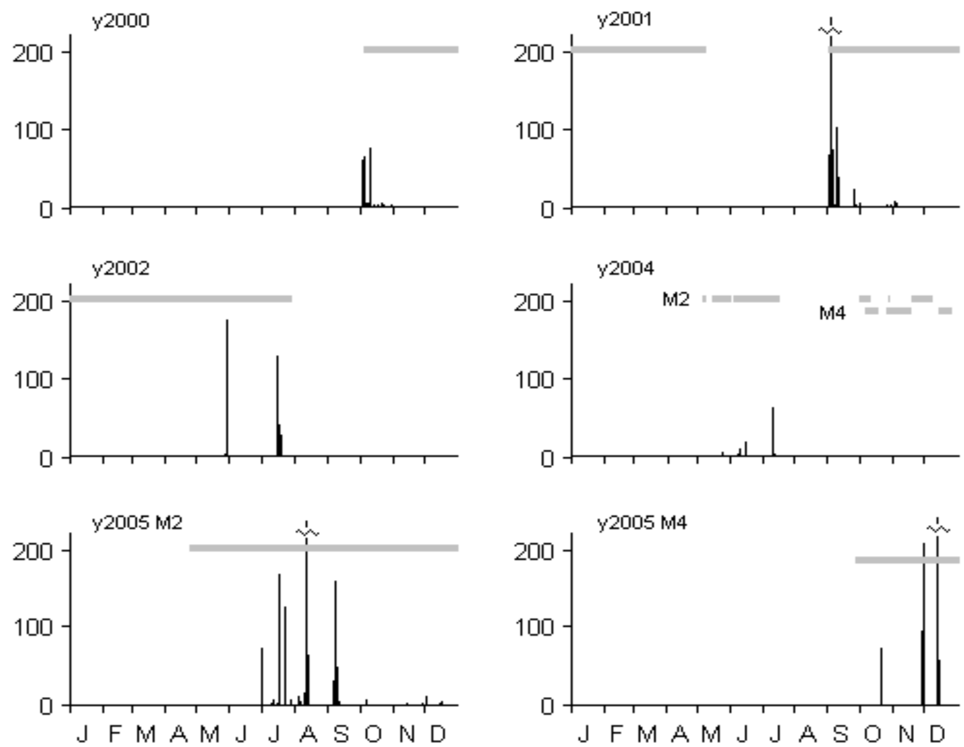


Figure 10. a) maximum number of 'good' right whale calls/day among SEBS middle-shelf recording sites (instrument depth <100 m), 2000-2006. b) calls/day for each year with recording effort; horizontal bars are recording duration; vertical bars are right whale calls/day (in 2000, data are calls/day from instrument with maximum calling rate on that day).

The number of days per month (not necessarily consecutive) with right whale calls at each SEBS site is shown in Figure 11. The months with the highest proportion of right whale calling days were July through October, with up to 11 calling days per month. The months with fewest right whale calling days were May, June, November, and December; calls were detected on no more than 3 days during these months. Right whale calls were recorded on at least one day per month in October through December 2005 at site BSM-4, and on one day in June 2005 along the slope south of the Pribilof Islands.

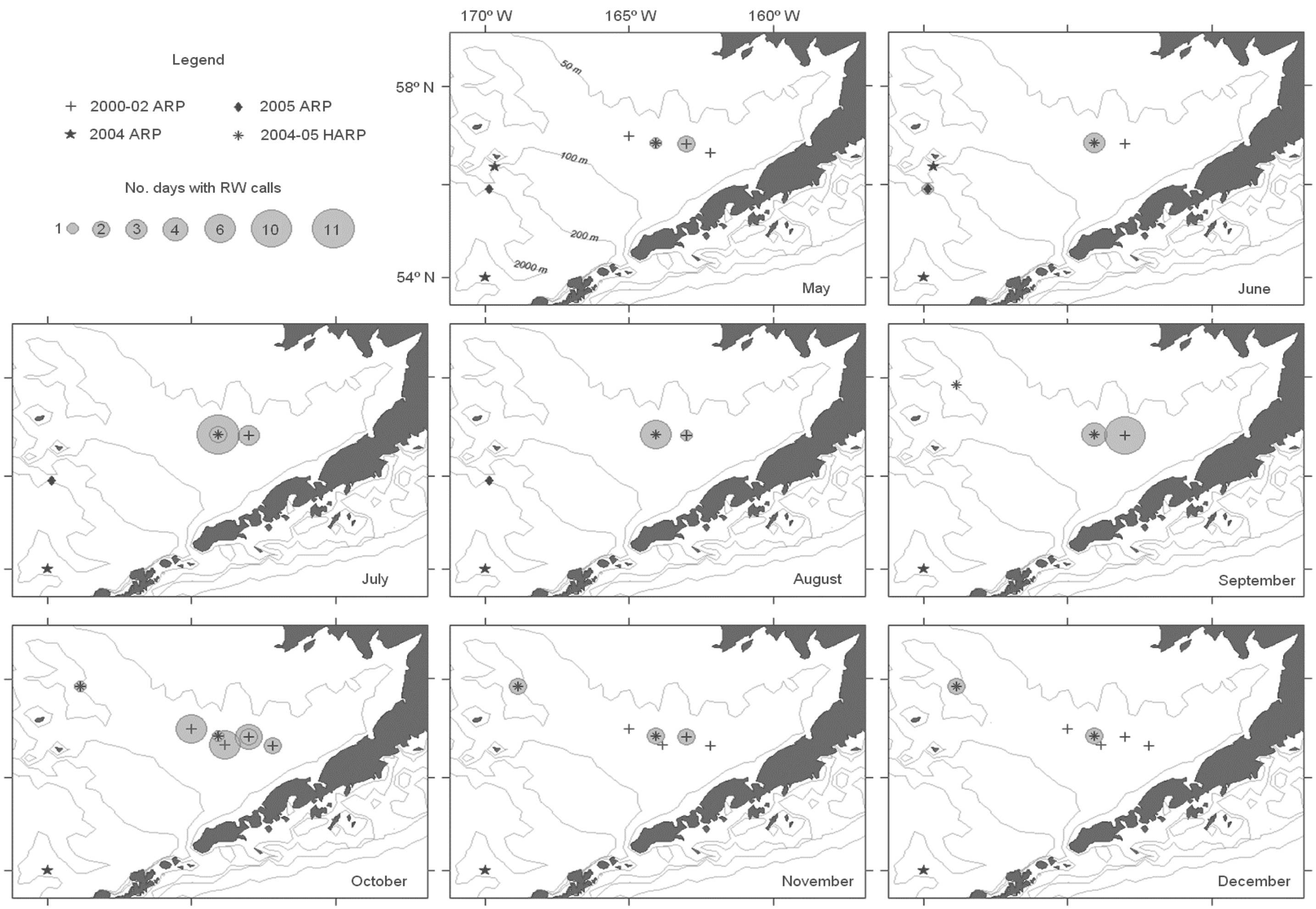


Figure 11. Number of days with 'good' right whale calls by month for recording sites. Calls recorded at same site during same month in different years are shown by more than one filled circle around site. No right whale calls detected in January-April (not shown).

Mean-adjusted right whale calling rates recorded on the SEBS middle-shelf (including BSM-4) showed significant diel variation (Figure 12; Kruskal-Wallis test; Chi-square=23.85, df= 4, p<<0.001). The mean rank for mean-adjusted calling rates during darkness was significantly higher than all other time periods; no other time periods had significantly different mean ranks from one another (darkness mean rank = 218.4; dawn, morning, afternoon & dusk = 138.7, 153.8, 157.3, and 156.0 respectively; Tukey-Kramer multiple comparison test). Sample size was 68 for each diel time period except dark (n= 51), due to the sun remaining above -12° overnight for several days before and after the summer solstice. During dawn, morning, afternoon and dusk, over half of the mean-adjusted calling rates were negative (Figure 12), indicating that the majority of calling rates (calls/hour) detected during those periods were lower than overall calling rates for the entire day. The nighttime (dark) period was the only period in which the majority of calling rates were higher than the overall calling rate that day. Average mean-adjusted calling rates (asterisks in Figure 12) were between lower and upper quartiles for dawn, morning, and afternoon periods (SE = 0.57, 0.43, and 0.38, respectively), but were skewed above the 75% percentile during dusk and dark periods (SE = 1.14 and 0.67, respectively), indicating that a few days with calls had high calling rates (outliers) during dusk and dark compared to the overall calling rate for that day.

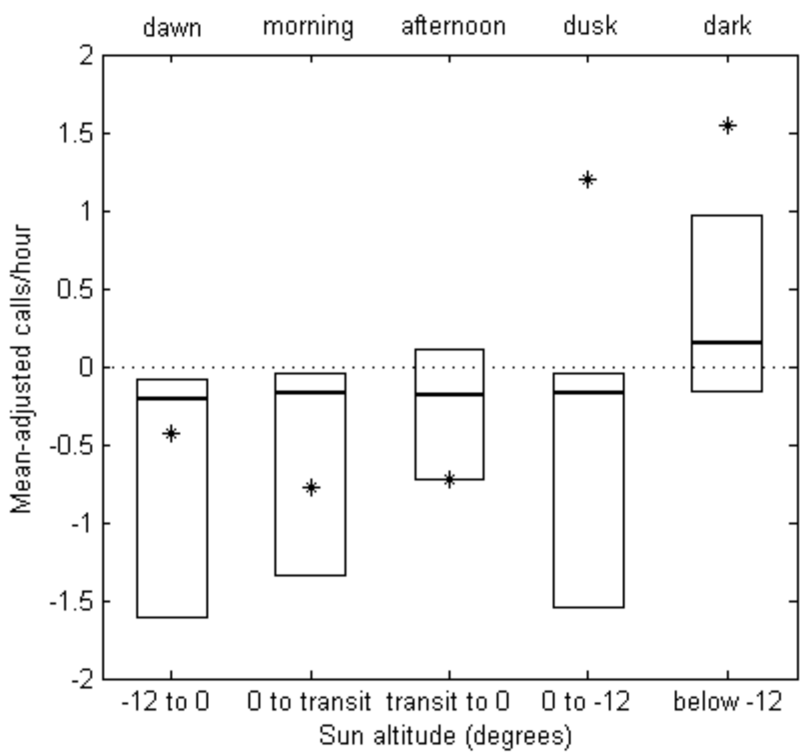


Figure 12. Boxplot of mean-adjusted calls/hour during dawn, morning, afternoon, dusk and dark periods. Lower and upper bounds of boxes represent lower and upper quartiles, respectively; bold lines are median values; asterisks are mean values.

Discussion

Long-term acoustic recordings from 2000-2006 provide a record of right whale presence in the southeast Bering Sea from late May through November in more than one year, and in one year as late as December. The detection of right whale calls as early as May is consistent with recent and historic sighting data, although a few sightings of right whales in the Bering Sea have been reported as early as April (Scarff 1991; Brownell *et al.* 2001). The presence of right whales in the SEBS in November and December has not been previously reported, and this finding underscores the usefulness of acoustic monitoring during times of year when visual search effort is typically not conducted. In addition, right whale calls were recorded at site BSM-4 on several days in October through December 2005 and at site MM4 (~1600 m depth south of Pribilof Is.) on one day in June 2005. These sites are outside the current critical habitat boundary for right whales in the Bering Sea and may represent important portions of their habitat that warrant further acoustic monitoring and visual search effort. Although we did not detect any right whale calls in 5 months of recording in 2003 near Kodiak Island, right whales have been visually and acoustically detected there during other efforts (Waite *et al*. 2003; Mellinger *et al*. 2004; Munger unpub. data) and right whale research effort should also be continued in this region.

Fewer or no right whale call detections on some recorders may be due in part to differences in detection range related to acoustic propagation. At range, R, greater than water depth, acoustic propagation may be approximated between a cylindrical and spherical spreading model and transmission loss (TL) as $20\log R > TL > 10\log R$, whereas for R less than water depth, sounds spread spherically and $TL \approx 20\log R$ (Clay and Medwin, 1977). Right whale calls may be more likely to be detected on the southeast Bering Sea shelf (depth < 100 m) than on deeper instruments (depth >1500 m), because this region is relatively flat and shallow for hundreds of kilometers, providing an acoustic waveguide that channels right whale calls and other low-frequency sounds for long distances (Wiggins *et al*. 2004). Right whale calls were routinely detected at ranges of 20 km on sonobuoys in a 1999 SEBS survey (McDonald and Moore 2002) and have been received on ARPs at ranges up to 60 km on the SEBS shelf (Wiggins *et al*. 2004) and at similar or greater ranges on sonobuoys deployed during vessel-based surveys in the SEBS in 2002 and 2004 (Munger unpub. data). We estimate the average detection range of 'good' right whale calls for SEBS middle-shelf hydrophones at up to 50 km; at times of low ambient noise this range may increase.

The low numbers of detected right whale calls and episodic occurrence of days with calls in this study reflect the low population size for eastern North Pacific right whales. We detected only hundreds of North Pacific right whale calls in each year of this study, whereas tens to hundreds of thousands of calls were recorded throughout a single migration season for bowhead whales in the Arctic (Clark, 1996), blue and fin whales in the Antarctic (Sirovic *et al*. 2004), and blue whales offshore California (Wiggins et al., 2005). These latter populations number in the thousands of whales, compared to the probable population size of fewer than 100 eastern North Pacific right whales.
The highest right whale calling rates (calls/day) were on SEBS middle-shelf instruments during August, September and December, and may be due to an increase in the total

number of calling whales within range or an increase in call production rate by individuals, or both. In a 1999 study in the North Atlantic, right whale sound production rates were positively correlated with the number of right whales per aggregation (Matthews *et al*. 2001). If this is true of North Pacific right whales, our recordings suggest that they may be present in smaller aggregations early in the season, form larger aggregations in late summer, and may occur in large aggregations (although for short time periods) late in the year, when they presumably begin migrating off the SEBS shelf. However, calling rates are also likely to be related to behavior, group composition, and other factors. Our call counts are based primarily on upswept calls, which comprise > 80% of North Pacific right whale calls and are the most common right whale call type across right whale species. These calls are thought to function as contact calls in southern right whales (Clark, 1983). Other call types such as 'gunshot', 'down', 'constant', 'high', or 'pulsive' calls, or blows and slaps (Clark, 1982; Parks et al., 2005) were associated with relatively more complex social interactions such as mating displays or aggression in southern and North Atlantic right whales (*E. australis* and *E. glacialis*, respectively), and the relationship between calling rates and behavior, group size, composition, and activity level was correspondingly more complex as well (Clark, 1983; Matthews et al., 2001 ; Parks and Tyack, 2005).

Right whale calling on the SEBS shelf instruments is episodic, suggesting that they are traveling in and out of recording range or may be silent for days to weeks. Silent intervals between days with calls ranged from 2 to 49 days during continuous recording over the right whale 'season', and up to six months from late fall through winter and early spring. In previous studies when right whales were known to be within recording range, silent intervals between right whale calling bouts were up to several hours in duration (McDonald and Moore 2002; Munger unpub. data); thus we presume that silences of at least 2-3 days indicate that right whales were not present within recording range. In May through July, right whale calls were detected on up to 3 consecutive days at most, suggesting that the whales travel occasionally through the SEBS middle-shelf study area during late spring/early summer but do not remain there for long periods. The greatest numbers of days with right whales were in July through October, and longest consecutive number of right whale calling days (3-5 days) were in September-October, suggesting that right whales travel through most frequently and remain in this area longer in late summer and early fall.

Right whale calling rates showed a minimum during daylight hours and a maximum during dark nighttime hours (Figure 12), suggesting that individual whales call more frequently at night, or that more individuals call at night. Either possibility implies a diel cycle to right whale acoustic behavior in the SEBS. Calling rates in North Atlantic and southern right whales also increase at night (Matthews *et al*. 2001; Clark 1983); and diel calling patterns have been reported for other baleen whale species as well (Au et al., 2000; Wiggins et al., 2005). One potential explanation for right whale diel calling behavior is that they may feed on vertically-migrating copepods, their primary prey, during the day when prey are concentrated at depth (*e.g.*, Baumgartner et al., 2003) and are less likely to produce calls while foraging at depth. An alternative hypothesis is that right whale calling rates are related to behavioral displays or interaction that includes visual cues, and higher calling rates at night may be a reallocation of display effort when visual cues are ineffective.

Conclusions

Based on North Pacific right whale call patterns, we hypothesize that the SEBS middle-shelf is an important habitat for right whales from May through December, and that right whales pass through the SEBS middle-shelf study area most frequently and remain for longer durations in July-October. We also provide evidence that right whales in the Bering Sea are occasionally present in deeper water along the shelf break/slope. During the long periods of silence (days to weeks) between right whale calling episodes, we hypothesize that right whales are traveling throughout the southeast Bering Sea, including parts of the middle and outer shelf outside of recording range, and in deeper water over the shelf break, where right whales were historically abundant. High right whale calling rates on the SEBS middle-shelf in August, September, and December may indicate larger right whale aggregations. Calling behavior on daily timescales may also be related to other behaviors such as foraging, traveling, and social interaction.

Further study is needed to understand the behavioral context of North Pacific right whale calls in order to relate call types and calling rates to abundance, behavior, and habitat use, such that we understand what proportion of the population we can detect acoustically and under which circumstances. Continued North Pacific right whale research effort using a combination of techniques (*e.g*. acoustic monitoring and visual search effort, satellite telemetry, photographic and genetic identification) is essential in order to better understand and predict the spatial and temporal distribution of these critically endangered large whales, which in turn may inform conservation efforts such as seasonal or dynamic habitat protection and vessel operating regulations. Ongoing research effort should be conducted in known, recent right whale habitats as well as to explore for right whale presence in historically important regions and outside of currently designated critical habitat boundaries.

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Appendix 1: Presentations and Publications

Abstracts:

Munger, L.M., M. McDonald, S. Moore, S. Wiggins, D.K. Mellinger, and J. Hildebrand. North Pacific right whales: long-term acoustic detection and localization in the Bering Sea. Oral presentation; abstract *in* Workshop on Detection and Localization of Marine Mammals Using Passive Acoustics, Halifax, Nova Scotia, Canada, 19-21 November 2003.

Munger, L.M. Tracking critically endangered North Pacific right whales (Eubalaena japonica) in Alaskan waters using passive acoustics. Abstract *in* Marine Science in Alaska: 2005 Symposium, Anchorage, AK, 24-26 January 2005.

Munger, L., J. Hildebrand, S. Wiggins and S. Moore. Passive acoustic research on endangered North Pacific right whales and fin whales in Alaskan waters. Poster; abstract *in* GLOBEC symposium: Climate Variability and Sub-Arctic Marine Ecosystems, Victoria, B.C., Canada, 16-20 May 2005.

Munger, L.M., A. Sauter, S. Wiggins, J. Hildebrand, S. Moore, P. Wade, S. Rankin, R. LeDuc, and J. Barlow. Passive acoustic research on North Pacific right whales (*Eubalaena japonica*) in Alaskan waters. Poster; abstract *in* 16th Biennial Conference on the Biology of Marine Mammals, San Diego, CA, 16-20 December 2005.

Munger, L.M., A. Sauter, S. Wiggins, J. Hildebrand, S. Moore, P. Wade, S. Rankin, R. LeDuc, and J. Barlow. Passive acoustic research on North Pacific right whales (*Eubalaena japonica*) in Alaskan waters. Poster; abstract *in* Marine Science in Alaska: 2006 Symposium, Anchorage, AK, 22-25 January 2006.

Publications:

Munger, L.M., S.M. Wiggins, S.E. Moore, and J.A. Hildebrand. North Pacific right whale (*Eubalaena japonica*) seasonal and diel calling patterns from long-term acoustic recordings in the southeastern Bering Sea, 2000-2006. *submitted to*: Proc. R. Soc. B (July 2007).