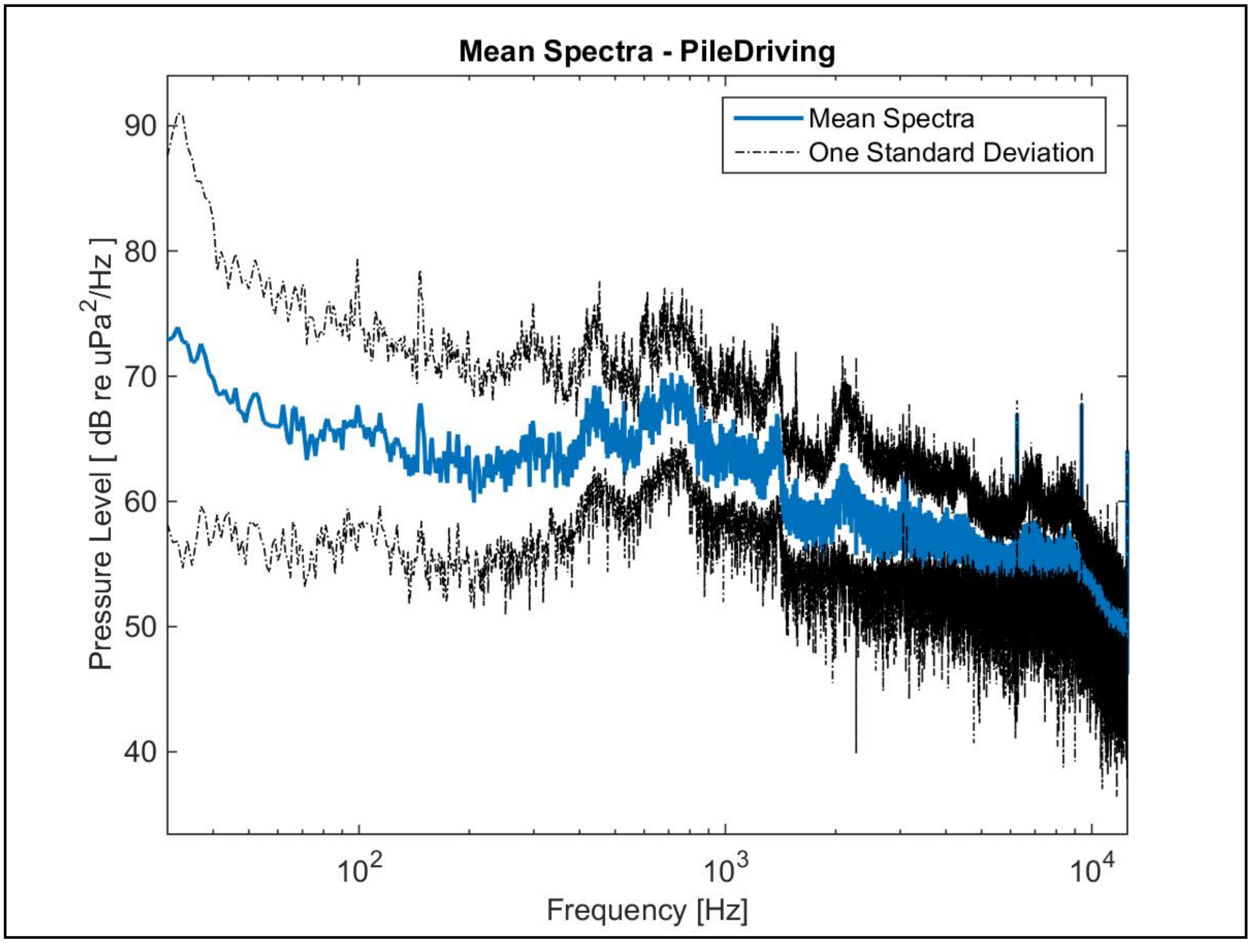
Final Wildlife Research Report ADF&G/DWC/WRR–2016–4

Anthropogenic Noise in Cook Inlet Beluga Habitat: Sources, Acoustic Characteristics, and Frequency of Occurrence

Manuel Castellote, Bruce Thayre, Michael Mahoney, Jeffrey Mondragon, Christine Schmale, and Robert J. Small



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Alaska Department of Fish and Game Division of Wildlife Conservation

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This Wildlife Research Report was reviewed and approved for publication by Robert J. Small, Marine Mammals Program Coordinator for the Division of Wildlife Conservation.

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Note: This report was originally provided as a final report on the project to NOAA Fisheries.

Cover Image: Averaged spectrum level and standard deviation for pile driving strikes recorded off Fire Island in August 2009. The spectrum level represents the sound intensity of the recorded signal at different frequencies. Pile driving was detected in different locations, some very distant from the source at the Port of Anchorage, suggesting that sound propagation for this source is particularly complex in Cook Inlet.

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1. SUMMARY

A subsample (8756 hours) of the acoustic recordings collected by the CIBA (Cook Inlet Beluga Acoustics) research program in Cook Inlet, Alaska, from July 2008 to May 2013, were analyzed to describe anthropogenic sources of underwater noise, acoustic characteristics, and frequency of occurrence and evaluate the potential for acoustic impact to Cook Inlet belugas. A total of 13 sources of noise were identified: Commercial ship, dredging, helicopter, jet aircraft (commercial or military non-fighter), jet aircraft (military fighter), outboard engine (small skiffs, rafts), pile driving, propeller aircraft, sub-bottom profiler, unclassified machinery (continuous mechanical sound; e.g., engine), unidentified 'clank or bang" (impulsive mechanical sound; e.g., barge dumping), unidentified (unclassifiable anthropogenic sound), unknown up- or down-sweep (modulated tone of mechanical origin; e.g., hydraulics). Several noise metrics were calculated (SPL in dB rms, SEL, dB 0-peak, power spectral density, 1/3 octave bands, and duration) and results were compared across noise sources, months and locations. A total of 6263 anthropogenic acoustic events were detected and classified, which had a total duration of 1025 hours and represented 11.7 % of the sound recordings analyzed. Anthropogenic noise was present in every single day sampled. Natural background noise in quietest days was in the range 95-99 dB rms, much lower than previously reported. Anthropogenic sources of noise were detected well in excess of 120 dB rms in many occasions, locations and months. Cairn Point was the loudest location and Eagle River was the quietest location. Lower Inlet locations were noisier in summer; however upper Inlet locations remained noisy year-round. Based on received levels and spatial and temporal prevalence, anthropogenic noise in Cook Inlet has the potential to mask beluga communication and hearing in most of the locations and periods sampled for this study. The potential communication and echolocation range reduction for Cook Inlet belugas by anthropogenic noise is very considerable.

2. INTRODUCTION

Because the Cook Inlet beluga population is endangered and their critical habitat is encroached by diverse human activities, in-water anthropogenic noise is considered a potential threat for their survival (NMFS 2008). The diversity and occurrence of anthropogenic noise sources in Cook Inlet have not yet been described and acoustically characterized in the context of their effects on Cook Inlet beluga (CIB) hearing and communication. Four different acoustic studies collected noise data and reported sound pressure level measurements, suggesting that background noise in Cook Inlet may often exceed 120 dB re 1 µPa (Blackwell and Greene 2002, Heenehan 2009, Širović and Kendall 2009, HDR 2011). However, diverse anthropogenic noise sources are well above this threshold and have the potential to affect CIB.

The Cook Inlet Beluga Acoustics (CIBA) research program began in 2009 and collected acoustic data over four years at 10 different locations in upper, mid, and lower Cook Inlet; these recordings represent the most complete set of sound recordings collected in Cook Inlet currently available. The primary objective of the CIBA research program was to detect beluga whales, whereas documenting anthropogenic noise sources was a secondary objective. Thus, acoustic instruments were programmed to obtain data to describe the seasonal distribution of CIB; the instruments would have been programmed differently for noise (see below). As such, although the noise recordings are not ideal, they can be used to document the presence of anthropogenic noise sources, their acoustic characteristics, and their frequency of occurrence in Cook Inlet. Specifically, this report addressed the following objectives with these recordings:

1. Describe the detailed acoustic characteristics of the different anthropogenic noise sources detected from a selection of the available recordings, with emphasis on the potential impact on CIB hearing and communication.
2. Describe the frequency of occurrence of these different types of noises in Cook Inlet beluga whale habitat.
3. Quantify the potential impact on CIB based on the current NOAA regulatory acoustic thresholds.

3. METHODOLOGY

3.1 Selection of data sets for anthropogenic noise analysis

The sound recording methods used by the CIBA research program allow accurate measurement of received noise levels because the recording system is calibrated (Lammers et al. 2013). However, the measurable range of noise levels is limited because these recording methods aimed to maximize detection of faint beluga signals, compromising the measurement of loud anthropogenic noises; see Methodological Limitation #2 below. Furthermore, moorings were designed to survive the harsh conditions of mid and upper Cook Inlet, rather than avoid self-noise generated by strong currents and debris hitting the mooring and acoustic instruments; such noise compromised the description of anthropogenic noise events occurring during high current periods.

The locations where acoustic instruments were deployed by the CIBA research program are shown in figure 1 and listed in Table 1, along with the number of days data were obtained at each location. These locations were selected based on the current and historical distribution of Cook Inlet belugas. A subset of these data was selected, on a monthly basis, to provide a representation of the diversity, spatial and temporal occurrence of anthropogenic noise occurring in Cook Inlet beluga critical habitat (Table 1). The selection was based on the amount and diversity of anthropogenic noise

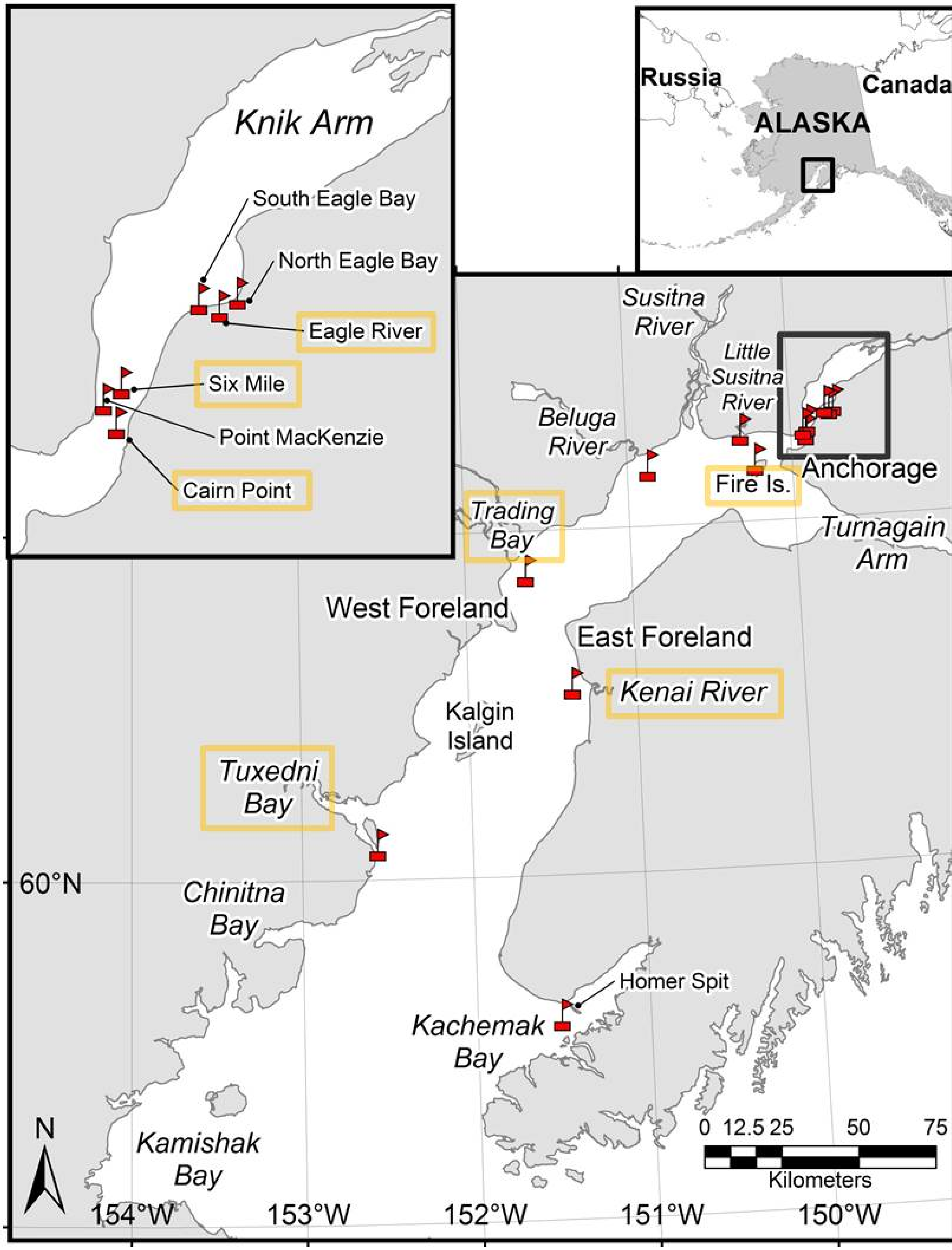

Figure 1: Acoustic mooring locations from CIBA research program in Cook Inlet, Alaska, deployed from July 2008 to May 2013. Data from mooring locations boxed in yellow were selected for this study.

Table 1: List of acoustic moorings and periods of deployment in Cook Inlet, Alaska, July 2008-May 2013, as part of the CIBA research program and data selected for the anthropogenic noise study. The start and end date for each location represents the date when the first mooring was deployed and the last mooring was recovered, respectively; there were periods in which moorings were not deployed at each location due to refurbishing equipment, loss of moorings, etc. The number of days for which acoustic monitoring took place (i.e., Effort) by the CPOD and EAR for each location is listed. For each location, the month, year, and number of days of recordings (EAR only) that were analyzed for noise events is listed, along with the percentage of total days of effort that were analyzed for noise events.

Effort					**Noise Analysis**		
Location	**Start Date**	**End Date**	**CPOD Days**	**EAR Days**	**Month, Year (#Days)**	**Total Days**	**% of Effort**
Beluga River	4 June2009	9 March 2012	821	833	-	-	-
Cairn Point	6 June 2009	5 April 2013	742	697	August 2010 (31) April 2011 (3)	34	4.9
Eagle River	7 July 2009	9 October 2012	298	423	August 2010 (31) September 2010 (28)	59	13.9
Fire Island	23 July 2008	3 May 2011	318	534	August 2009 (23) September 2009 (28)	57	10.7
Homer Spit	1 July 2009	20 April 2012	737	901	-	-	-
Kenai River	1 July 2009	22 April 2012	531	784	April 2012 (21)	21	2.7
Little Susitna River	23 May 2011	27 September 2011	127	127	-	-	-
North Eagle Bay	6 June 2009	18 November 2011	134	197	-	-	-
Point Mackenzie	23 July 2008	16 May 2013	338	378	-	-	-
Six Mile	2 December 2011	21 May 2012	0	171	December 2011 (29) May 2012 (21)	51	29.8
South Eagle Bay	6 June 2009	30 September 2011	153	125	-	-	-
Trading Bay	30 June 2009	22 April 2012	302	590	February 2012 (29) March 2012 (31) April 2012 (21)	52	8.8
Tuxedni Bay	2 July 2009	21 April 2012	735	776	March 2012 (31)	31	4.0

found in the recordings when the data was analyzed for odontocete signal detections as part of the CIBA objectives. Specifically, recordings were selected from moorings (1) deployed near Anchorage (Cairn Point, Six Mile, and Fire Island), where anthropogenic activities are most concentrated and beluga presence is important; (2) at the mouth of Eagle River in Knik Arm, near military activities from the adjacent Joint Base Elmendorf Richardson (JBER) where belugas feed on salmon runs in summer and fall; and (3) in the mid and lower inlet, areas where belugas may occur more frequently during winter and spring, overlapping with oil and gas exploitation and commercial shipping. Overall, 14 months of recordings from 7 mooring locations across all seasons during 2009-2012 were analyzed (Table 1). Selected data covered the months of February, March, April, May, July, August, September, and December. Areas that were monitored by the CIBA research program but had little or anthropogenic influence where not included in this study (e.g. Beluga River), similarly, areas where anthropogenic activities were abundant but belugas were absent were not included neither (e.g. Homer). Because this study was not aimed to describe the natural ambient noise (without anthropogenic influence) of Cook Inlet, or the noise in areas were belugas have not been detected during the CIBA study, the selection criteria allowed maximizing the analysis effort on data from periods and locations with a strong overlap in beluga and anthropogenic noise occurrence.

3.2 Acoustic recordings

Ecological Acoustic Recorders (EARs) were deployed between 2008 and 2013 at sites throughout Cook Inlet as part of the CIBA research program, with custom designed low-profile moorings to resist the harsh conditions of the Inlet (Lammers et al. 2013). Acoustic data were sampled at a rate of 25 kHz, which resulted in recordings obtained from 0.01 to 12.5 kHz. A 10% duty cycle was used to prolong battery life, which resulted in a recording file of 30-seconds in duration every five minutes (i.e., 300 seconds) throughout the 24 h cycle.

3.3 Detection and classification of anthropogenic noise events

Raw data from Binary EAR files were converted into ewav files for analysis; these files are similar to the standard sound wave (.wav) digital audio format. Acoustic analysis of ewav files was conducted using the MATLAB-based program Triton (Scripps Institution of Oceanography, La Jolla, CA) to view long-term spectrograms of ewav files, play back recorded sounds, and detect and classify anthropogenic noise events. Acoustic data is averaged over several seconds to allow generating long-term spectrograms, but when measurements are done over specific selections, the data is processed from uncompressed, non-averaged raw files. We identified the following 13 classes of anthropogenic noise events (listed alphabetically):

1. Commercial Ship
2. Dredging
3. Helicopter
4. Jet Aircraft – Commercial or military non-Fighter[1]
5. Jet Aircraft – Military Fighter
6. Outboard Engine (small skiffs, rafts)
7. Pile Driving (impact hammer method)
8. Propeller Aircraft
9. Sub-bottom profiler

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[1] In the figures, this noise class is labeled "Jet aircraft – military non-fighter" to reduce the length of the legends.

10. Unclassified Machinery (continuous mechanical sound; e.g., engine)
11. Unidentified 'clank or bang" (impulsive mechanical sound; e.g., barge dumping)[2]
12. Unidentified (unclassifiable anthropogenic sound)
13. Unknown up- or down-sweep (modulated tone of mechanical origin; e.g., hydraulics)

Classification of anthropogenic events was made manually by playing and inspecting the spectrogram of each signal. A classification scheme was made with printed spectrograms and ewav clips used as reference for comparison. Only undoubtful events were assigned to known noise source classes, and all doubtful events were classed under the "unidentified" or "unclassified" classes to minimize error. Only noises that were clearly from anthropogenic origin were included in the analysis.

If an event was detected in 2 or more consecutive files, we presumed the signal was sustained throughout the entire 5 minute cycle. Multiple noise events that occurred overlapped and events masked by self-noise, from high current flow noise, were only used to account for their presence, but not for acoustic measurements because discerning acoustic energy from the overlapped events or from the event and the current noise was not possible. However, continuous noise events that were overlapped by impulsive noises were assumed to be originated by the same source and thus were selected for the analysis (e.g. a towed barge could generate both the noise of the tug boat engine and clanking noises from the chains used to tow the barge). C-PODs, an echolocation logger that detects and classifies odontocetes echolocation signals, were also deployed by the CIBA program; however, these instruments do not record sound and thus noise events were obtained only from EAR data.

The 'ship recall log' from the Port of Anchorage (POA) represents information on the temporal presence of a known source of anthropogenic noise, commercial ships, so we compared data from this log with recordings from the Cairn Point mooring in an attempt to reclassify unclassified machinery events as commercial ship noise in data from Cairn Point, Six Mile and Fire Island. The arrival and departure times of commercial vessels was obtained from the POA (pers. comm. S. Ribuffo 2 August 2013) to assess noise events from commercial ship activities. We added 30 minutes prior to arrival times in the log and 30 minutes after departure time in the log to include tugboat operations associated with the commercial vessels. Initially, we included a "tug boat" noise classification, yet distinguishing between noise from tugs and commercial vessels was too challenging, often with complete overlap in occurrence.

3.4 Noise measurements

Hydrophone and EAR gain and frequency responses were corrected for all noise measurements, such that true absolute dB values were obtained; i.e., re to 1µPa unless a different reference is specified.

By definition, noise events are classified as either impulsive or continuous (i.e., non-impulsive), and different measurements are used to distinguish these two temporal classifications. In our analysis, we used the current NOAA definition for impulsive and continuous classification of noise events (NOAA 2013) based on a duration criterion of 1 second (i.e., signals shorter than 1 s are considered impulsive and longer than 1 s are considered continuous). However, in the context of noise impact to belugas, this method does not account for the essential property of impulses: a rapid rise-time to maximum pressure followed by a decay that may include a period of diminishing and oscillating

[2] Clank or bangs were discrete events, but often occurred in series with random intervals.

maximal and minimal pressures. Mammalian hearing is most readily damaged by impulsive sounds with rapid rise-time, high peak pressures, and sustained duration relative to rise-time (explained in detail in Southall et al. 2007). We considered this characteristic as equally important and thus decided to explore modifying the NOAA criteria, incorporating the rise-time property of signals. For impulsive events we modified the duration criterion to take into account events with a rapid rise-time typical of impulsive signals. Specifically, when maximum amplitude was within 0.05 seconds of onset, the duration criterion was increased from the NOAA standard of 1 second to 5 seconds to be considered impulsive (it should be noted that the duration criterion is independent of the duration of the event, for example, an event lasting 2 seconds with maximum amplitude within the first 0.05 seconds will be considered and impulsive event of 2 seconds in duration); of the 566 events classified as impulsive for this study, only 13 (2.3%) were greater than 1 second in duration. These events, even if longer than 1 second, have the potential to generate the same impact as < 1 second impulsive signals to acoustically sensitive marine fauna.

After we classified all noise events as either impulsive or continuous, based on the measurements described above, seven acoustic metrics were calculated using custom written Matlab codes. It should be noted that the applied modification of the current NOAA definition for impulsive and continuous classification of noise events does not affect the way acoustic metrics are calculated or their result in dB values. Metric #7 was calculated only for impulsive events as these pertain only to this type of signals:

1. Sound pressure level (SPL) in Root Mean Square (RMS) (in dB rms): Calculated over the total duration of each event (defined in point 5) and the full band of the recording (0-12.5 kHz). Note: there were negligible differences in dB rms when measured over the full band (0-12.5 kHz) or just over frequencies affected by each noise event, because most events influenced the full recorded range of 0-12.5 kHz. This is the metric used in the current NOAA acoustic guidelines to define acoustic thresholds.

2. Pressure in 1/3 octave band levels (in dB re $\mu Pa^2/Hz$): Corresponds to mean values of the center frequency of 30 frequency bands; results from this metric are presented as a figure. This is the metric used to represent how the mammalian ear integrates acoustic pressure.

3. Sound exposure level (SEL, in dB re $1\mu Pa^2$-s): Defined as rms(SPL) + log(T) where T is the duration of the event, including standby periods when the detection spans consecutive sound files or the interval between consecutive signals if they are generated in a sequence. This metric corresponds to the unweighted SEL_{cum} definition in the proposed reviewed NOAA Acoustic Guidelines..

4. Power spectral density (PSD in dB re $1\mu Pa^2/Hz$): Referred as spectrum in this report, presented in 1 Hz bins with standard deviation.

5. Duration of event: Measured as the difference between the end and start times, including recording stand by periods when events spanned over multiple consecutive files. This metric is also provided as the mean duration and standard deviation for each noise class, including all the events detected in each location and month. For events occurring in sequences (i.e. pile driving, sub-bottom profiler and clank or bang), the duration comprised the time elapsed from the onset of the first detected signal to the last one in the sequence.

6. Threshold bins: For each of the 13 sound classes, all noise events were binned (by percentage) into 4 dB rms threshold bins, following the current NOAA acoustic guidelines (See below in 'Methodological Limitations' for why the upper bins were delineated at 153 dB):

   a. Signals less than 120 dB
   b. Signals greater than or equal to 120, and less than 125 dB
   c. Signals greater than or equal to 125 and less than 153 dB
   d. Signals greater than or equal to 153 dB

7. Pressure in zero-peak: Calculated by dividing events into 0.05 second segments and then finding the segment with maximum pressure. This metric corresponds to the dB_{peak} definition in the proposed reviewed NOAA Acoustic guidelines. This metric is suitable for impulsive signals and is a good replacement for SPL in dB rms because signals of short duration are problematic for dB rms calculation.

3.5 Methodological Limitations

Because the CIBA research program was designed primarily to collect data relevant to the long-term detection of beluga whale signals, and not anthropogenic noise, there are two important limitations that must be acknowledged.

1. Recorder power consumption is a limiting factor to allow long-term recordings. In order to reduce power consumption in a recorder, the two parameters that define the power consumption of any recorder are the speed at which data is recorded that is the sampling rate, which in turn defines the frequency coverage of the recording, and the recording and stand-by period's duration, that is the duty cycle. For all CIBA deployments, because the primary objective was to detect beluga vocalizations rather than documenting anthropogenic noise events, a sampling rate was selected high enough to collect the frequencies where most of the acoustic energy of beluga social calls is centered, that is in the range 0-12.5 kHz. Therefore, the sampling rate selected allowed covering any sound produced up to 12.5 kHz. Any anthropogenic noise generating acoustic energy only above 12.5 kHz would not be detected in our recordings. Although this is a limitation, it is not too problematic because most of the anthropogenic noises have most of the acoustic energy below 12.5 kHz. Only transducer originated noise sources, such as depth/fish sounders, scientific echo sounders and military sonar are able to generate acoustic energy exclusively above 12.5 kHz. From these, only depth sounders are commonly used in Cook Inlet, although these noise sources are always associated to shipping noise, which is detected within the 0-12.5 kHz.

2. The duty cycle (10%) used to obtain months-long deployment durations resulted in sound files of 30 seconds in duration. Thus, noise events longer than 30 seconds or cut by the beginning or ending of the sound file where they were detected were truncated, resulting in all pressure related measurements (i.e. SPL, SEL, peak pressure) being inherently conservative; duration measurements however were only partially truncated because the stand-by interval was accounted when signals lasted more than one consecutive file. Only signals lasting less than 30 seconds and limited by the beginning or ending of the file where they were detected were truncated (i.e. the event started during the stand-by period prior to being detected or ended during the following stand-by period). The total number of events or the total time accounted for each noise class and its reported percentage is obviously underrepresented because any event that fell into the stand-by period could not be detected. Therefore, absolute presence of anthropogenic noise cannot be inferred from our data. For all CIBA deployments, the recording

gain was set on the EARs to enhance the detection of faint, far away beluga vocalizations. However, this gain setting compromises the recording quality of loud signals as they become distorted by too much gain, and no longer useful to reliably provide any sound pressure based characteristic. Therefore, signals louder than 153 dB (peak to peak) would reach the limit of the EAR system to accurately record the signal. When exceeded, the recorded waveform reflecting the acoustic properties of the received signal becomes clipped (i.e. the upper and lower limits of the waveform are cut). Clipped signals are still recorded and can be identified, yet any measurement of its loudness properties or contribution at different frequencies becomes biased. This limitation impedes an accurate assessment of signals with the highest dB levels. The proportion of events for each noise class, mooring location, and period that were in the greater than 153 dB bin (i.e., the methodological limit of this study) is suggestive of the probability of this noise class reaching higher noise levels. As a survey of the density and distribution of noise events, clipped events are included with non-clipped events in the results. Because of this important limitation, overall levels should be considered lower than what was present, and spectral character may not be accurate if the number of clipped signals outnumbers non-clipped.

4. RESULTS AND DISCUSSION

From the 8756 hours of data selected for this analysis, we obtained a total of 6263 anthropogenic acoustic events, which had a total duration of 1025 hours and represented 11.7 % of the sound recordings analyzed. In total, we identified 13 sources of anthropogenic noise, which we will refer to as noise classes in the rest of this report. There is no doubt that many other noise classes are present in Cook Inlet, but we did not identify them in our analysis or they were not present within the selected sampling periods and locations. Also, noise classes that we categorized as unidentified might include more than one noise source; additional data (e.g. industry operation schedules) or additional research (e.g. concurrent visual observations and acoustic recordings) is required to determine if additional noise sources are included in our sound recordings. Some unidentified machinery noise was very stereotypic (i.e. easily distinguishable with unique acoustic structure) and repeatedly detected in some locations; we have assigned subjective noise classes to these cases (e.g. unknown up or down sweep). Future efforts could help identify these noise classes, such as interviews or meetings with operators used to the noises generated by their activities; e.g. tug boat pilots, dredge operators, etc.

Some noise classes, in particular pile driving, sub-bottom profiler and clank or bang, generated long sequences of discrete events. Because these long sequences could contain several thousands discrete signals, total duration (time interval from the first to the last detected signal) was logged but not the total number of discrete signals. This methodological approach must be considered when comparing the number of events for each noise class detected in each location and month, because the number of events will not reflect the number of discrete signals detected. However, SEL values can be used to compare or evaluate the amount of acoustic energy received over the duration of the events, which reflects both the received levels of the discrete signals as well as the duration of the intervals between signals. The duration and interval between consecutive signals for both pile driving and sub-bottom profiler were measured in a small subsample of all the detections (100 first intervals of first and last sequence) and is presented in table 2. We considered this subsample to be representative of the variability. Little variability in both duration of signal and intervals between signals for both noise sources was observed visually during the analysis process. Signal duration and signal interval was not attempted to be measured for the clank or bang noise class because this presented an extremely wide variability. Some clanks or bangs signals appeared to be a cluster of multiple discrete impulsive signals, other times this noise was received as a rapid succession of multiple signals that could be consequence of a sound propagation effect (e.g. multipath arrival) or a rapid iteration of the same type of percussive sound.

Table 2: Signal duration and interval duration between consecutive signals for sequences of pile driving and sub-bottom profiler noise.

Noise source	Mean Signal duration (S.D.) Measured as start to end of first arrival (in case of multipath arrivals)	Interval duration (S.D.) Measured as end time to start time of first arrival (in case of multipath arrivals)
Pile driver	0.12 s (0.05)	0.6 s (0.39)
Sub-bottom profiler	0.042 s (0.015)	0.2 s (0.01)

Table 3: Number of anthropogenic noise events, grouped by noise class, detected by month in the 7 locations sampled in Cook Inlet, Alaska, during the period July 2008-May 2013. Note that not all the months were entirely sampled; the column # of events/day indicates how many events were detected per day.

Location	**Month**	**Noise Class**	**# of events**	**#of events/day**
Eagle River	August (# days=31)	Jet Aircraft-Non-Fighter	1	
		Jet Aircraft-Military Fighter	30	
		Outboard Engine	21	
		Propeller Aircraft	2	
		Unidentified	1	
		Monthly Total	**55**	**1.8**
	September (# days =28)	Jet Aircraft-Military Fighter	38	
		Outboard Engine	7	
		Unidentified	4	
		Monthly Total	**49**	**1.8**
Six Mile	May (# days=21)	Jet Aircraft-Non-Fighter	4	
		Commercial Ship	42	
		Dredging	27	
		Jet Aircraft-Military Fighter	4	
		Pile Driving	22*	
		Unclassed Machinery	5	
		Unidentified Clank Bang	11	
		Monthly Total	**114**	**5.4**
	December (# days=29)	Jet Aircraft-Non-Fighter	22	
		Commercial Ship	22	
		Helicopter	7	
		Jet Aircraft-Military Fighter	1	

[*] These values reflect the number of sequences detected but not the number of events within each sequence.

		Unclassed Machinery	73	
		Unidentified	2	
		Unidentified Clank Bang	4	
		Monthly Total	**131**	**4.5**
Cairn Point	April (# days=3)	Commercial Ship	5	
		Dredging	42	
		Outboard Engine	4	
		Propeller Aircraft	3	
		Unclassed Machinery	1	
		Unidentified	1	
		Unidentified Clank Bang	2	
		Monthly Total	**58**	**19.3**
	August (# days=31)	Jet Aircraft-Non-Fighter	7	
		Commercial Ship	1832	
		Dredging	36	
		Jet Aircraft-Military Fighter	13	
		Unclassed Machinery	412	
		Unidentified	109	
		Unidentified Clank Bang	1884	
		Unknown Up or Down Sweep	464	
		Monthly Total	**4757**	**153.5**
Fire Island	August (# days=23)	Jet Aircraft-Non-Fighter	11	
		Commercial Ship	155	
		Jet Aircraft-Military Fighter	3	
		Outboard Engine	10	
		Pile Driving	24*	
		Sub-bottom Profiler	1*	
		Unclassed Machinery	26	
		Unidentified	32	
		Unidentified Clank Bang	14	
		Monthly Total	**276**	**12**
	September (# days=28)	Jet Aircraft-Non-Fighter	35	
		Commercial Ship	123	
		Jet Aircraft-Military Fighter	1	
		Propeller Aircraft	2	
		Unclassed Machinery	3	
		Unidentified	17	
		Monthly Total	**181**	**6.5**
Trading Bay	February (# days=29)	Commercial Ship	94	
		Unclassed Machinery	23	
		Monthly Total	**117**	**4**
	March (# days=31)	Commercial Ship	88	
		Unclassed Machinery	115	
		Unidentified Clank Bang	1	
		Monthly Total	**204**	**6.6**

* These values reflect the number of sequences detected but not the number of events within each sequence.

	April (# days=21)	Commercial Ship	62	
		Unclassed Machinery	144	
		Unidentified	2	
		Monthly Total	**208**	**10**
Kenai	April (# days=21)	Commercial Ship	70	
		Jet Aircraft-Non-Fighter	2	
		Outboard Engine	6	
		Pile Driving	1*	
		Propeller Aircraft	1	
		Sub-bottom Profiler	1*	
		Unclassed Machinery	3	
		Unidentified	1	
		Monthly Total	**85**	**4**
Tuxedni	March (# days=31)	Commercial Ship	22	
		Propeller Aircraft	1	
		Unclassed Machinery	1	
		Unidentified	3	
		Unidentified Clank Bang	1	
		Monthly Total	**28**	**1**

4.1 Amount of clipping

Quantifying the amount of clipping which occurred, and for which specific noise classes, is important because presence and duration are the only non-biased noise related measurements possible for clipped events; i.e.. all other noise related measurements in clipped sound data are biased. Although clipping occurred in many noise class events, only 8 events were clipped at lower inlet locations, whereas over 5600 events were clipped at upper inlet locations. Further, the great majority (90.5%) of clipped events in the upper inlet occurred in August (9.5% in the other 4 months) and a large majority was in only two noise classes (Fig. 2).

For lower inlet locations, only 8 events were clipped, all for commercial ship noise, 6 in Trading Bay in March and April, and 2 in Kenai in April; none were clipped in February. Among upper inlet locations, 72.8% of the 5621 total clipped events were in either commercial ship events or unidentified clank bang events, which could be related to shipping; e.g., tug boat operations or barge operations. About one-third of all events for each of these two noise classes were clipped: 775 of 2515 (30.8%) for commercial ship noise and 638 of 1917 (33.3%) for unidentified clank bang. Importantly, the reported noise measurements (SPL, SEL, etc.) for these two noise classes will underestimate the real noise field generated because many of the loudest events (see Fig. 8 and 9) exceeded the clipping level, and thus were excluded from the sound pressure analysis; this underestimation will be of similar proportion in both noise classes because the percentage of affected events was similar. Clipping of commercial ship events might occur when ships pass very close to the acoustic mooring, and predominance of clipped in August could be related to a change in the shipping procedures from summer to winter (e.g. reduced speed in winter due to ice, change of used course) or the acoustic propagation conditions among months we analyzed.

[*] These values reflect the number of sequences detected but not the number of events within each sequence.

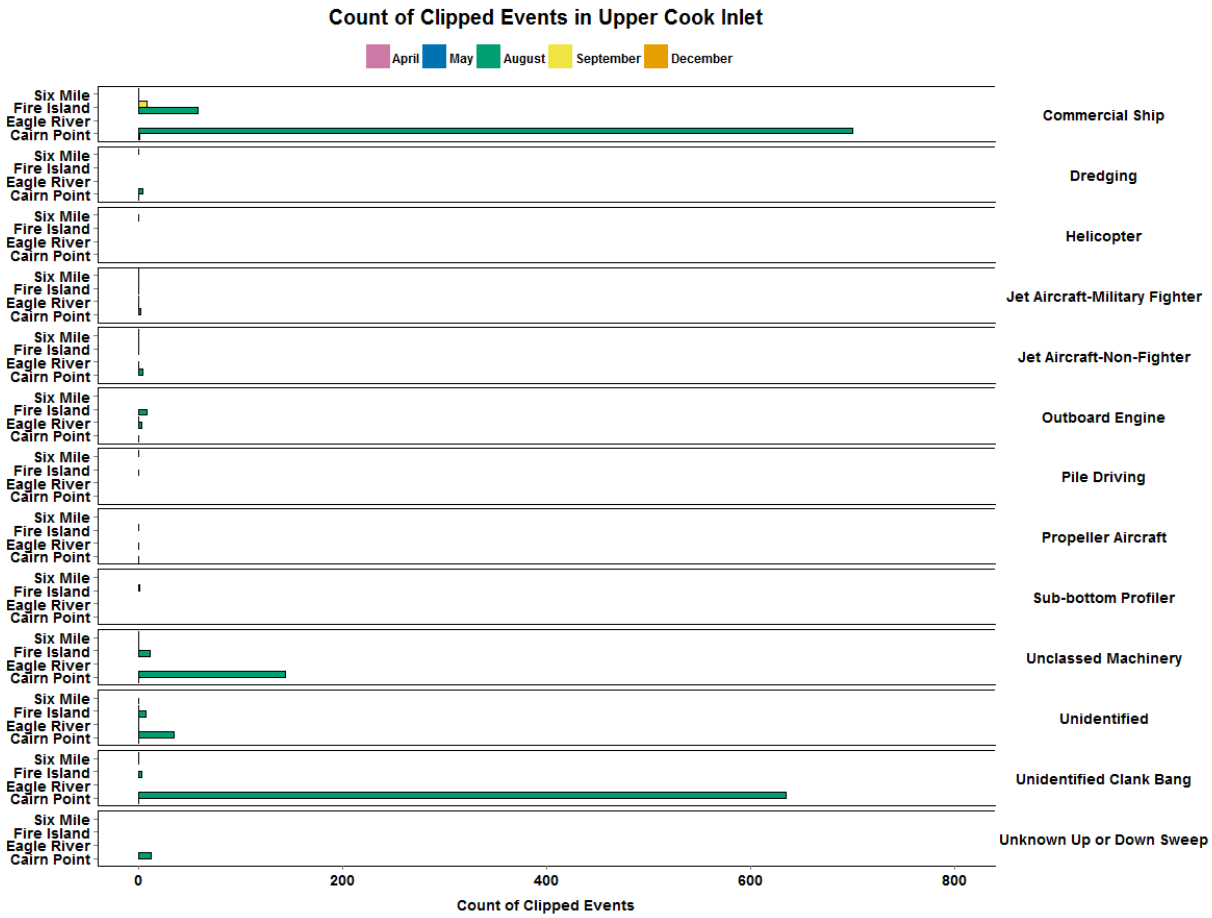


Figure 2: Number of clipped acoustic events by noise class, location and month for the 4 locations sampled in the upper Inlet (Cairn Point, Eagle River, Fire Island and Six Mile).

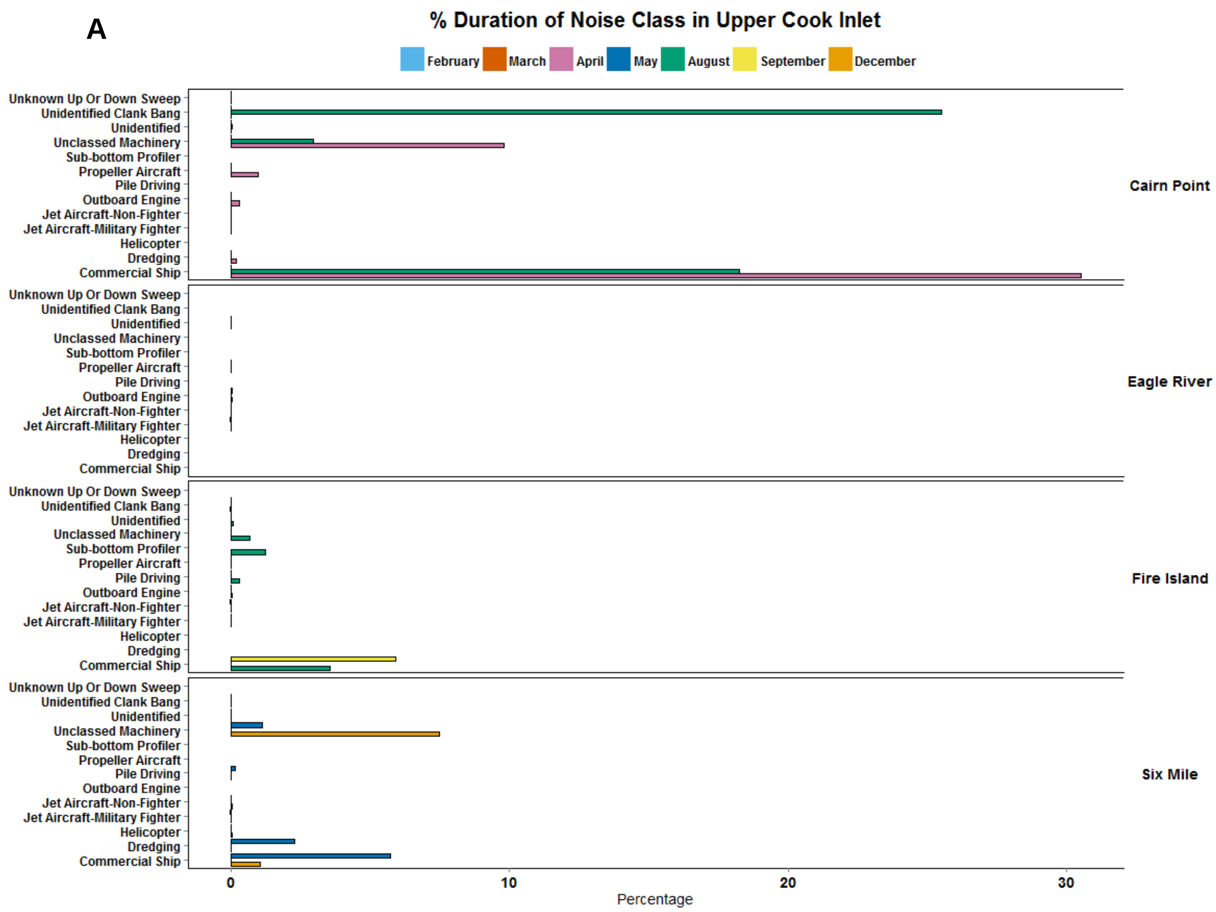
4.2 Presence of anthropogenic noise by location and month

This section provides an overview of the amount of time anthropogenic noise was detected by site, month, and noise class. The two sets of figures included here are a good graphical representation to compare soundscapes across sites, including noise source diversity (i.e., how many noise classes were detected), the average duration of the events for each noise class (i.e. how long these events lasted when detected), and how often these noise classes were recorded (i.e. what % of the recording for each site contained noise of each class). Noise classes and their acoustic properties are discussed further below (sections 3b and 4); here, we only show their presence in a temporal domain.

4.2.a Percent duration

The next two figures are intended to provide a sense of the temporal persistence of each noise class by location and month. The percent duration is calculated from the total amount of recorded time at each site and month; thus, providing a sense of how regularly each noise class was detected. Note that percent duration of signals generated in sequences (e.g. pile driving) account for the total duration of the sequence and do not represent the percent duration of each discrete signal, as explained in section 3.4 and indicated in the second paragraph of section 4.

Cairn Point includes the highest percentages and diversity of noise classes due to the activities in and around the POA; i.e., shipping, tug boat operations, dredging, and other shore industrial activities. Eagle River was the quietest of all sampled locations. Whereas commercial ship noise predominates the lower Inlet, more diversity is observed in the upper Inlet, with noise from different industrial activities. An exception is Trading Bay, where unidentified and unclassed machinery noise is persistent, possibly related to the presence of multiple oil and gas platforms and related operations.



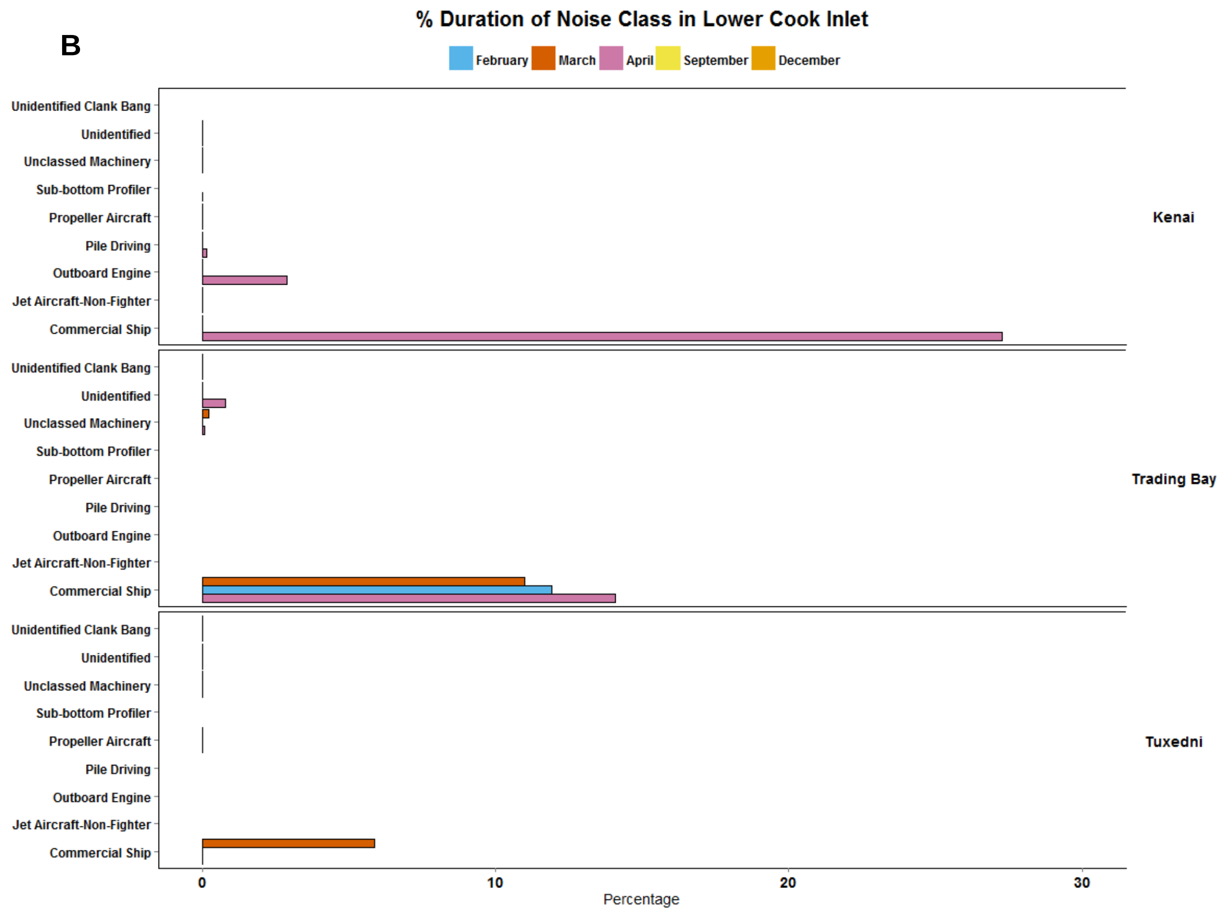
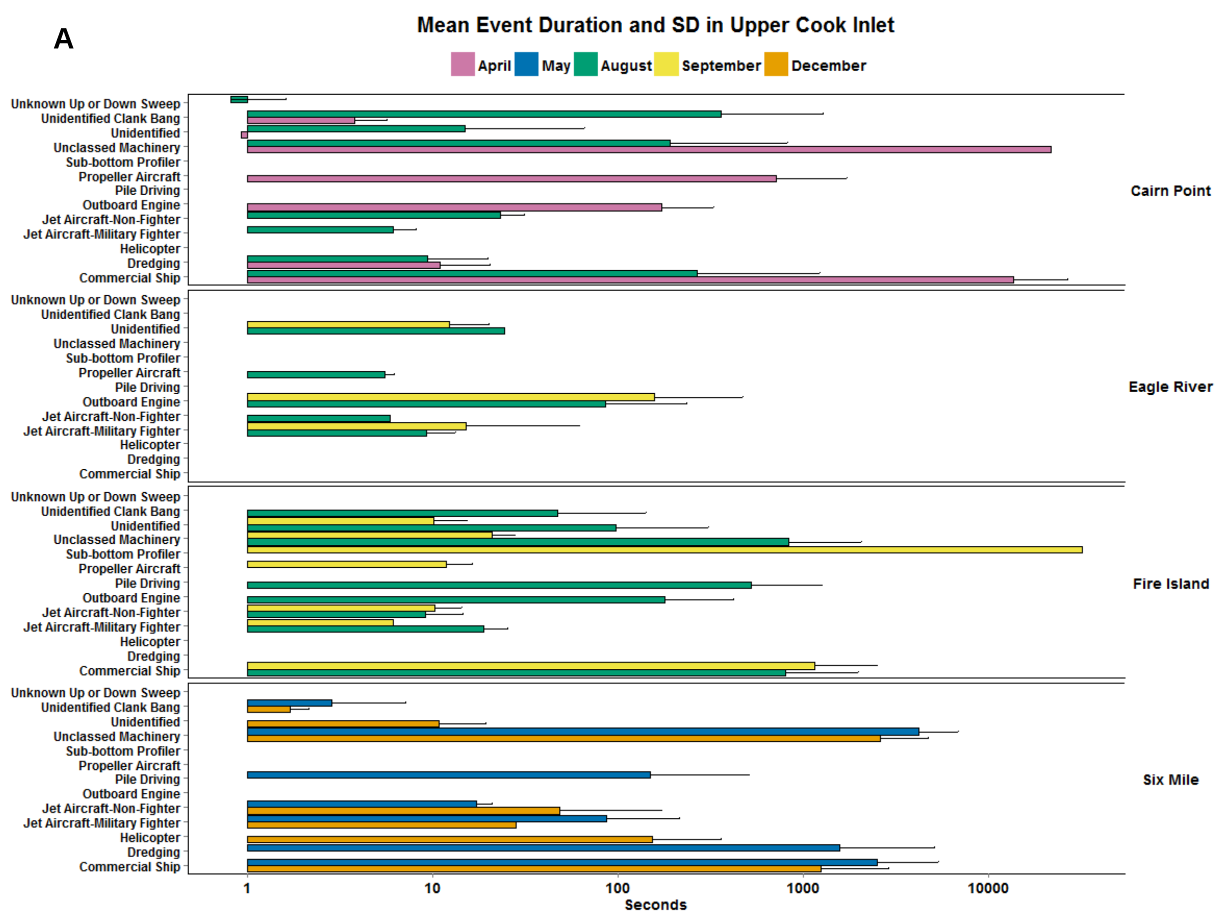


Figure 3: Percent duration of all the acoustic events detected at each site by month and noise class. Upper panel (A) includes the 4 locations sampled in the Upper Inlet (Cairn Point, Eagle River, Fire Island and Six Mile), and the lower panel (B) includes the 3 locations sampled in the Lower Inlet (Kenai, Trading Bay and Tuxedni). Percentages are calculated from the total amount of recording time for each month and location. Note that up to three months were selected per location (see table 1), therefore, not all months were sampled in all locations.

4.2.b Duration of events

The next two figures represent an overall view of the average duration of the anthropogenic noise events detected by location and month, which allows comparisons of event durations among noise classes and across months and locations. Note that duration of signals generated in sequences (e.g. pile driving) account for the total duration of the sequence (from first to last signal in a sequence) and do not represent the duration of each discrete signal, as explained in section 3.4 and indicated in the second paragraph of section 4.

Most of the noise classes identified fall under the category of continuous signals (longer than 1 second in duration). However for pile driving, sub-bottom profiler and most of the clank or bang events described here, although occurring in long sequences, discrete signals were often shorter than 1 second, or less than 5 seconds but with a rapid rise-time and thus classified as impulsive. Unknown up or down sweeps were also often classified as impulsive because their duration was less than 1 second. Fig. 4 shows both the mean duration and SD, providing an overview of which noise classes are considered continuous (> 1 second) or impulsive (<1 second or 1-5 seconds with rapid rise-time).



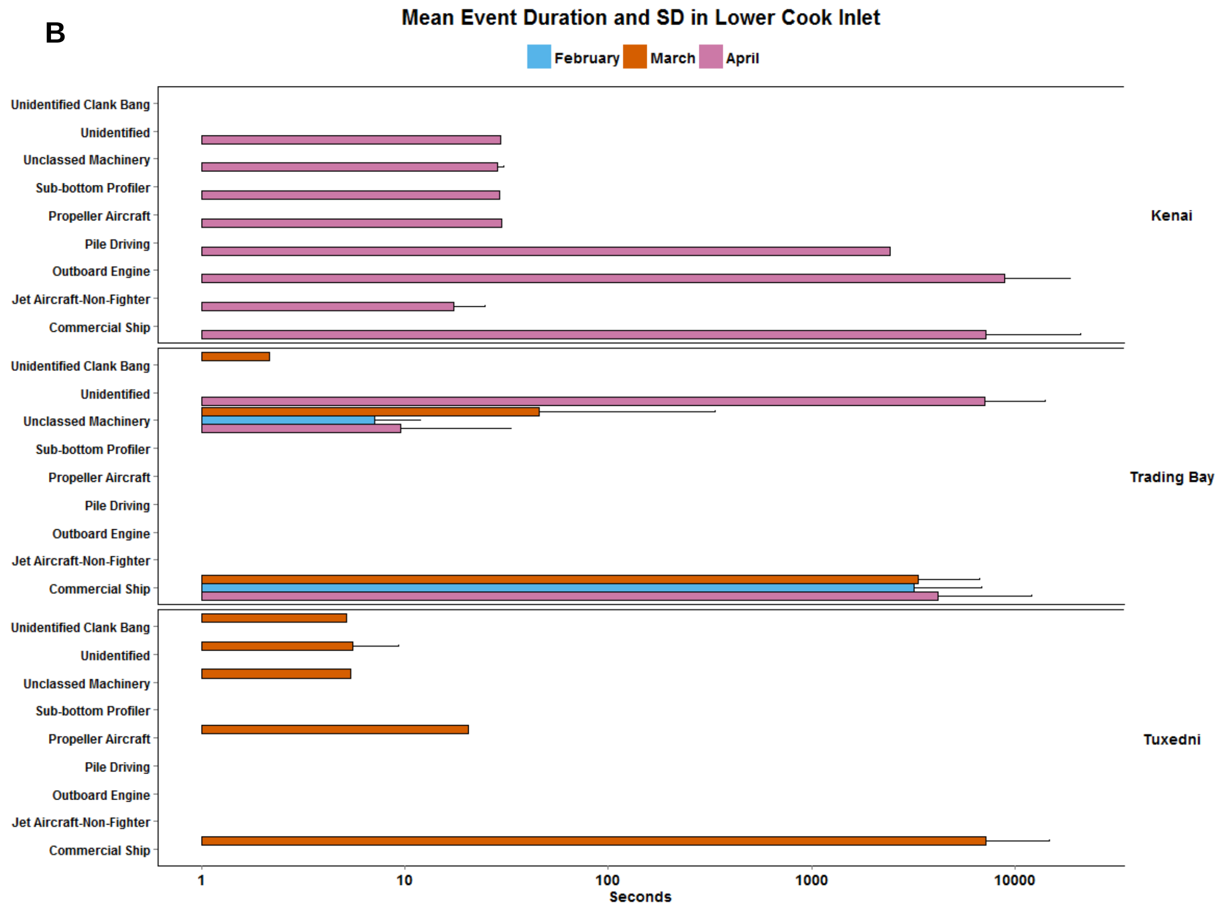


Figure 4: Average duration and standard deviation of noise classes detected at each site by month. Upper panel (A) includes the 4 locations sampled in the Upper Inlet (Cairn Point, Eagle River, Fire Island and Six Mile), and the lower panel (B) includes the 3 locations sampled in the Lower Inlet (Kenai, Trading Bay and Tuxedni). Note that up to three months were selected per location (see table 1), therefore, not all months were sampled in all locations.

Overall, the longest events were from sub-bottom profiler, unclassed machinery, commercial ship, outboard engine, dredging and pile driving. Shortest events are aircraft related noise, although propeller aircraft in Cairn Point were relatively long. Commercial ship events were a bit longer in duration in the lower inlet compared to the upper inlet, which could be related to differences in speed (i.e. moving slower in the upper Inlet will cause events with longer duration), or improved sound propagation by deeper and less restricted waters in the lower inlet. Unclassed machinery and unidentified clank or bang noise durations were a bit longer in the upper inlet, which could be related to a higher amount of industrial activities (e.g. dredging, tug boat operations). Interestingly, the lower inlet was much quieter during winter months, which was not the case for the upper inlet.

Belugas must pass by the Cairn Point area when moving into and out of Knik Arm, which is considered an important foraging area within critical habitat (NMFS 2008). Saxon Kendall et al. (2013) suggested belugas might be displaced towards the west side of the lower Knik Arm when transiting the Cairn Point area due to the noise generated in and around the POA. Our results indicate that the duration and diversity of anthropogenic noise classes are relatively similar between Six Mile (in lower Knik Arm) and Cairn Point (Table 3, Fig. 3), yet the amount of detected events per minute at Cairn Point was much higher than at Six Mile (Table 3). These results indicate that although physical displacement of belugas from the waters around the POAPOA might reduce the anthropogenic noise exposure to belugas transiting through the lower Knik Arm, the exposure is still considerable at the western side of lower Knik Arm. Importantly, most of the anthropogenic noise is concentrated in the summer months (August and September), when belugas use this area more intensely, accessing the upper areas of Knik Arm to feed on eulachon and salmon (Goetz et al. 2012).

4.3 Sound pressure level (SPL)

This section describes the loudness of the different areas monitored in Cook Inlet by month, as well as the contribution of each noise class by month and location. The figures included here allow an Inlet wide comparison of average received noise levels and when and where anthropogenic noise is louder or quieter. Details on the acoustic properties of each noise class are provided in section 4.

4.3.a Background SPL

This sub-section describes received noise levels (SPL in dB rms)(Table 4) and spectrum (Fig. 5) for background noise of each location during the quietest sampled day (24 hours) and the quietest 30 seconds of the quietest day. The statistical distribution of sound pressure levels over time, presented as percentile levels, is commonly used for descriptions of environmental noise. However, because of the high levels of currents generating flow noise and amount of debris colliding with the mooring in the upper inlet, and the high persistence of anthropogenic noises inlet-wide, self-noise and anthropogenic noise would largely bias any percentile results. A substantial portion of our data cannot be considered to be a good representation of natural background noise condition in Cook Inlet, and thus requires a fine selection of recording segments where both self-noise and anthropogenic noise are absent to allow proper characterization of background noise. Our approach to process the data to identify quietest periods guaranteed the absence of anthropogenic noise or self-noise. However, inspection of the waveform of the selected quietest 24 hours for each location and month indicated that they all included anthropogenic noise events. Therefore, quietest periods of 24 hours were too long to allow proper representation of the natural (i.e. without human influence) background noise conditions of each location. We did not find any single24 hour period without anthropogenic noise presence in any of the selected locations and months, highlighting the widely spatial dispersal and temporal persistence of anthropogenic noise in the Cook Inlet beluga critical habitat. For this reason, we decided to analyze dB rms values for the quietest 30 seconds of the quietest days. These values represent baseline background noise levels without or with minimal anthropogenic noise influence. We considered these values as the reference values for each location to compare to anthropogenic noise contribution.

Table 4 indicates that only Tuxedni Bay has day-long received levels below 100 dB rms, however when considering the quietest 30 seconds of the quietest day, all the sampled locations are below 100 dB. These results suggest that daily noise variability is very considerable. For each of these locations, all the recordings corresponding to these quietest days contained anthropogenic noise or self-noise for some periods. However, the 30seconds quietest selections did not show any obvious signs of anthropogenic noise or self-noise, and thus should be considered the best representation of the natural background noise levels of each area under silent conditions (i.e. no human influence, and no self-noise). It should be noted that the noise related problem with strong currents is the amount of self-noise generated by the water flowing around the hydrophone capsule of the recorder, affecting a wide range of frequencies. But the contribution of natural noise generated by high currents in upper Cook Inlet will only affect the 0-1kHz frequency range (HDR, 2011).

Table 4: Received noise levels (SPL in dB rms) over the full band (0-12.5 kHz) for the quietest day (24 h) of all sampled days and the quietest 30 seconds sequence within the quietest day at each sampled location.

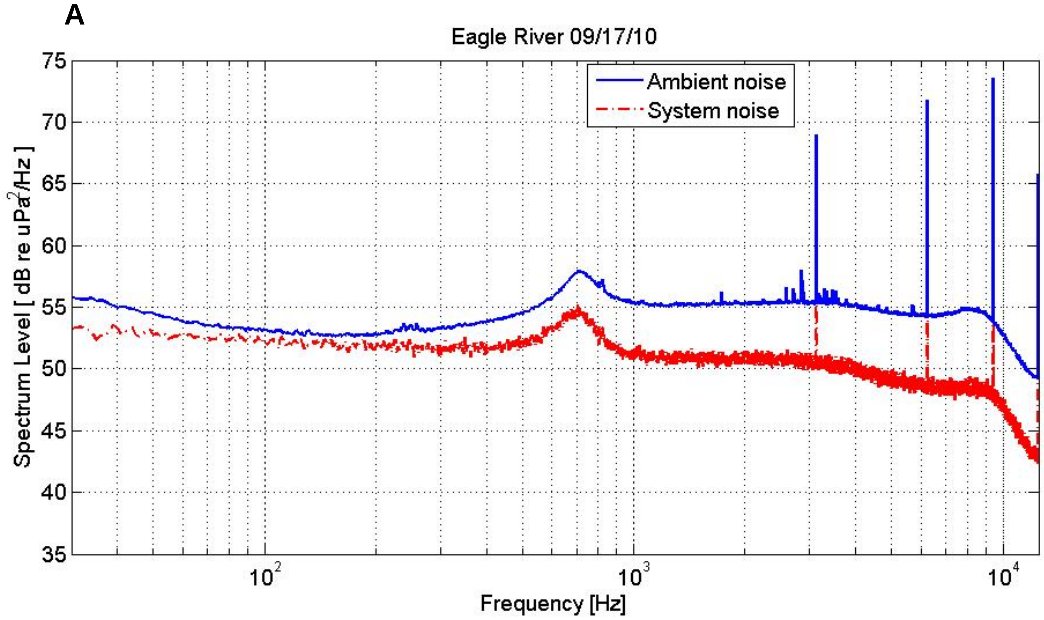
Location	Quietest day (24 h) in dB rms	Quietest 30 s in dB rms
Eagle River	110.78	95.23
Six Mile	115.97	97.01
Cairn Point	116.22	99.51
Fire Island	120.73	97.07
Trading Bay	102.25	94.95[3]
Kenai River	101.37	94.95
Tuxedni Bay	96.03	95.28

The natural background noise levels reported here will only show spectral differences below 1 kHz when compared to natural levels at peak current periods. Belugas have poor hearing below 1 kHz, with thresholds in the 100-120 dB range (Aubrey *et al*. 1988), therefore, the contribution of natural noise by high currents is irrelevant when considering the potential for impact on Cook Inlet beluga hearing. Differences over 20 dB can be observed between results from the quietest 24 hours or from the quietest 30-second selections, which highlights how easily baseline background noise measurements can be misinterpreted when anthropogenic noise, and self-noise in high current areas, is not effectively avoided.

The next figure (Fig. 5) shows the averaged spectrum in the full band 0-12.5 kHz for the quietest 24 hours of the sampled period at each location. Each panel also includes the system noise spectrum; i.e., the minimum noise level that the EAR provides reliably. Any background noise spectrum overlapping or very close to the system noise spectrum will likely represent recording system noise rather than the area's ambient noise, and is thus not reliable.

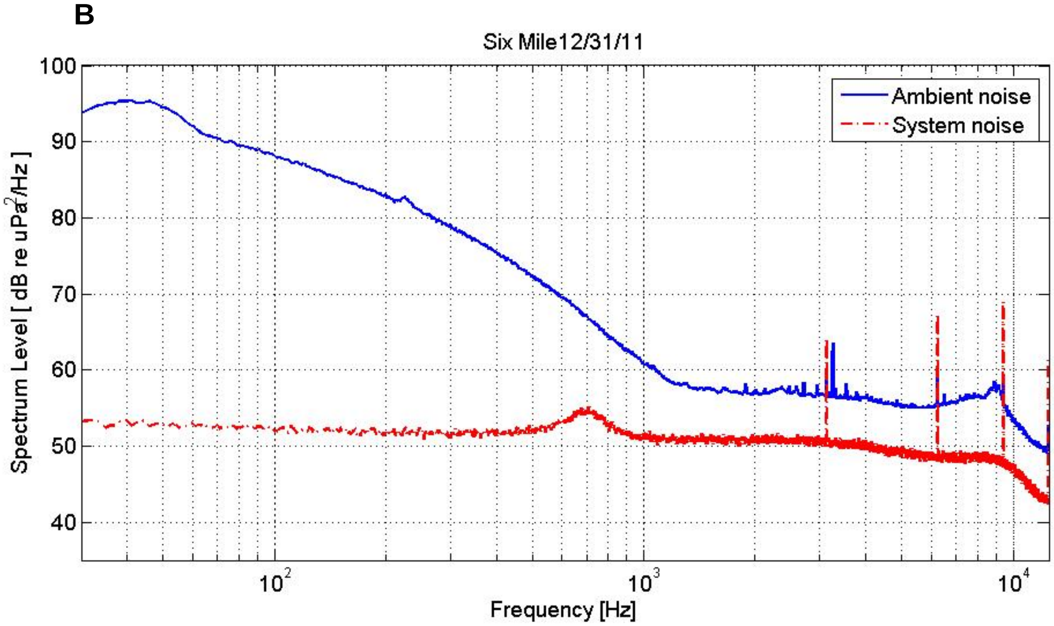
[3] EAR system noise for 30 seconds samples with a 0-12.5 kHz bandwidth was 90.4 dB rms, therefore the reported quietest 30 second samples were not affected by system's noise.

A



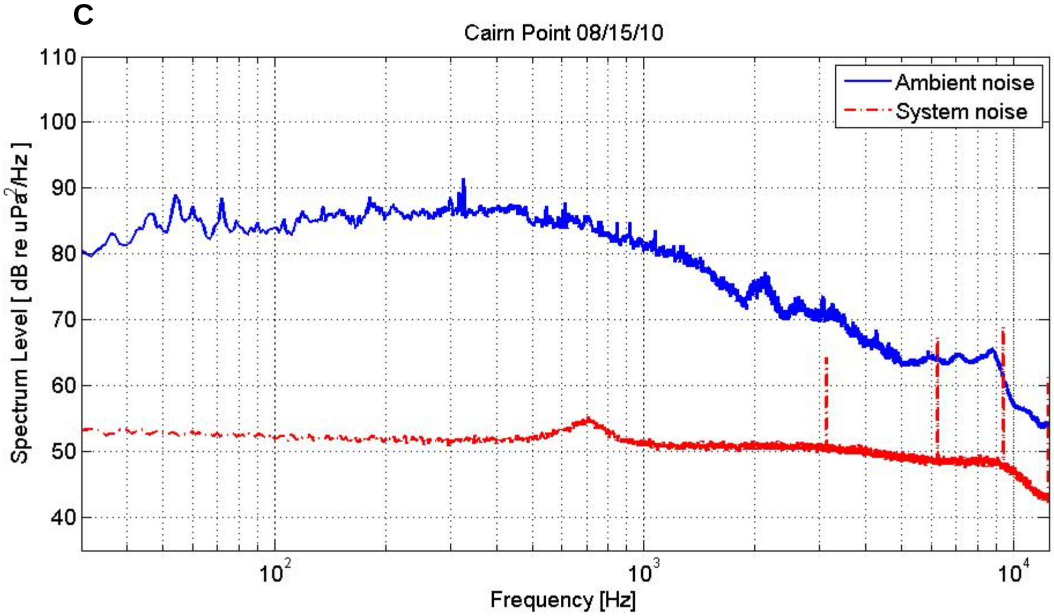
Eagle River ambient noise spectrum from 17 September 2010 is the lowest of all the locations analyzed. Levels are very close to the system noise levels, and the shape of this spectrum seems to be affected by the system noise, in particular in the range 400-1000 Hz, as well as the peaks observed at 3000 Hz, 6000 Hz and 9000 Hz. Therefore, although this analysis shows how low spectrum levels are in this area, the shape of this spectrum is probably biased by system noise.

B



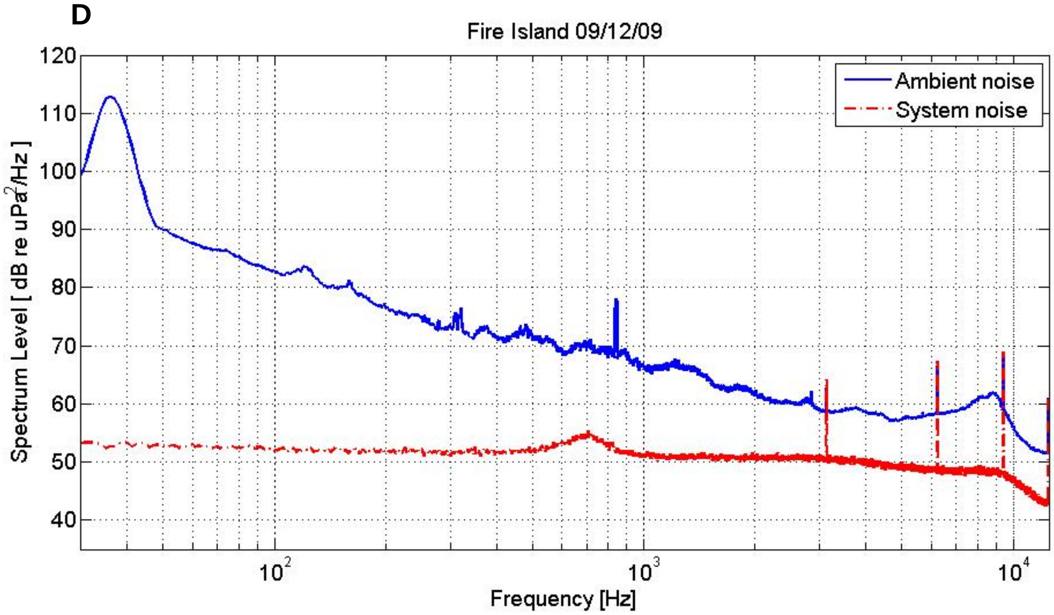
Spectrum in Six Mile on 31 December 2011 indicates there is considerable noise in the lower frequencies. Spectrum levels do not get close to those of Eagle River until approximately 1500 Hz, which may be related to the higher current velocity at Six Mile that would generate higher self-noise at the mooring, or elevating the overall ambient noise of this area independently of self-noise.

C

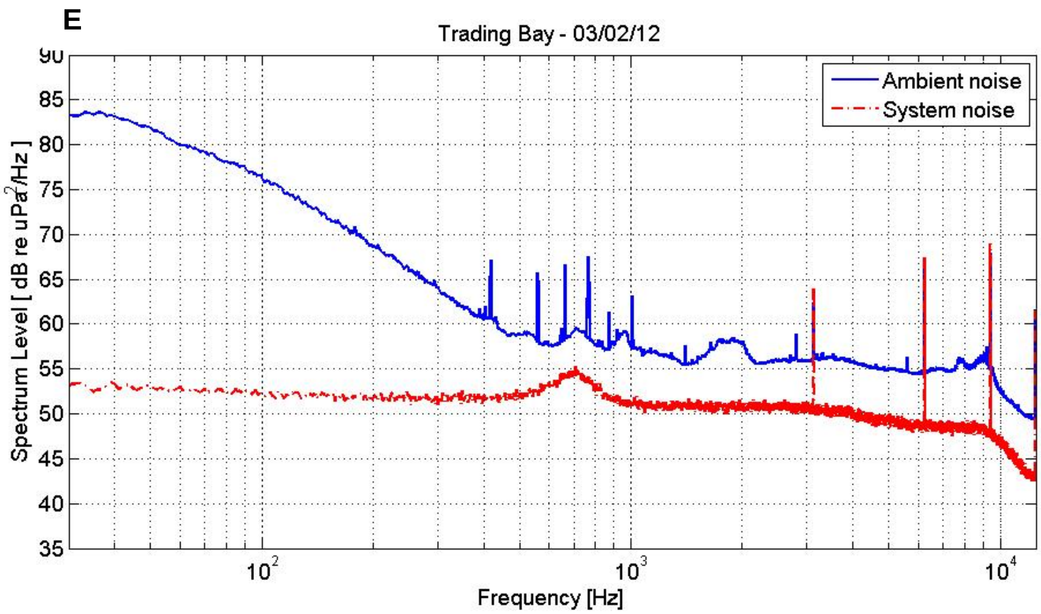


Cairn Point spectrum of 15 August 2010 shows considerable energy in the low and middle frequencies. Lower frequencies are below the levels reported for Six Mile, but still much higher than Eagle River. As at Six Mile, this is a high velocity current area and thus self-noise or overall elevated ambient noise levels might be common at this location, but mid frequency contribution could be related to anthropogenic activities even during the lowest noise period sampled.

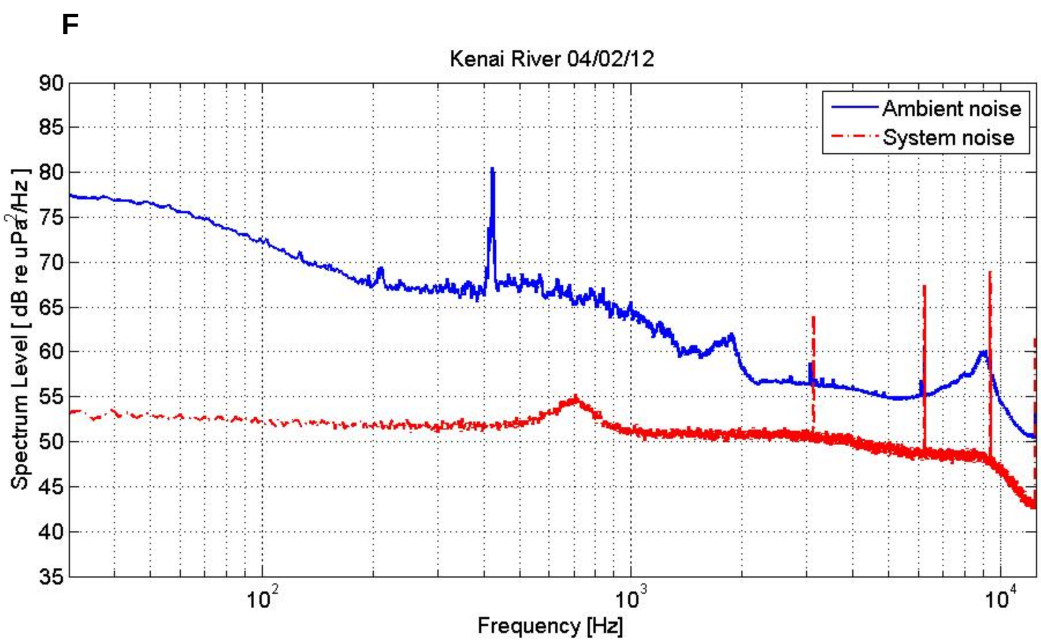
D



Fire Island spectrum of 12 September 2009 shows a general decrease from a peak in acoustic energy around 25 Hz up to the maximum frequency sampled. The shape and levels are similar to the ones reported in Six Mile, likely also from strong current velocity, elevating the lower frequency levels higher than what was reported in Eagle River.

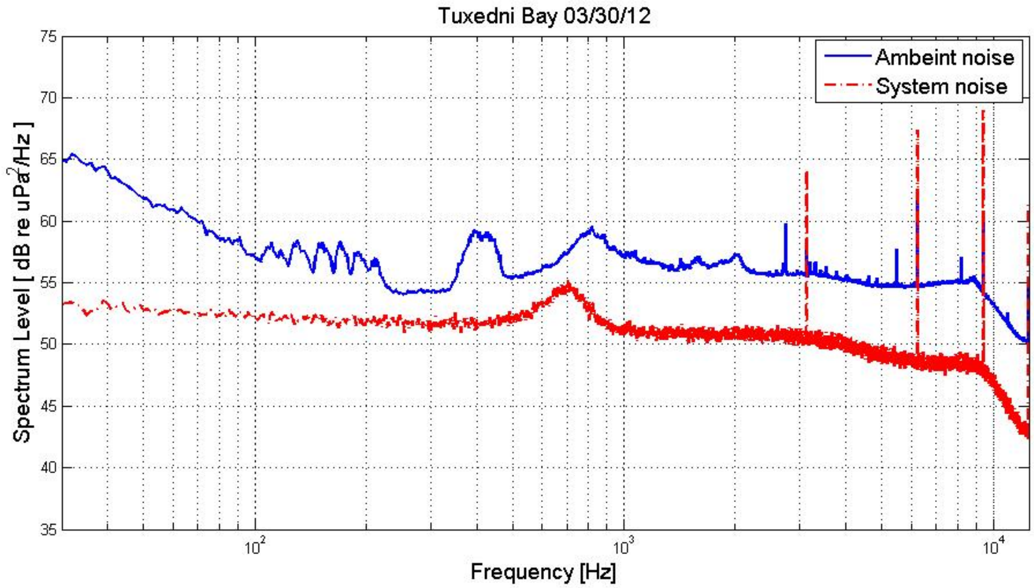


The shape of the Trading Bay spectrum of 2 March 2012 follows the one reported at Six Mile and Fire Island, with highest acoustic energy in the lower end but at lower levels than the other sites. This difference might be related to the lack of strong currents, resulting in overall lower ambient noise levels, although the peaks observed in the mid frequencies 400-1000 Hz are probably of anthropogenic origin, indicating that a fraction of the noise reported in the lower 500 Hz of the spectrum could also be influenced by anthropogenic activities occurring during this quietest day in March 2012 in Trading Bay.



Kenai River spectrum levels of 2 April 2012 are low compared to the other locations, but still above Eagle River levels. The peak at 400 Hz is probably related to anthropogenic activities, because the elevated noise level and higher variability are in the mid frequencies.

G



Tuxedni spectrum of 30 March 2012 is similar to Eagle River, being the second quietest location from all the sampled areas in Cook Inlet. The low levels of noise in the lower frequency range indicate a lack of current velocity near this site. However, the high variability from 100 Hz to 1000 Hz indicates some anthropogenic activities occurred within this quietest period.

Figure 5: Mean spectrum levels for the quietest 24 hour period in each location (blue) sampled in Cook Inlet, Alaska, and system noise spectrum (red). Locations are A- Eagle River, B- Six Mile, C- Cairn Point, D- Fire Island, E- Trading Bay, F-Kenai River, and G- Tuxedni Bay.

None of the spectra shown in Figure 5 appear to exceed hearing thresholds for beluga (Aubrey et al. 1988, Castellote et al. 2014). Therefore, none of the baseline ambient noise levels in these locations have any potential for masking the communication of belugas, at least for the frequency range analyzed, which includes the most influenced frequencies by anthropogenic noise sources. These results indicate that even if the upper Cook Inlet is considered a naturally loud environment and thus acoustically poor (NMFS 2008), ambient noise might only be above beluga hearing thresholds on particularly elevated periods (e.g. strong current periods, storms). When these spectra are compared to other published results on underwater ambient noise, quiet locations in Cook Inlet (e.g. Eagle River, Tuxedni Bay, Trading Bay, Kenai River) are well below spectral levels reported for exceptionally quiet periods in open waters (Rolland et al. 2012), or abyssal trenches (Barclay and Buckingham 2014). Spectra and received SPLs for quiet locations in Cook Inlet are also below the estimated natural ambient noise levels in Saguenay Fjord in the St. Lawrence estuary, Canada (Gervaise *et al*. 2012).

Interestingly, ice noise was never identified in any of the data sets analyzed for this study. However, Fig. 5 shows how the quietest day for the winter months analyzed in this study in locations where ice is expected include elevated noise levels in the lower frequencies (e.g. Six Mile on 31 December 2011, Trading Bay on 2 March 2012, Tuxedni on 30 March 2012). Most of the current knowledge on sea ice noise is related to multiyear ice under mechanical or thermal stress (Pritchard 1990,) or glacierized fjords (Petit *et al*. 2015). However, little is known on the noise production of new ice or first year ice. The elevated noise levels identified in winter quietest days could be related to noise generated by this thin ice, which was not identified in the analysis process. Further research to better understand the effect of ice presence in the background noise conditions in Cook Inlet would be desirable.

4.3.b Overall mean anthropogenic SPL by month and location

This sub-section includes one single figure showing the mean SPL of all detected anthropogenic noise events for each location. Mean values are calculated by month, independently of the noise classes detected. Understanding that these measurements do not include the background noise occurring between noise events is important, because these results should not be confused with natural ambient noise measurements (shown in section 3a), SPL values for noise classes (shown section 3c) or SPL values of noise events (shown in section 4a).

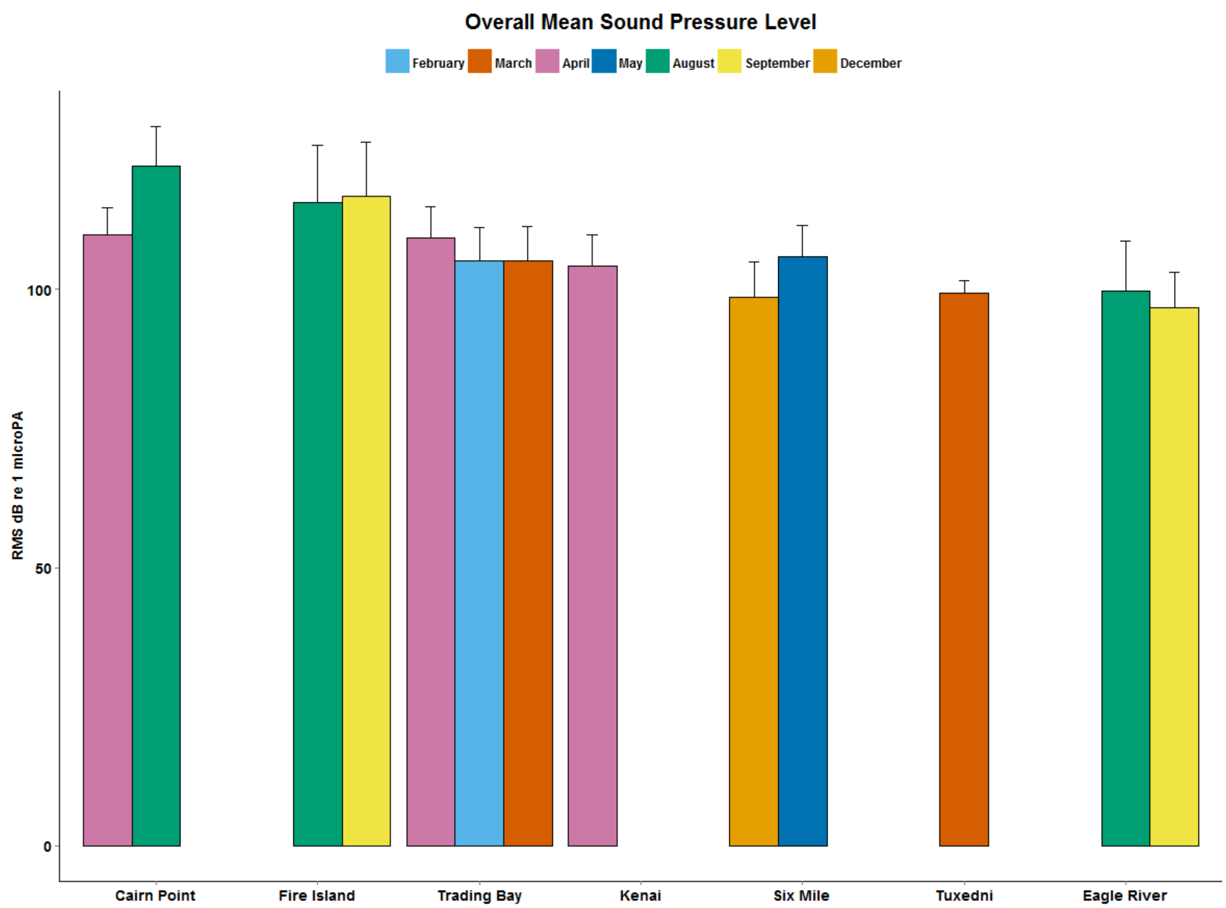


Figure 6: Overall mean anthropogenic sound pressure level (SPL) calculated as dB rms re 1 microPa and standard deviation from all the anthropogenic noise events of each location and month, independently of the noise class. Locations are ordered from noisiest to quietest.

Figure 6 allows a clear comparison of overall average sound pressure levels (SPL) for detected anthropogenic noise in each sampled location and month. Lowest SPL were found in Eagle River in September (96.6 dB) and loudest in Cairn Point in August (122.1 dB). Biggest differences between months were found in Cairn Point, with 12.3 dB between August and April.

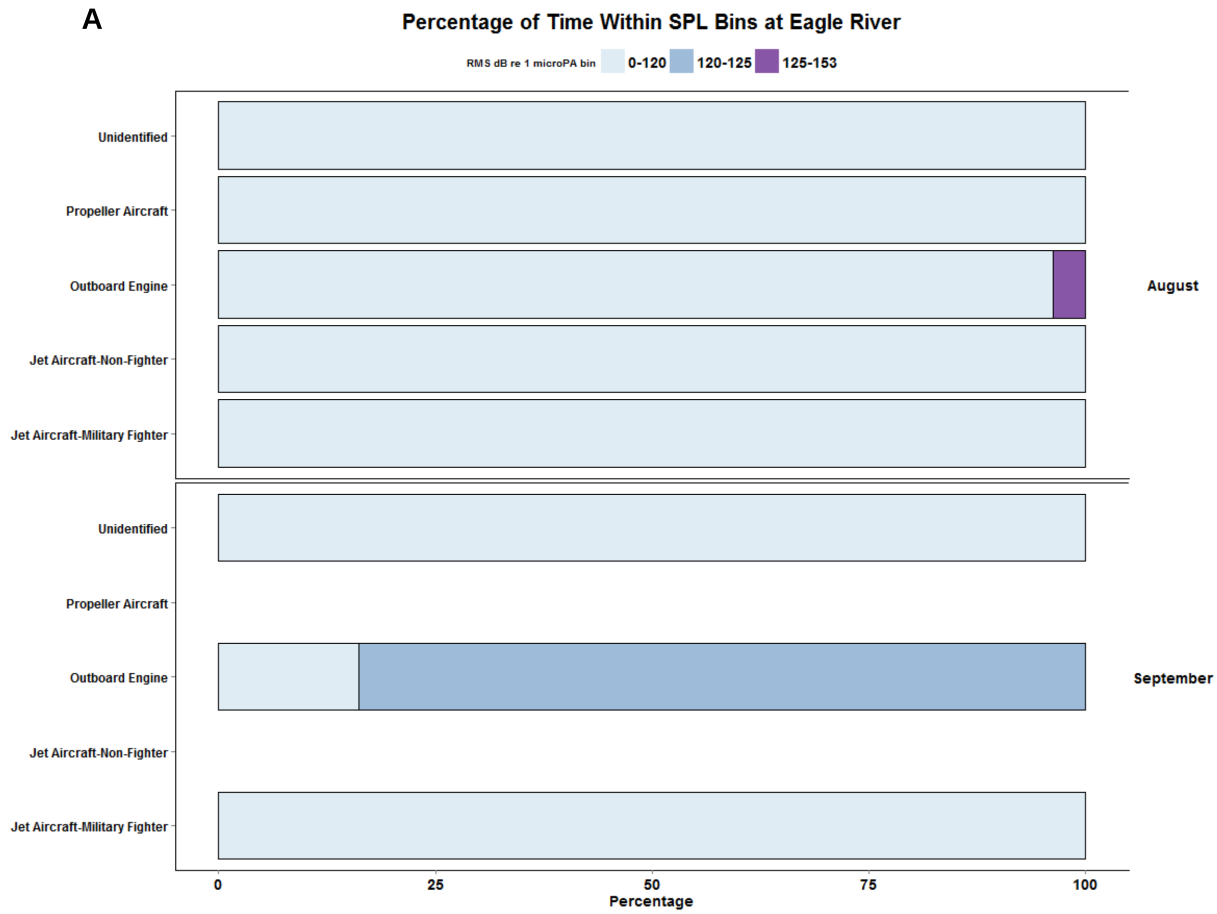
Table 5: Comparison of SPL (in dB rms) for the full bandwidth (10-12.5 kHz) between the quietest 30 s of recording and the overall mean SPL of all anthropogenic noise detected in each sampled location in Cook Inlet, Alaska.

Location	Natural ambient noise (quietest 30 s in dB rms)	Anthropogenic noise (overall mean dB rms)	Difference in dB
Eagle River	95.23	98.28	3.05
Six Mile	97.01	101.96	4.95
Cairn Point	99.51	122.0	22.49
Fire Island	97.07	116.11	19.04
Trading Bay	94.95	106.74	11.79
Kenai	94.95	104.20	9.25
Tuxedni	95.28	99.32	4.04

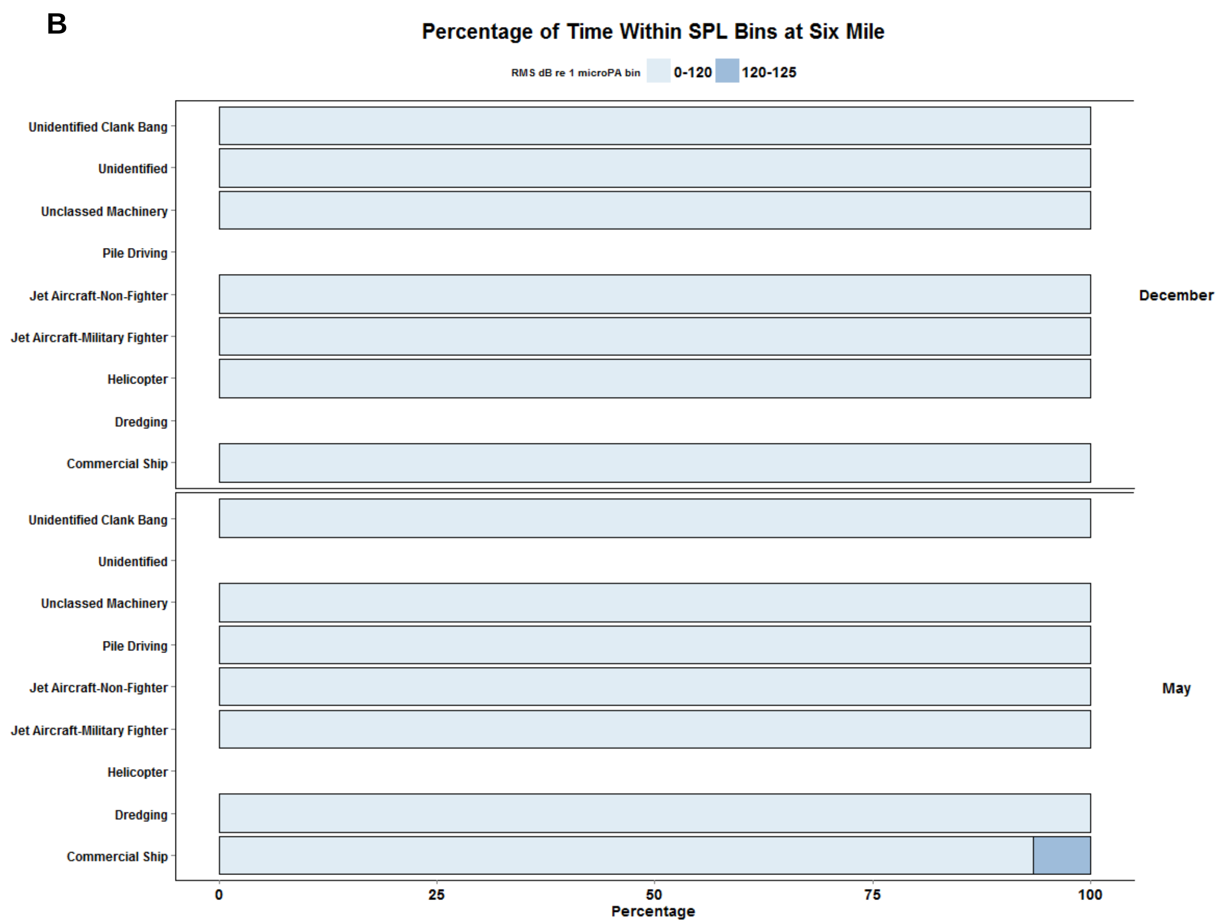
Results in Table 5 indicate that anthropogenic noise, on average, increases background noise by 3.05 dB to 22.5 dB. It is important to note that anthropogenic noise levels shown in this table are mean values, therefore much higher contributions to the background noise are possible.

4.3.c Noise class SPL distribution over time

The next figure shows the percentage of time that SPL for each noise class was within a specific dB bin; i.e., 0-120, 120-125, and 125-153, the NOAA noise threshold ranges. The figure allows a comparison across locations and months to highlight how often noise classes where louder or fainter, within specific dB bins. It should be noted that both impulsive and continuous noise classes are presented in each figure panel to allow a comparison of the diversity of noise classes identified in each location and month together with their loudness.

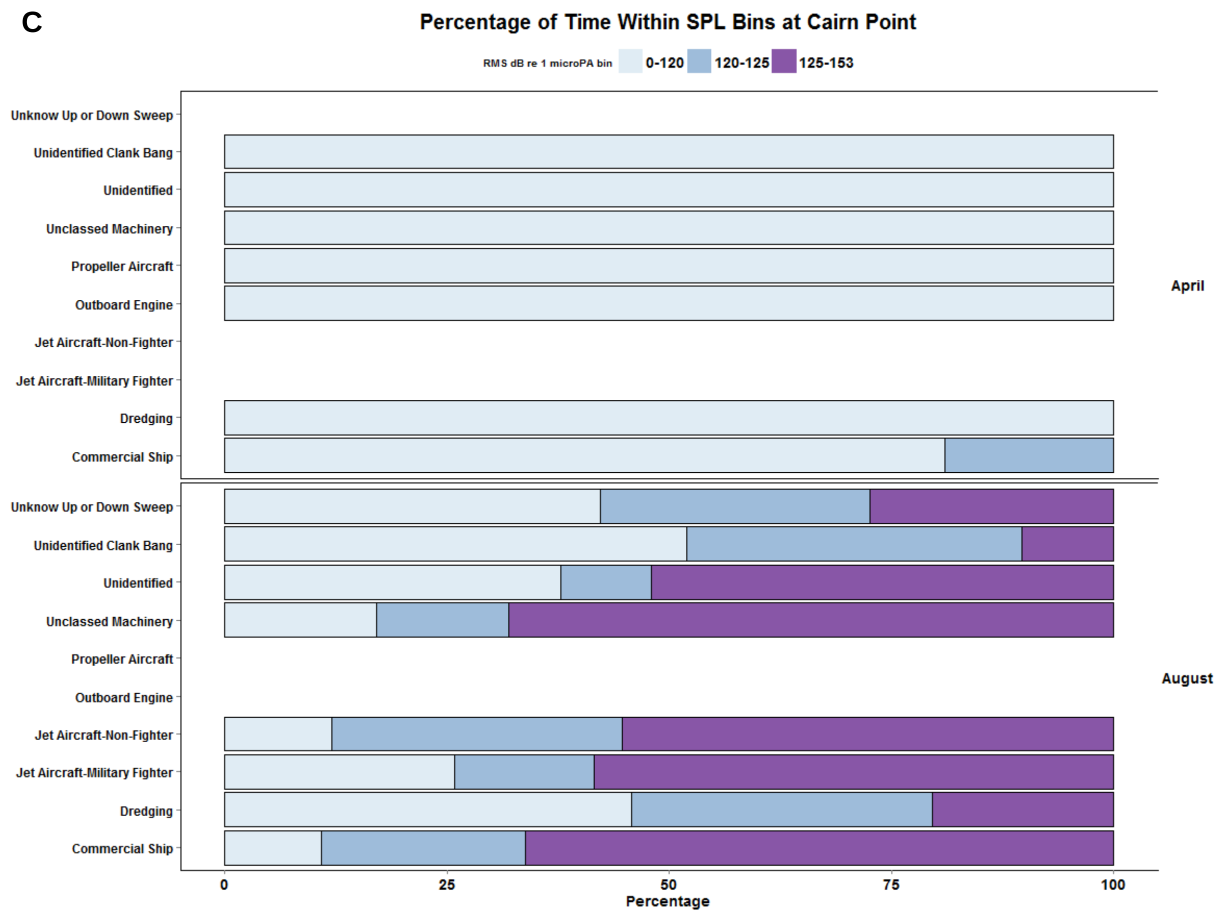


Outboard engine is the only noise class in Eagle River that exceeds 120 dB in September for over 75% of the time detected, and above 125 dB in August for a small fraction of the time detected. Despite being the average quietest location (Fig. 6), outboard engine events exceeded 125 dB.

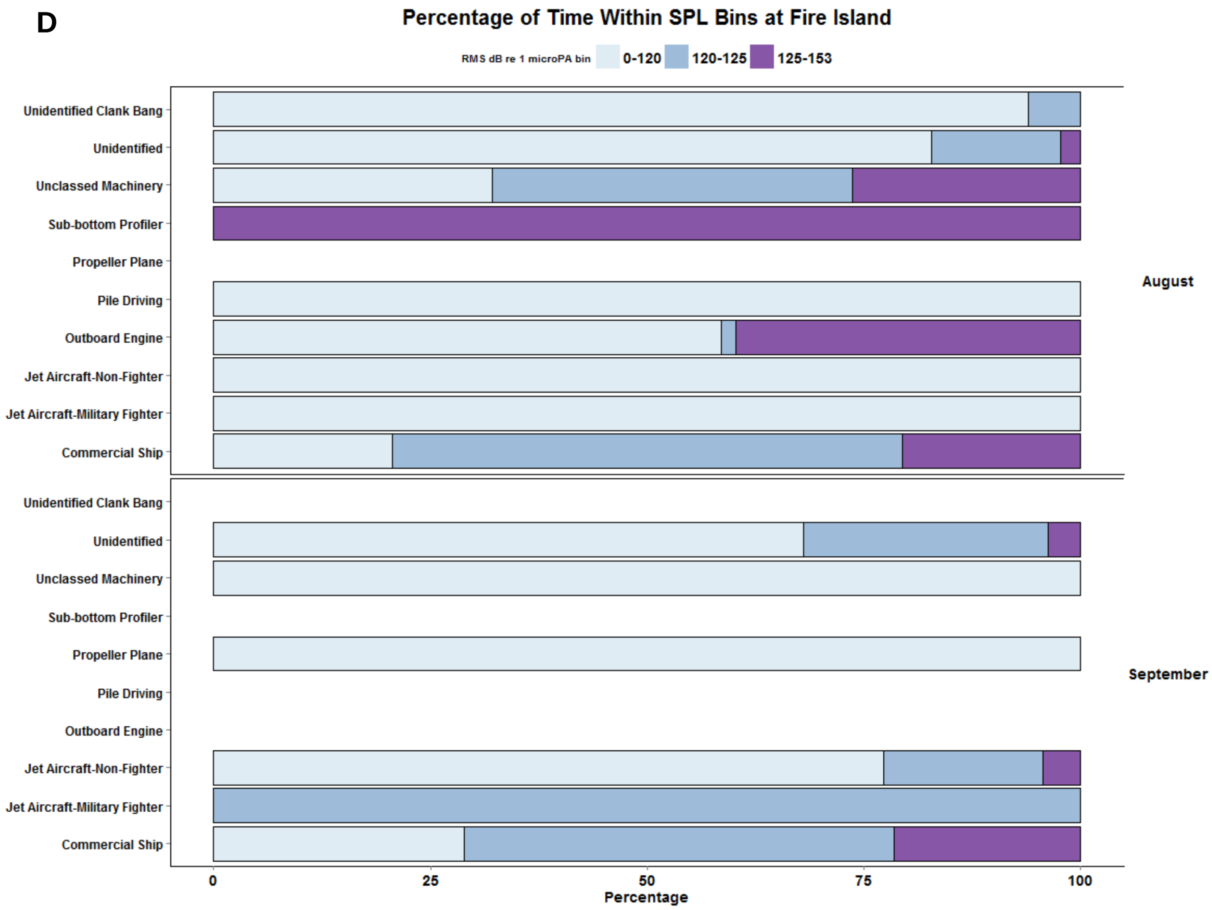


Despite a large number of noise classes detected at Six Mile, only commercial ship exceeds 120 dB and for a small fraction of time in May.

C

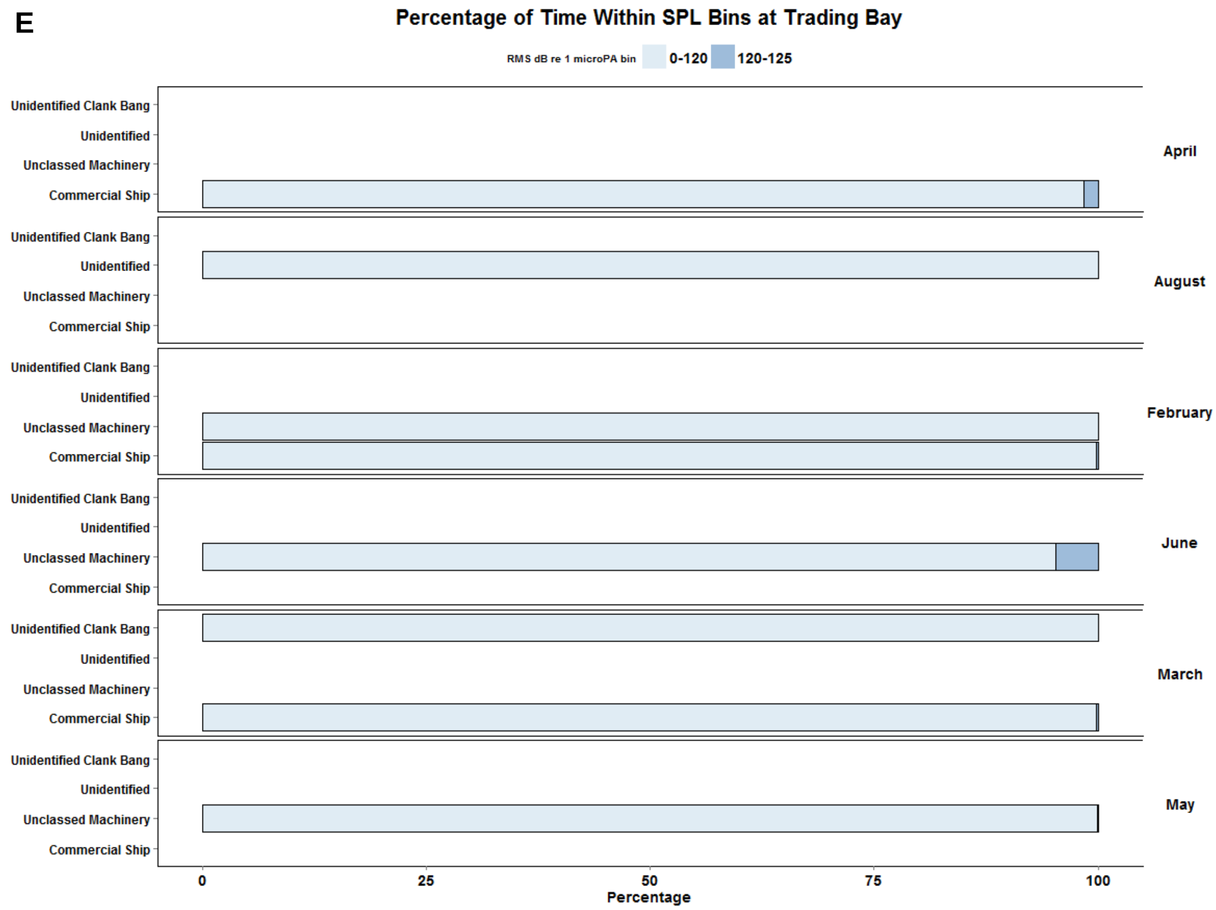


Cairn Point is the busiest location with highest percentage of time above 125 dB for multiple noise classes. Anthropogenic noise contribution shows substantial differences between April and August, with all noise classes identified in August exceeding 125 dB for some fraction of time. Commercial ship and unclassed machinery are loudest, related to both shipping activity near the POA and from the port expansion project. Unidentified clank or bang, which was a very prevalent noise class in Cairn Point (Fig. 3), seems to be the fainter signal of all the classes identified at this site. Interestingly, jet aircraft (commercial or military non-fighter) noise is near the levels of commercial shipping at this location in August, while absent in April. This might be related to an increase in activity at the Anchorage International Airport in summer months, but could also be related to differences in management, perhaps the east-west take-off and landing strip was used less, directing airplanes further away from the mooring deployment location.



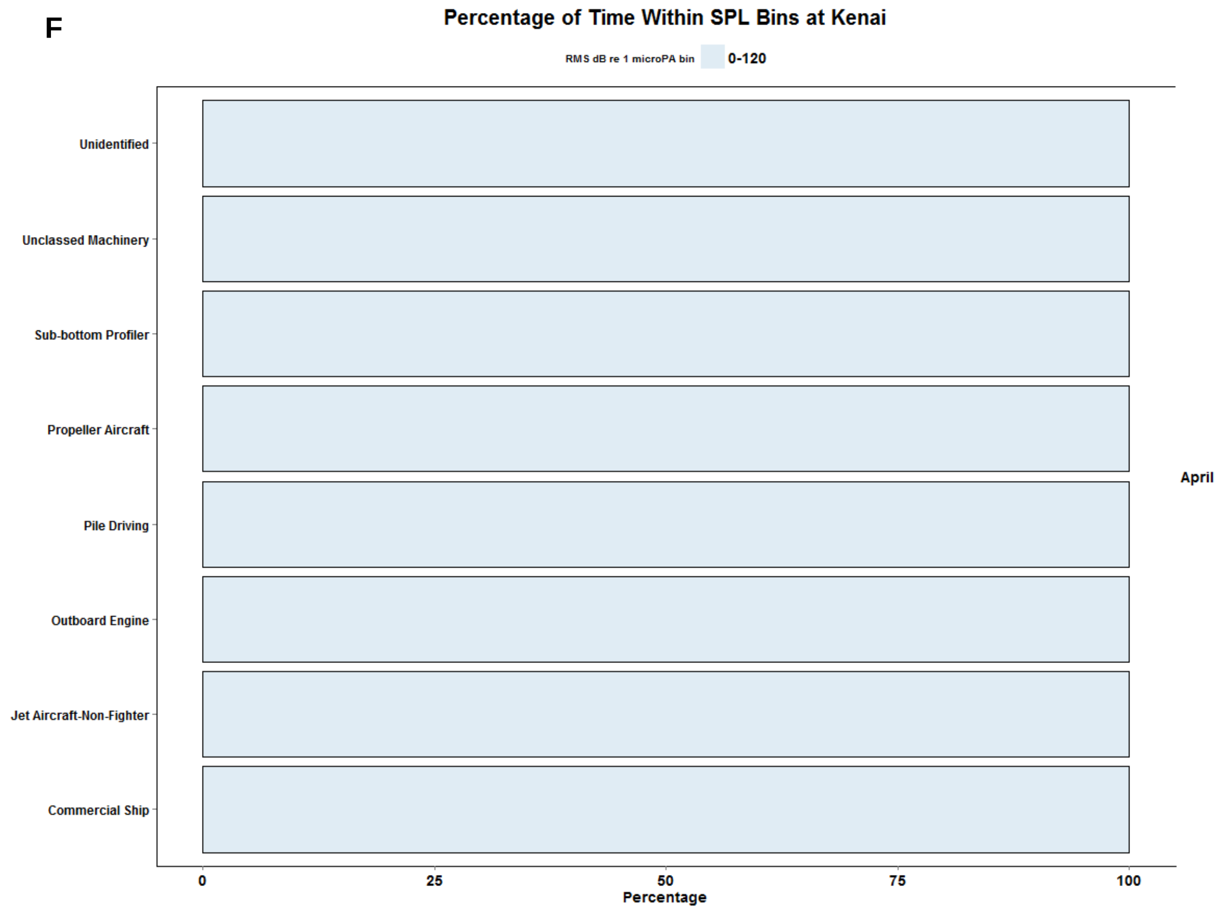
The most prominent result in this panel is the sub-bottom profiler detected in August exceeding 125 dB for 100 % of the time. This is the only noise class with such high loudness level from all the data analyzed in this study. Commercial ship is ranked the second predominant noise class in this area in August; however, unidentified clank or bang noise is fainter here. Presuming this sound is from tug boat operations (assisting ships to recall or depart the POA or maneuver barges), this lower loudness is probably related to the distance to the area where tug boats operate, mostly around the POA. In contrast, outboard engine, despite not being very prevalent (Fig.3) is the second loudest noise class in this area. Interestingly, commercial airplane is slightly louder in September than August. There is a decrease in the number of noise classes identified and their loudness in September when compared to August.

E



Trading Bay seems a very quiet environment when observing the low diversity of noise classes and SPL distribution in time for all noise classes; however, mean event duration (Fig. 4) indicates that while commercial ship and unclassed machinery are not very loud they occur for a long period of time, thus obtaining a relatively high mean overall SPL for this area (Fig. 6).

F



Both Kenai (above) and Tuxedni (below) are very quiet environments, slightly above Eagle River in overall mean SPL. However, outboard engine presence is more prevalent in these two Lower Inlet locations (Fig. 3) but louder in Eagle River (see Eagle River panel above in this figure). This could be related to the location of our moorings. Because Eagle Bay is very shallow, small rafts tend to follow the deep channel formed near the east shore of the Arm, which was the chosen location to deploy our mooring. In contrast, both Kenai and Trading Bay are not shallow and narrow passages and rafts could have been detected primarily at long distances at fainter sound levels.

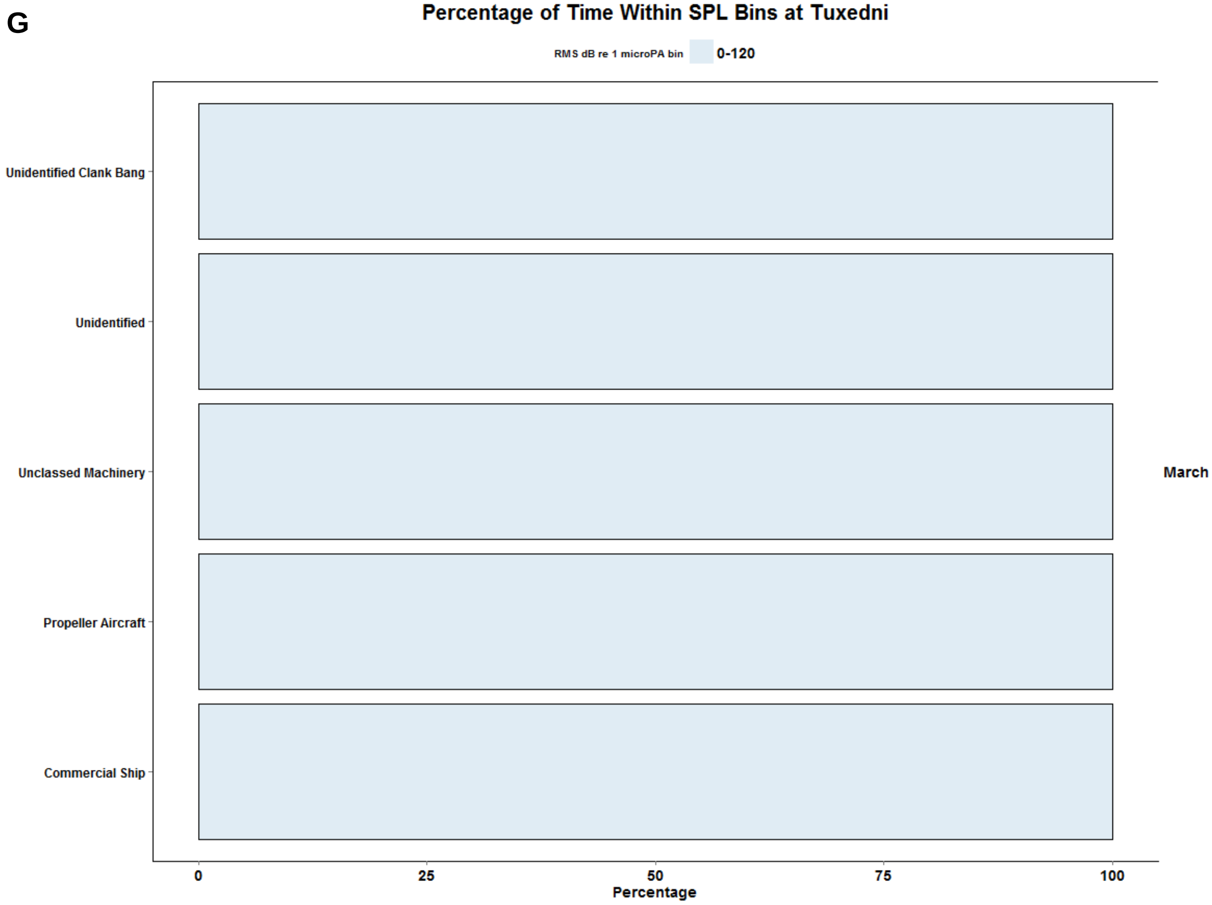


Figure 7: SPL distribution over time for each noise class detected in each location and month sampled in Cook Inlet Alaska, calculated as percentage of time over the total recording time for each month, within the bins 0-120, 120-125 and 125-153 dB. Bins are based on NOAA acoustic thresholds. Locations are A- Eagle River, B- Six Mile, C- Cairn Point, D- Fire Island, E- Trading Bay, F- Kenai River, and G- Tuxedni Bay.

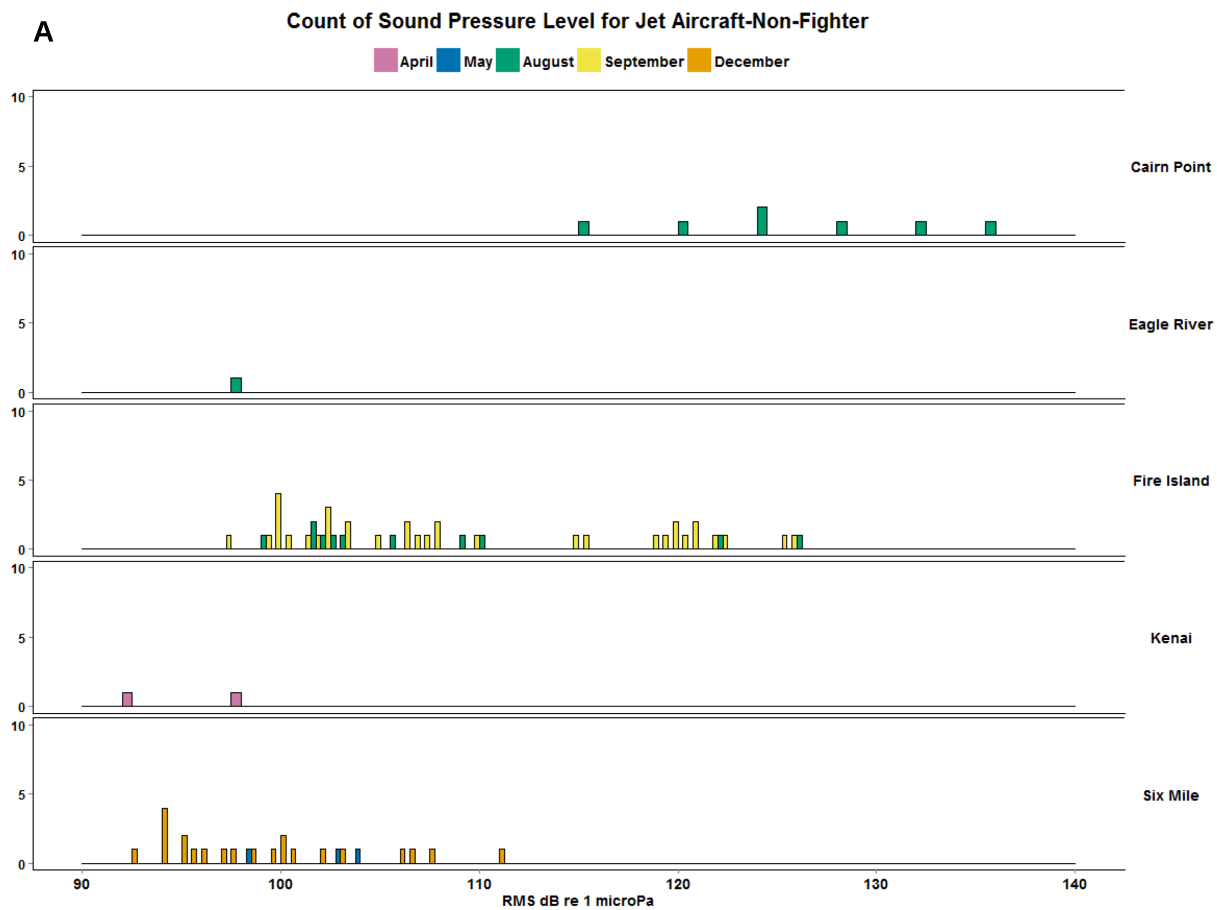
4.4 Acoustic metrics for each noise class

This section includes the acoustic characteristics measured in all the events from all the noise classes identified in this study, which are SPL, SEL, dB 0-peak, and 3rd octave peak. These are presented as dB histograms of the frequency of occurrence. These histograms are a good graphical representation of how the loudness of all the events of each noise class is distributed across a dB scale. The dB scale is maintained constant between panels of the same figure to allow comparing the dB range across noise classes, locations and months.

This section also includes noise class characteristics in the frequency domain. These are presented as the average spectrum for both power density and 3rd octave bands for each noise class. The average values are calculated with all the events of each noise class in each location.

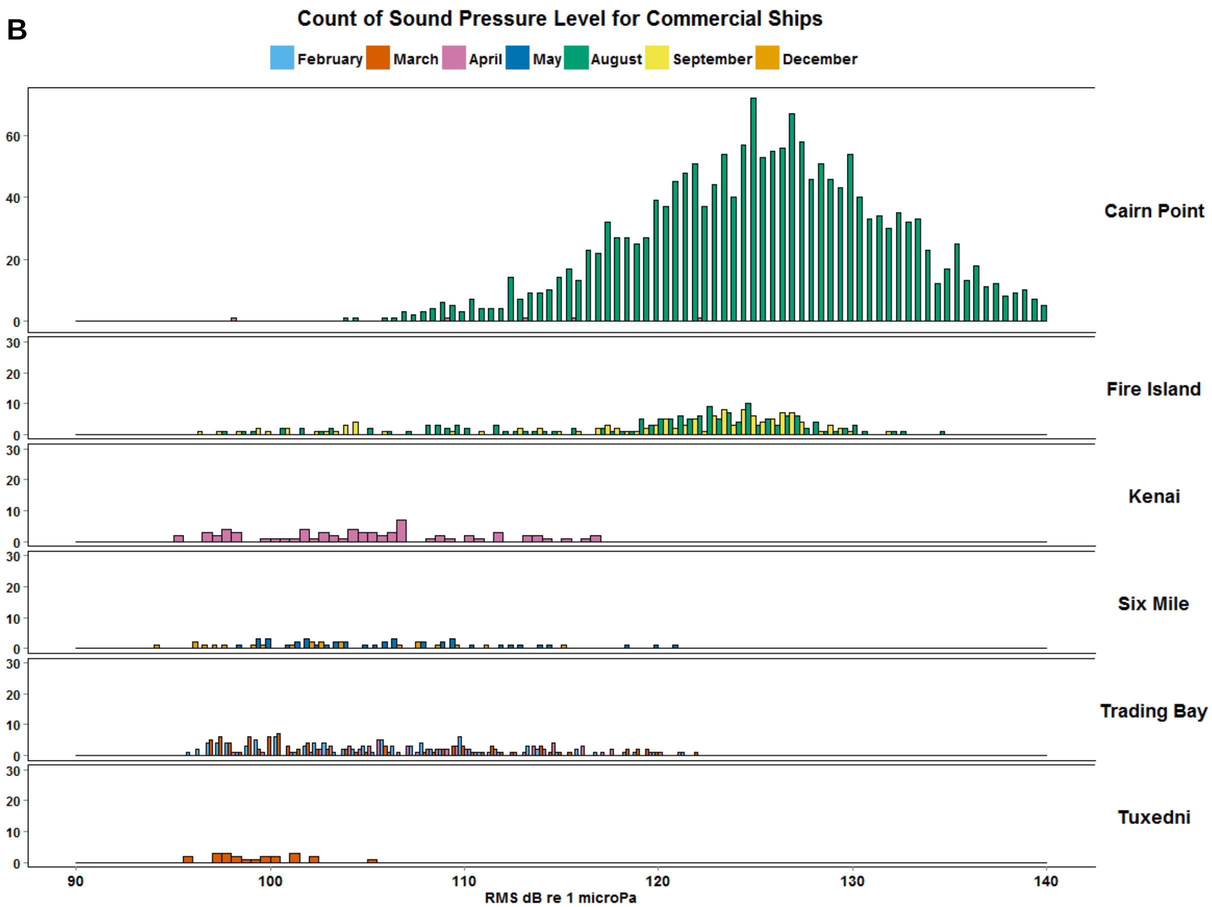
4.4.a SPL histograms

This metric represents the loudness of the detected events independently of their duration. The figure below shows the distribution of loudness in SPL for all the events of each noise class and for each location and month, across a dB scale spanning from 90 to 140 dB. The upper limit of 140 dB rms is based on the technical limitation to reliably record any sound louder than 153 dB peak (see methods). For a perfect sinusoid wave the SPL in dB rms will be 9 dB below the peak value, putting our SPL dB rms upper limit at 144 dB. Note that y-axis scale is different across panels.

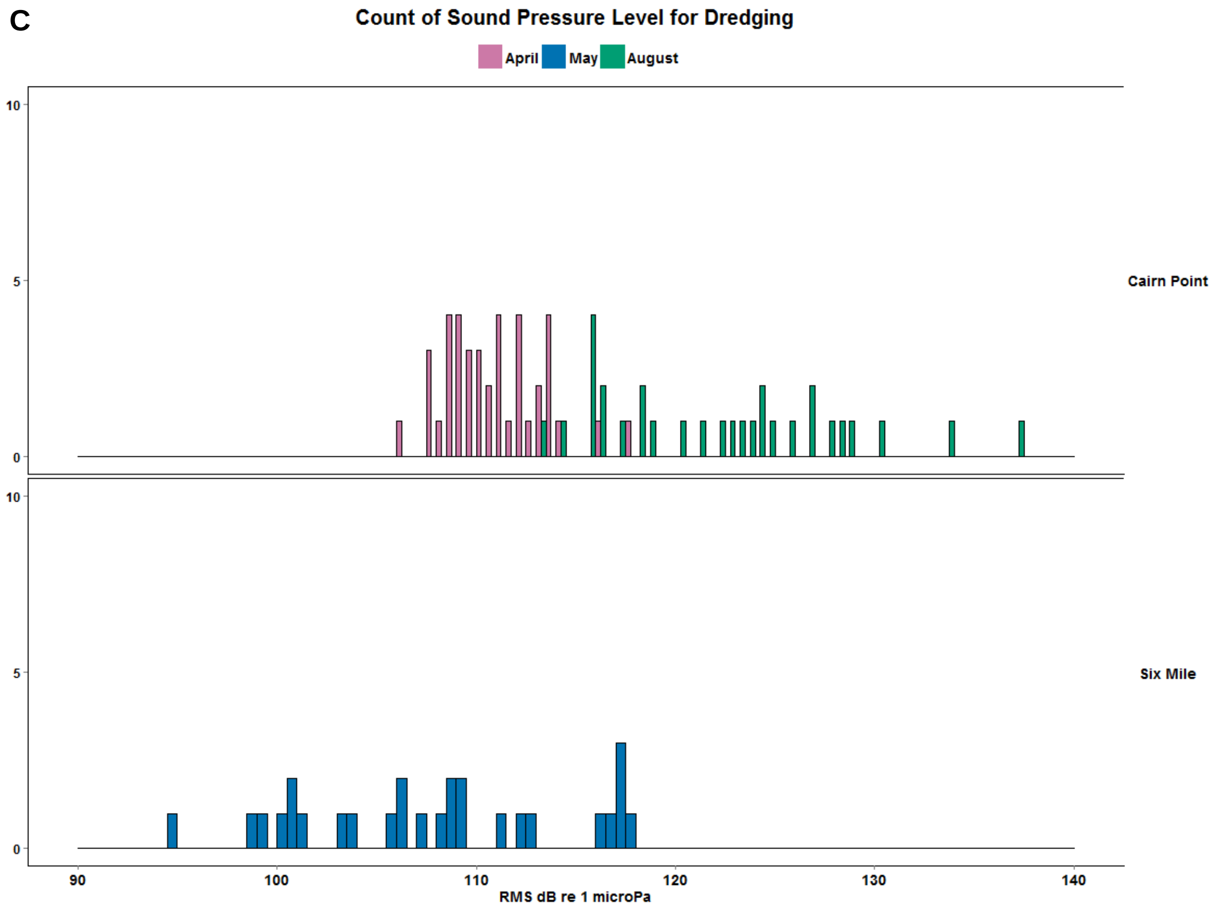


Jet aircrafts were difficult to discern between commercial and military non-fighter types. The acoustic signature was too similar to allow a direct classification, thus we have grouped these events in one single noise class termed jet aircraft - commercial or military non-fighter. However, it can be expected that mooring locations closer to the Elmendorf Air Base might get exposed to military non fighter jet aircraft noise while mooring locations near the Anchorage International Airport might get exposed to commercial jet aircraft noise.

This noise class was loudest in Cairn Point due to the proximity to the Elmendorf Air Force Base. Fire Island is the second loudest location for this noise class because the path for landing and take-off from the Anchorage International Airport east-west strip crosses over this mooring location. Because the mooring location in Fire Island is further away from the airport than at Cairn Point from the Air Force base, aircrafts tend to be higher in altitude than in Cairn Point, and thus received SPLs tend to be lower.

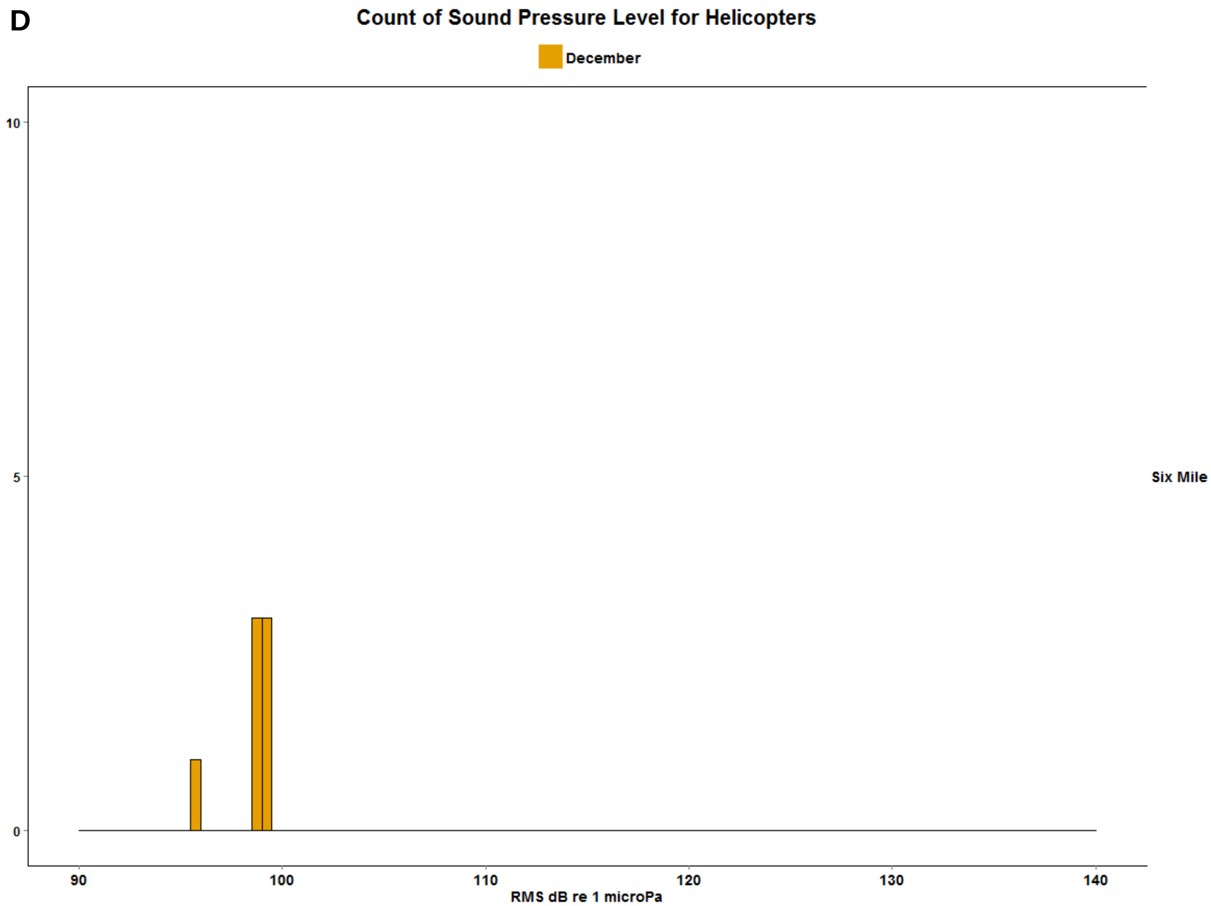


Commercial ships are the most prominent source of anthropogenic noise across Cook Inlet both in % of time (Fig. 3) and duration of the events (Fig. 4), and for Cairn Point, also in received SPL. Received SPLs are slightly lower in Fire Island, probably due to the distance of the shipping lane to the mooring location, but might also be related to the range in which tug boats assists vessels when approaching or departing the POA. Six Mile is near Port MacKenzie but, in contrast, received SPLs are not as high as in Cairn Point. While this suggests that perhaps ship noise exposure to belugas is lower in the western side of the lower Knik Arm, ship noise events reached 120 dB rms at Six Mile, which suggests that the received noise levels right across the arm in front of the port might be very considerable. Even if belugas could potentially be displaced towards this side of the arm, they would still be exposed to ship noise in levels higher than 120 dB rms. Also, it is important to note that clipping occurred mainly in events of this noise class, thus the reported SPLs here are conservative.



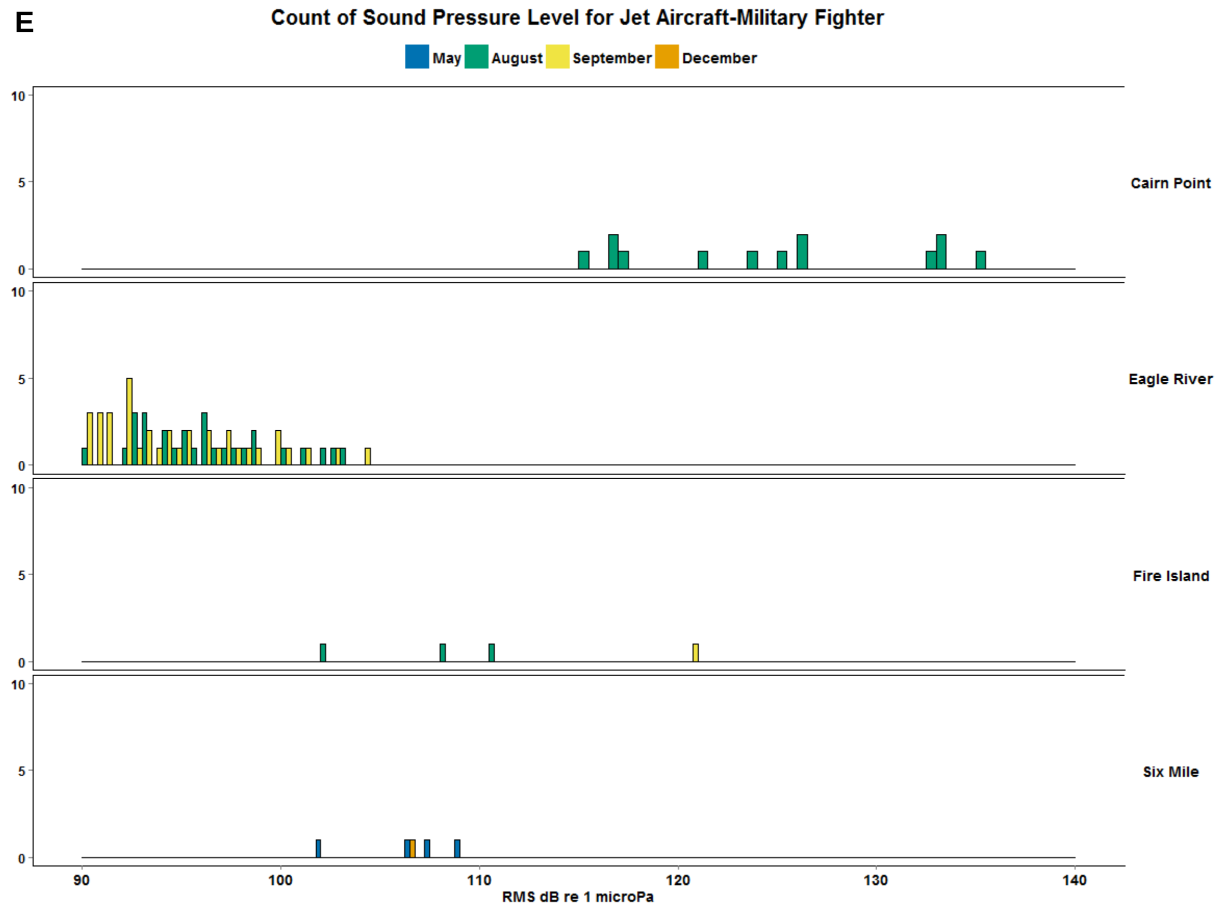
Dredging noise was only detected in Cairn Point and Six Mile, although this noise class was difficult to discern and could be an important contributor in other noise classes such as unclassed machinery and unidentified. Dredge activity logs have been requested to the POA[4] to assist in the classification of this noise source, but data has not yet been received. The detection of multiple events of dredge noise at Six Mile suggest, as with the case of commercial ship noise, that belugas are exposed to this noise source even if they avoid the eastern side of the lower Knik Arm. Six Mile SPLs did not exceed 120 dB rms but were close to this threshold. This suggests that dredge noise right across the arm in the dredging area, which is half the distance to Six Mile, might well exceed 120 dB rms, thus exposing any beluga that access or exits Knik Arm to relatively high levels of noise from this activity.

[4] Requested to Julie Anderson, Port of Anchorage operations project manager for the U.S. Army Corps of Engineers. October 2014.

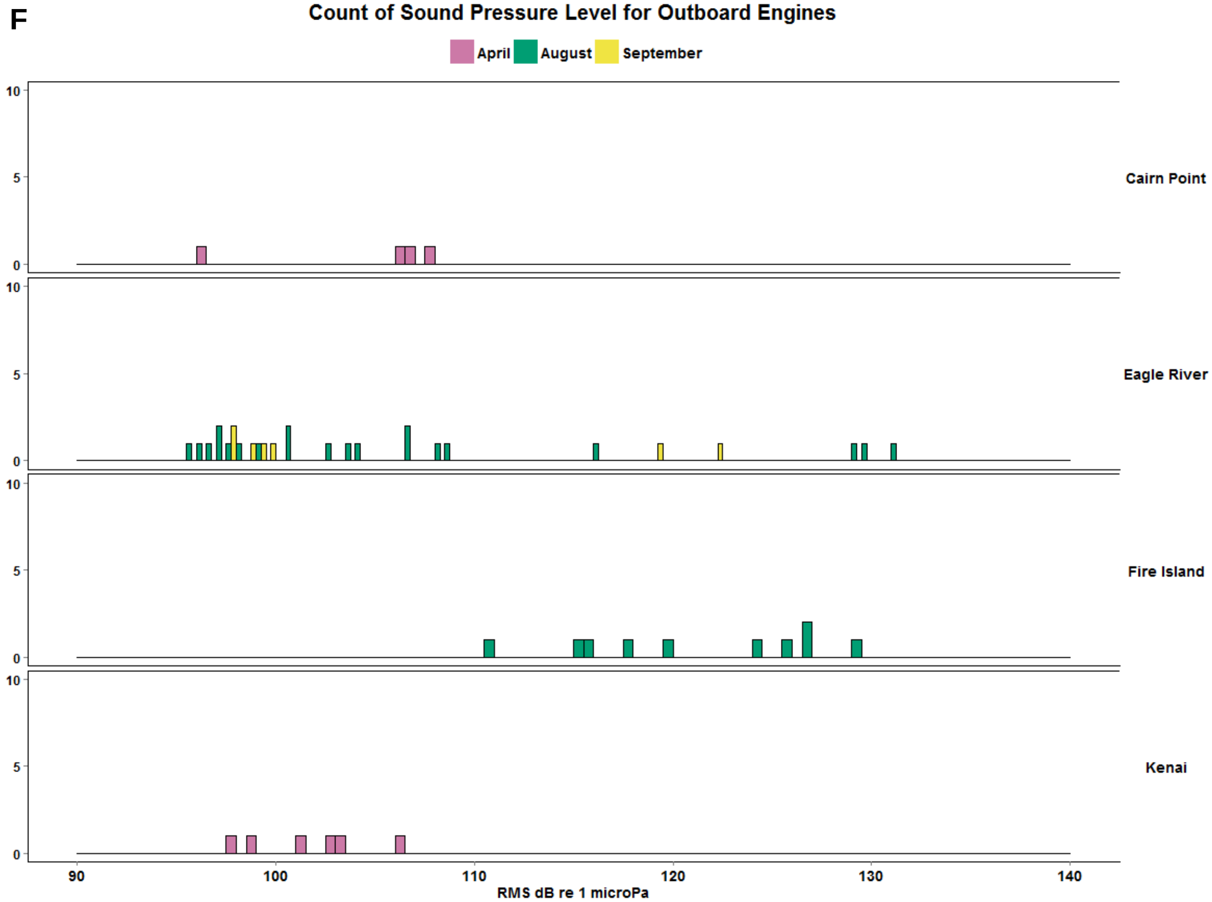


Helicopter noise was detected in only 7 times, all at Six Mile in December. This is a small sample size but important as it contributes to the diversity of anthropogenic noise detected in the data.

E

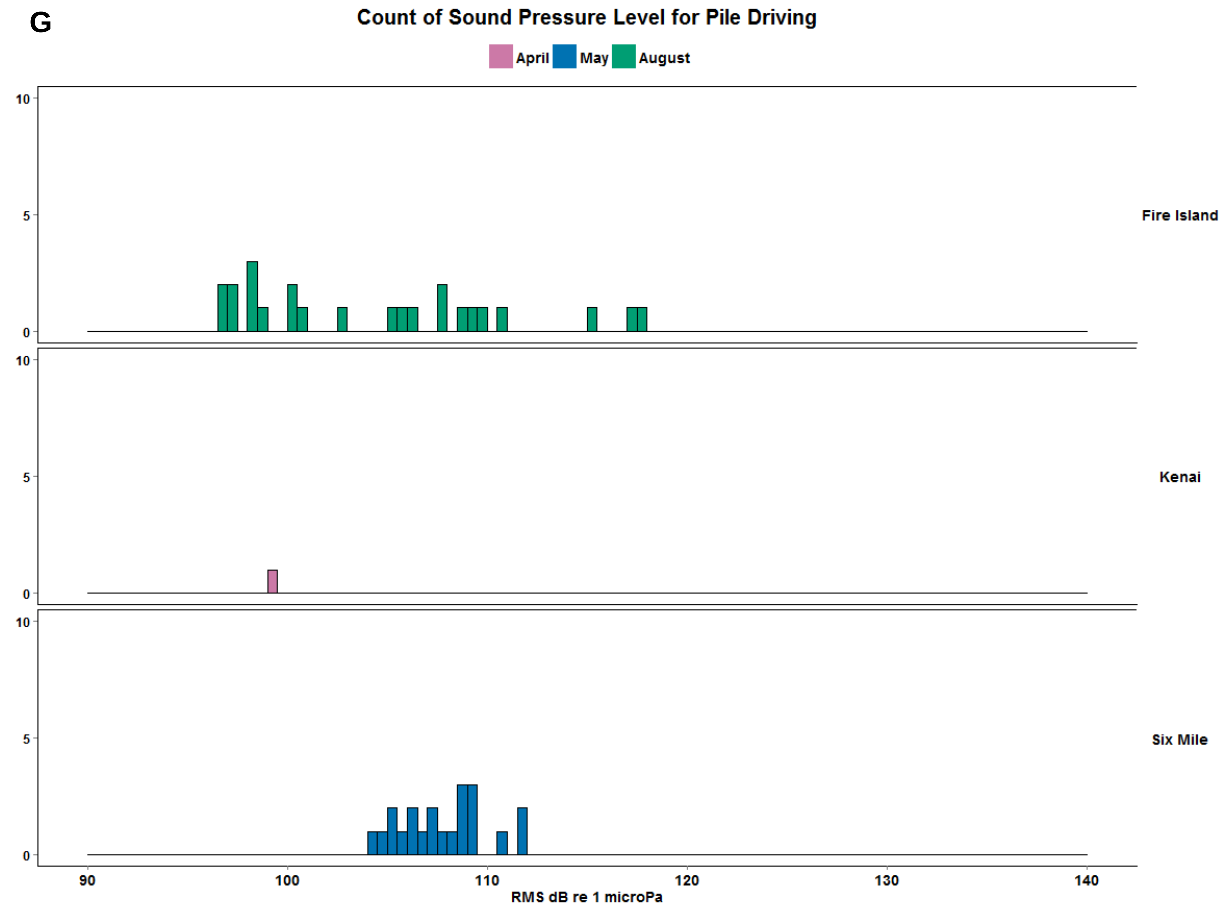


Jet aircraft fighters were detected only in the upper Inlet. Loudest events were detected in Cairn Point, due to the proximity to the Air Force base. Many events were also detected in Eagle River, however received SPLs there were lower than in Cairn Point, which might be related to differences in altitude between both sites when the jets were detected.



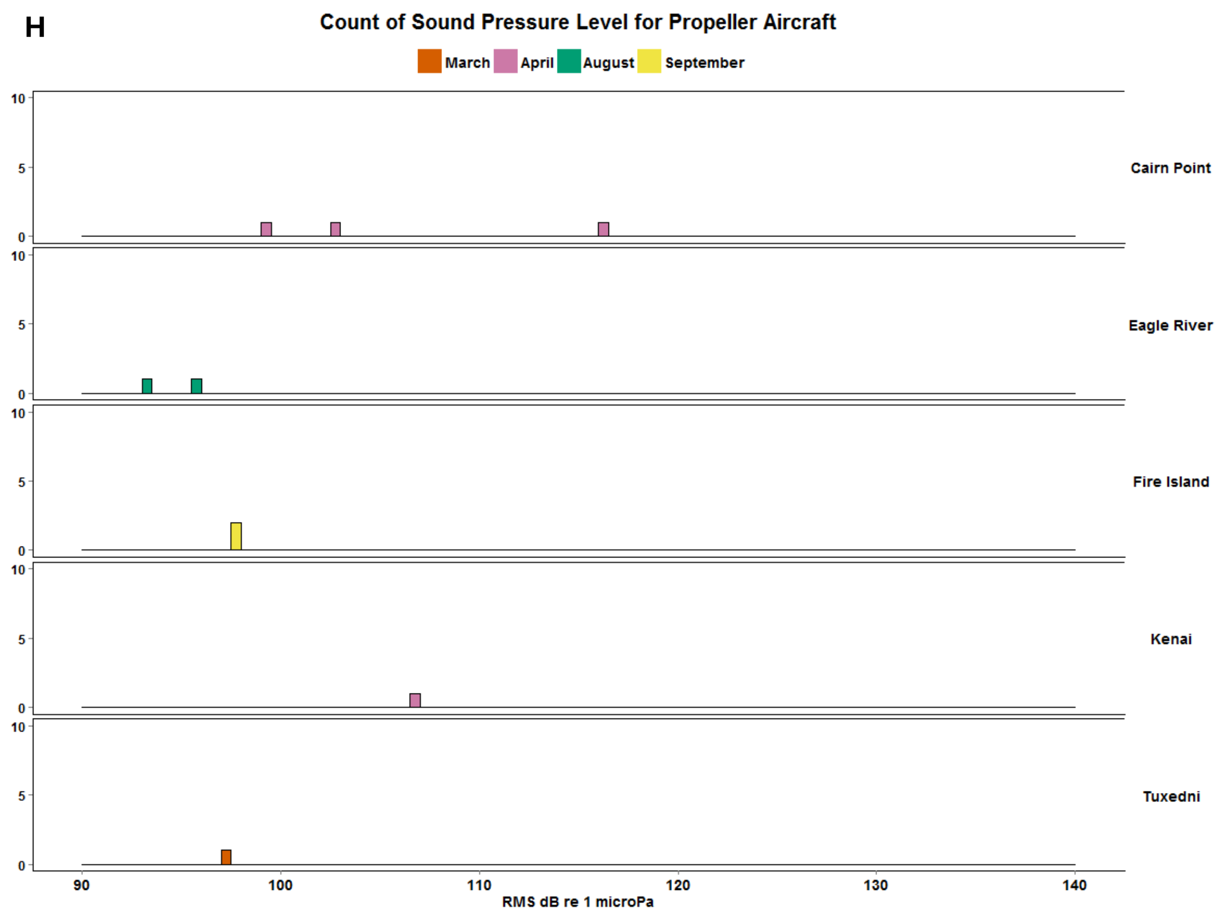
Outboard engines were detected in 4 different locations, both in the upper and lower Inlet. SPLs are varied and probably reflect the different distances at which these noise sources were detected rather than differences in the noise source itself. In total, there were 48 events detected in 3 different months, suggesting that outboards are often used in Cook Inlet, at least from April to September.

G

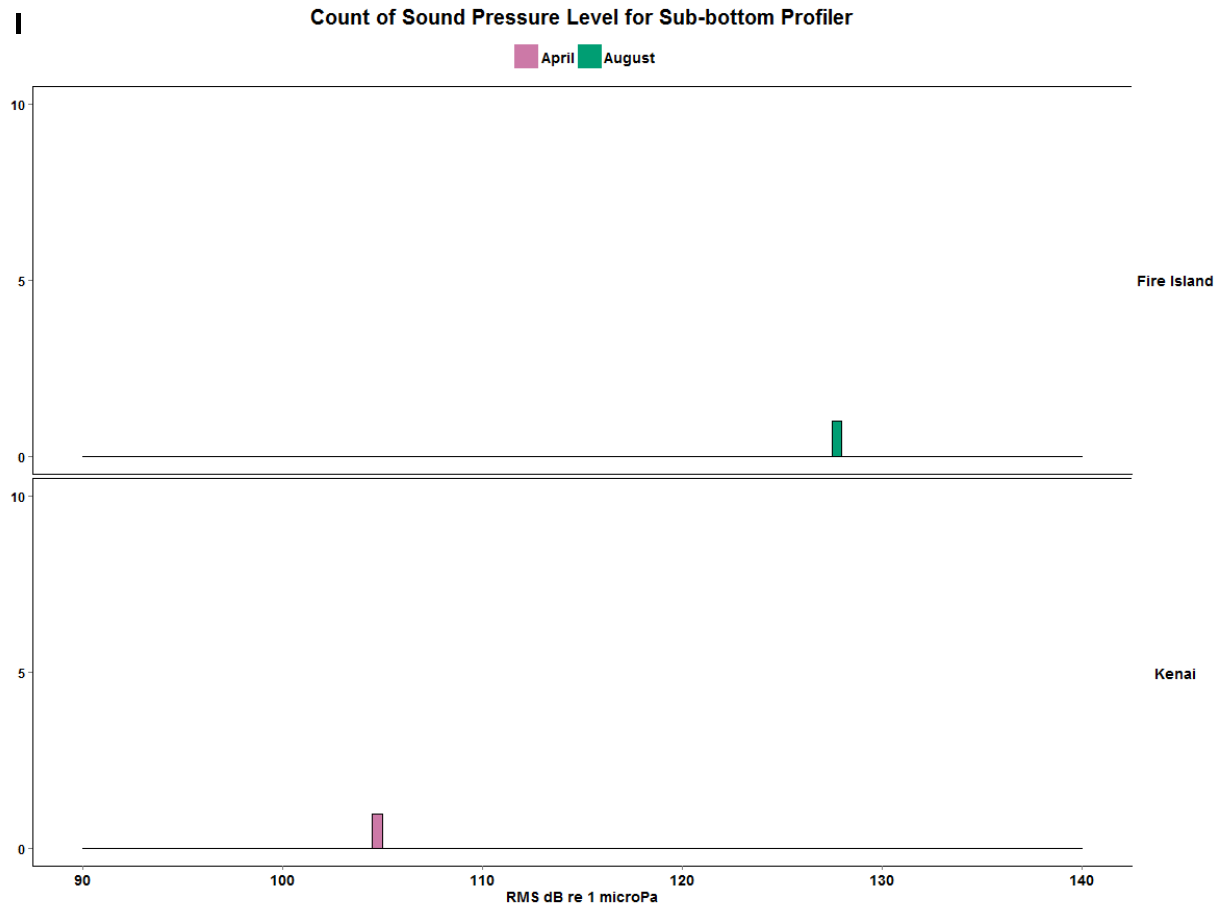


Pile driving was most probably originated in the POA (metal sheet driving), as part of their expansion project. We are not aware of other pile driving activities in Cook Inlet during the sampled period. This noise class was detected at Fire Island, Six Mile and Kenai. We do not have detections in Cairn Point because the selected data from this location did not overlap with pile driving activities in the POA. Loudest events occurred at Fire Island, even if this location is further away from the piling location than Six Mile. However, reported SPLs should be interpreted with caution because these events include all the sound recording from the first detected pile blow to the last one, which occur in a sequence that can last minutes to hours. Thus, this metric includes both the noise generated by the hammer blows to the pile and the silence between impacts in the sequence (see table 2); therefore received levels in SPL are vastly underestimated.

It is interesting to note that even if the pile driving activity is presumed to be originated at the POA, received levels in Fire island are above background noise levels (because otherwise would have not been detected). This suggests that this pile driving event ensonified well in excess of the background noise levels a vast region of Knik Arm and the upper Inlet, covering for sure the Knik Arm width, leaving no area free of this noise disturbance for belugas to access or exit the Arm.



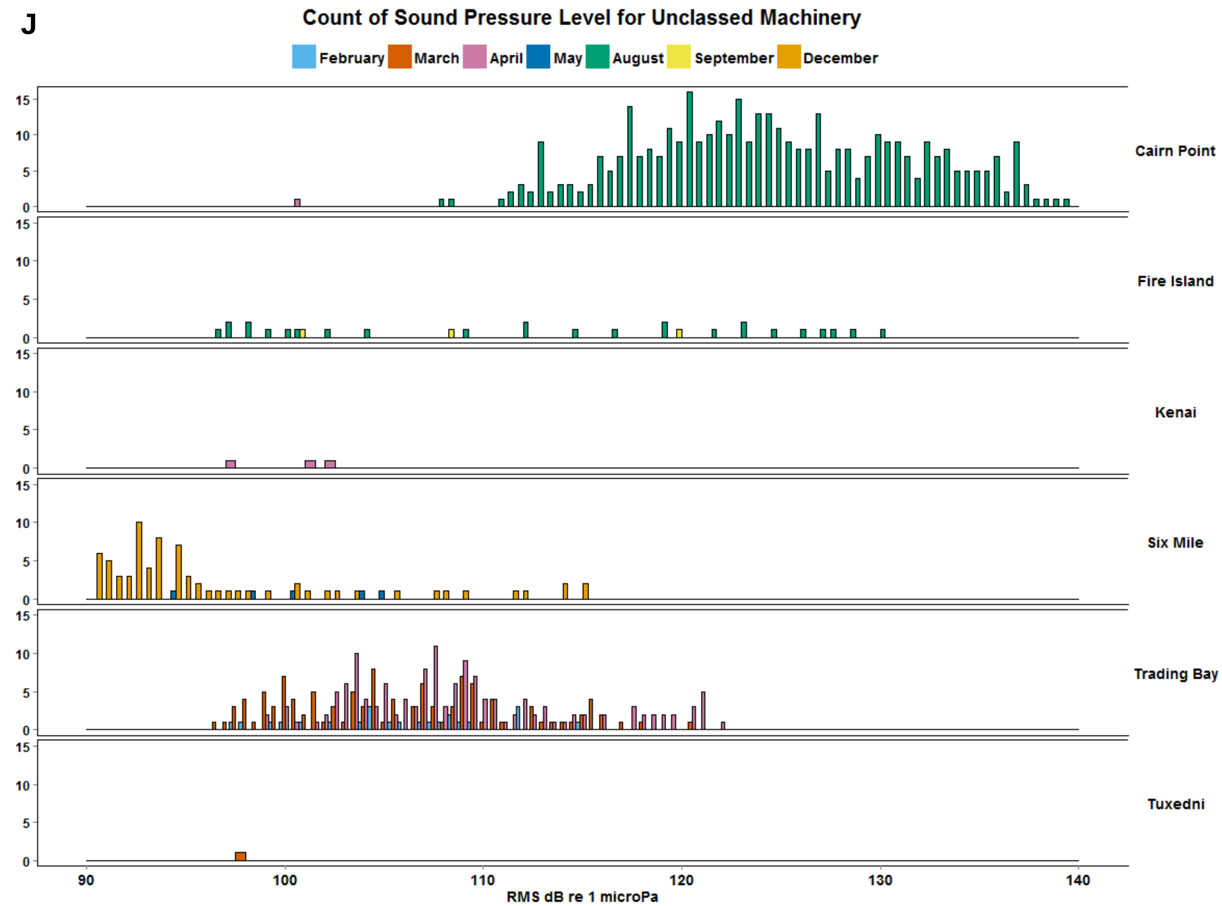
Propeller aircrafts were detected in 5 locations both in the upper and lower Inlet. SPLs ranged from 92 to 115 dB.



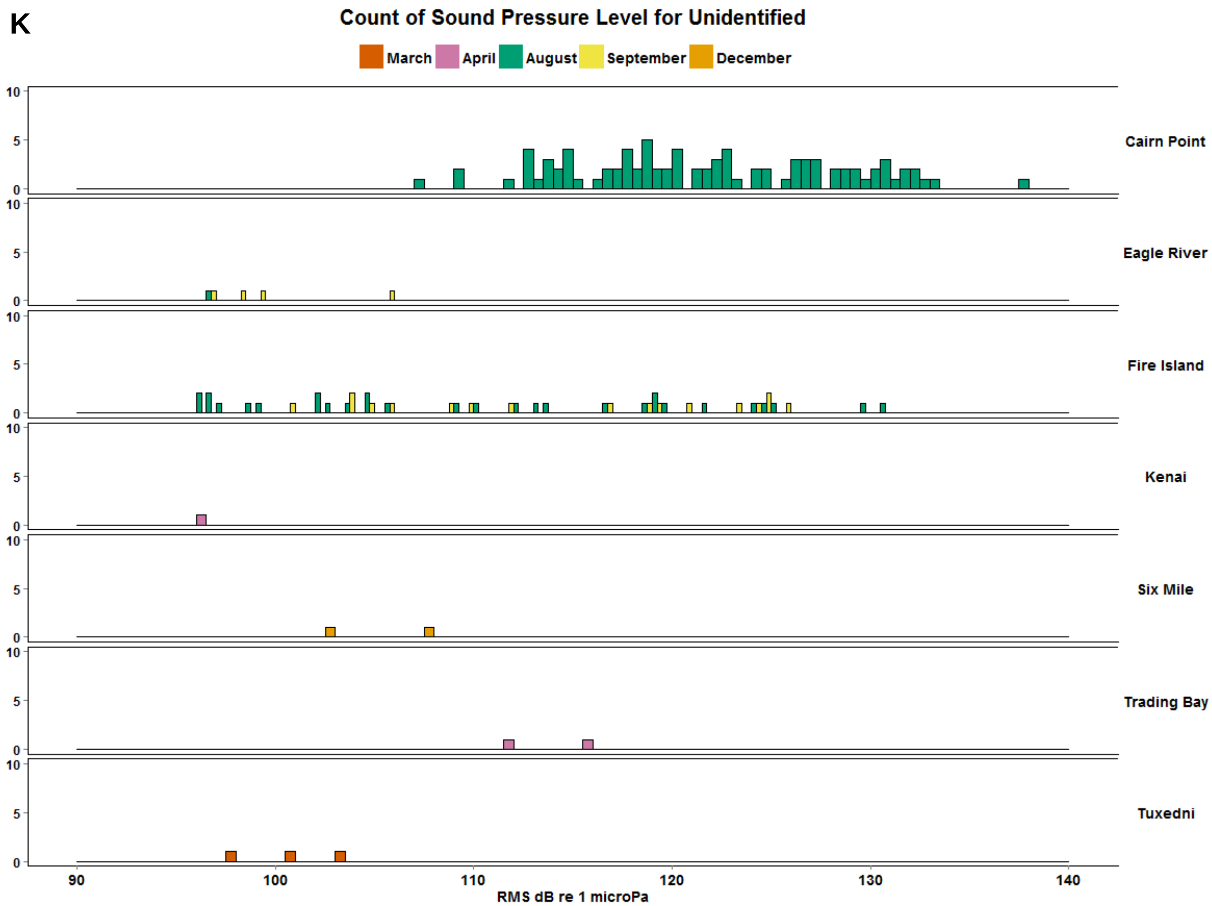
Transducer generated sweeps in a sequence (see table 2) from a sub-bottom profiler were detected at the Fire Island deployment location for more than 9 consecutive hours in August 19th 2009 and in Kenai on April 1st 2012. This activity in Fire Island was related to a survey for a marine renewable energy project; however the survey in Kenai has not been identified.

Similar to pile driving, reported SPLs for sub-bottom profiler noise should be interpreted with caution because these events include all the sound recorded from the first detected sweep to the last one, which occur in a sequence that lasted hours. Thus, this metric is including both the noise generated by the transducer used for the survey and the silence between sweeps in the sequence (see table 2); therefore received levels are vastly underestimated. SPLs reported in Fire Island, considering that the silence intervals between sweeps are included in the calculation, suggest that this activity ensonified a wide area with levels exceeding 120 dB rms. Furthermore, this noise class also suffered clipping (Fig. 2), another reason to consider the SPLs reported here as very conservative.

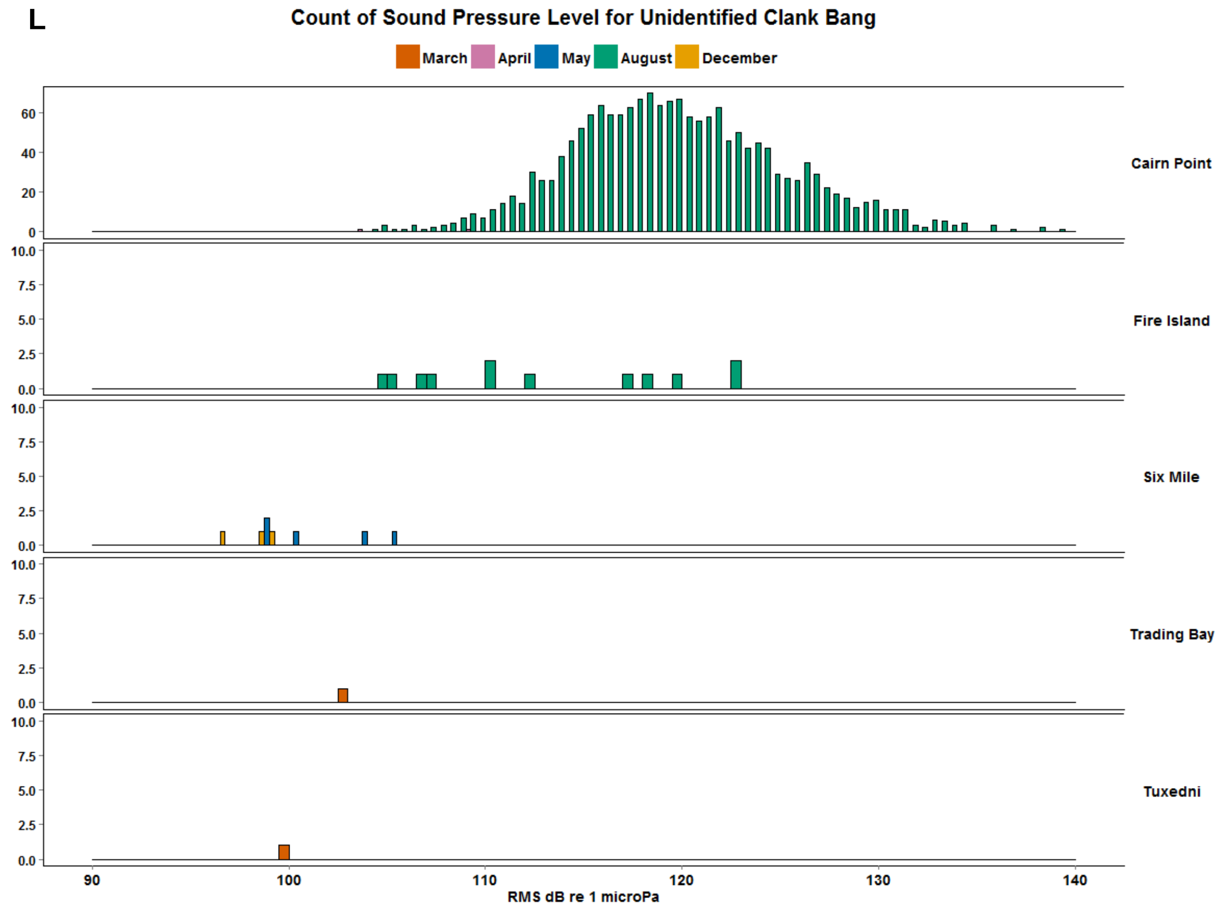
J



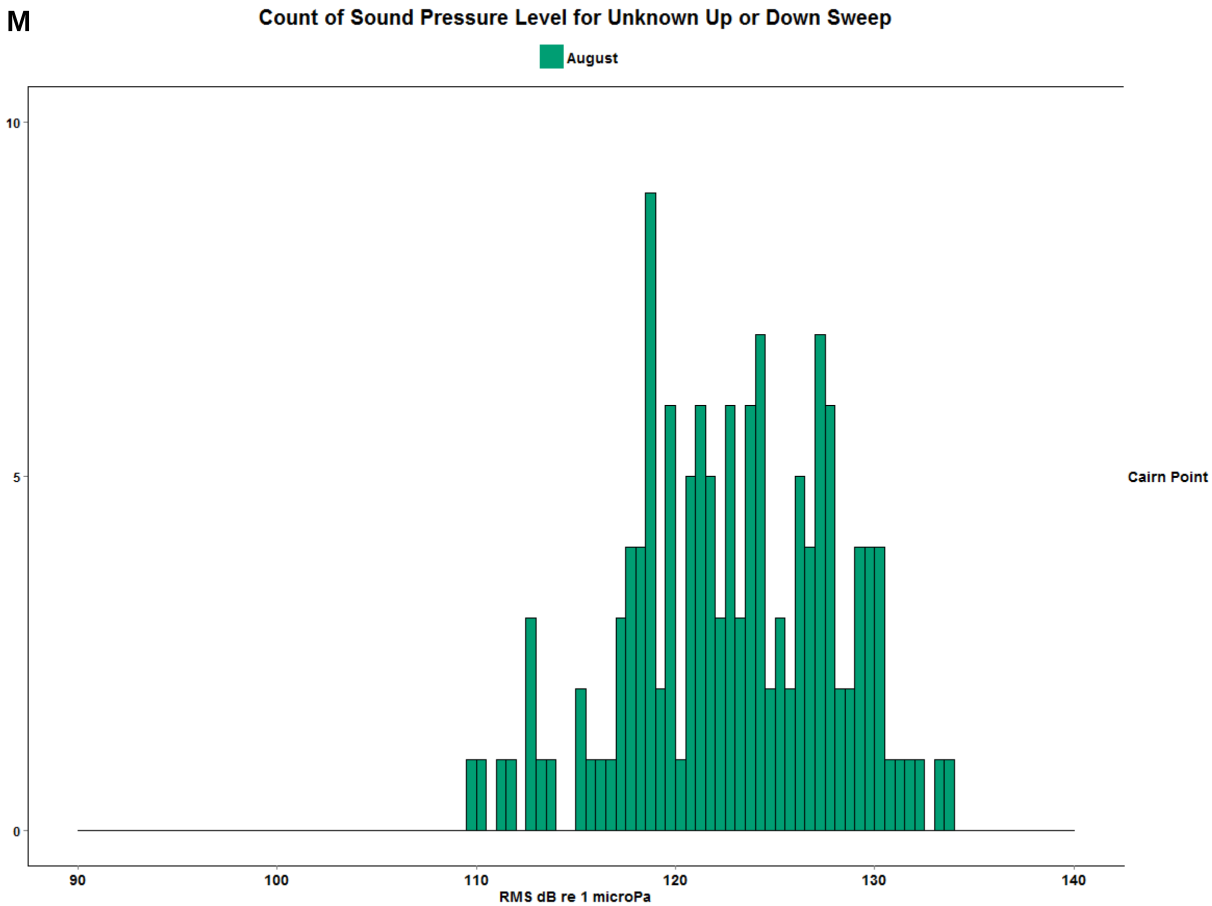
Unclassed machinery is present in all the analyzed datasets and corresponds to any mechanical or engine noise that we were not able to classify. Cairn Point and Six Mile include the highest percentage of time for this noise class (Fig. 3) and with longest duration (Fig. 4), however SPLs are higher in Trading Bay than in Six Mile. Cairn Point is exposed to most of the noise derived from the construction activities at the POA, as well as dredging activities and the shipping activity of the port itself. Six Mile might get noise from the POA but is closer to Port MacKenzie. Trading Bay included recurrent unclassed machinery noise that could be related to the oil and gas production activities in or around the multiple platforms in that location.



Unidentified noise class included anthropogenic sources of noise that were not clearly originated from machinery but were clearly not natural. This noise class occurred in all the analyzed data sets. In most occasions, these events occurred concurrently with other sources of anthropogenic noise. Cairn Point and Fire Island included the loudest events for this noise class. Because Cairn Point is an area where many anthropogenic activities concur in summer, it is expected to have a high number of noise events related to anthropogenic activities, and thus a high number of unidentified events. Fire Island is still exposed to many of the activities occurring around Cairn Point, but could also be have an important influence from commercial shipping as all traffic from and to the POA uses the area where the mooring was deployed. This suggests that an important fraction of the events classified as unidentified might be related to commercial shipping.



Similar to unidentified noise class, unidentified clank or bang noise include the highest percentage of time (Fig. 3) and with longest sequence duration (Fig. 4) in Cairn point and Fire Island (as discussed earlier, this noise class often occurred in series with random intervals). As discussed in Figure 7, this noise class might be related to shipping operations, where tug boats assist commercial vessels or barges and impact sounds are generated. Loudest events occur in Cairn Point, followed by Fire Island, which might be a direct reflection of the distance from the recorders to the area where these noises are generated. Clipping was also important for this noise class, therefore reported SPLs here are conservative.



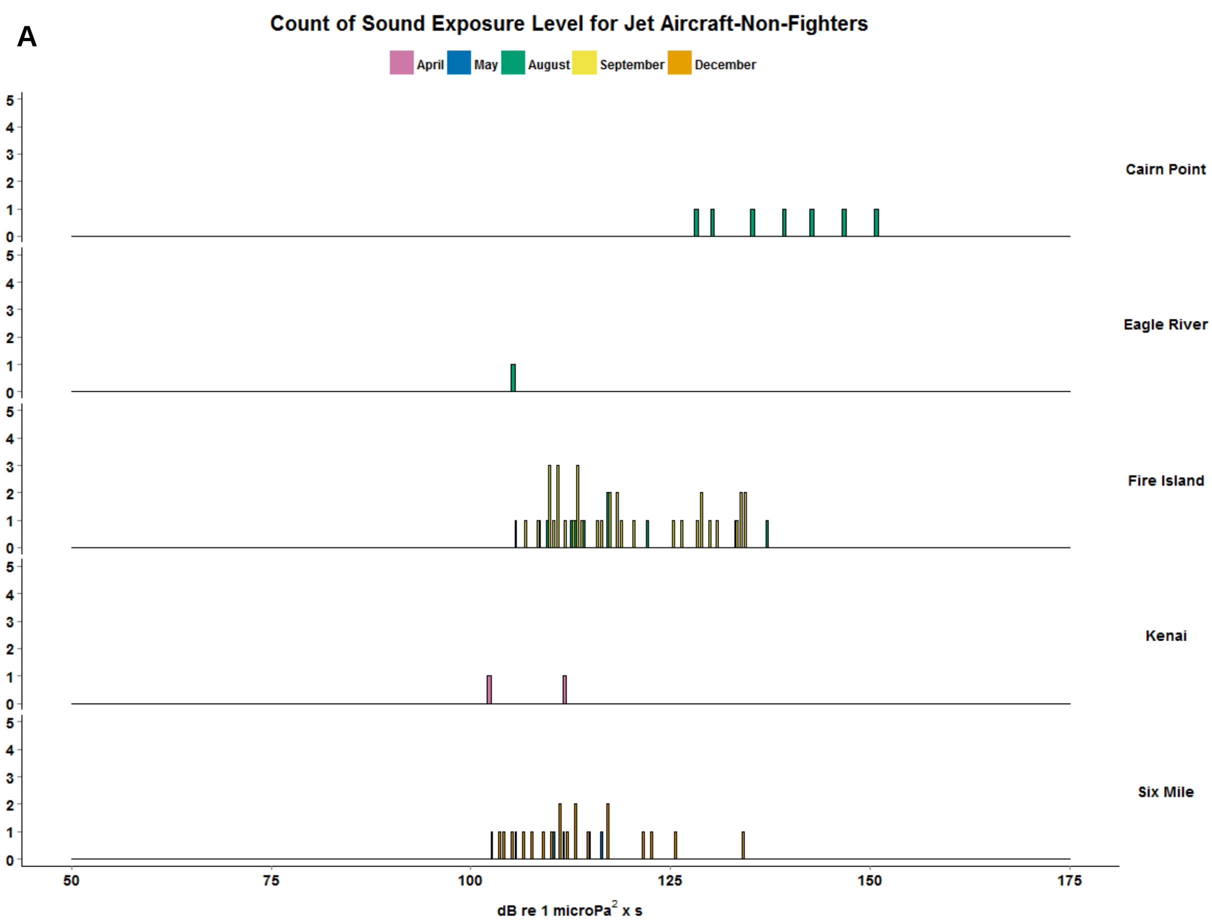
Unknown up or down sweep noise was a very particular and prevalent event that occurred exclusively at Cairn Point (data from August 2010). This noise class was concurrent with unclassed machinery and often occurred during changes in intensity of the related machinery noise or what it was believed to be a reduction in rpm. It is not believed to be originated from dredging operations[5]. This noise class should be related to an in-water activity occurring in a restricted area around Cairn Point, at least during August 2010.

Figure 8: SPL in dB rms by noise class, month and location from all the anthropogenic noise events detected in the sampled locations in Cook Inlet, Alaska. Noise classes included are A- jet aircraft (commercial or military non-fighter), B- commercial ship, C dredging, E- helicopter, F- outboard engine, G- pile driving, H- propeller aircraft, I- sub-bottom profiler, J- unclassed machinery, K- unidentified, L- unidentified clank or bang, and M- unknown down or up sweep.

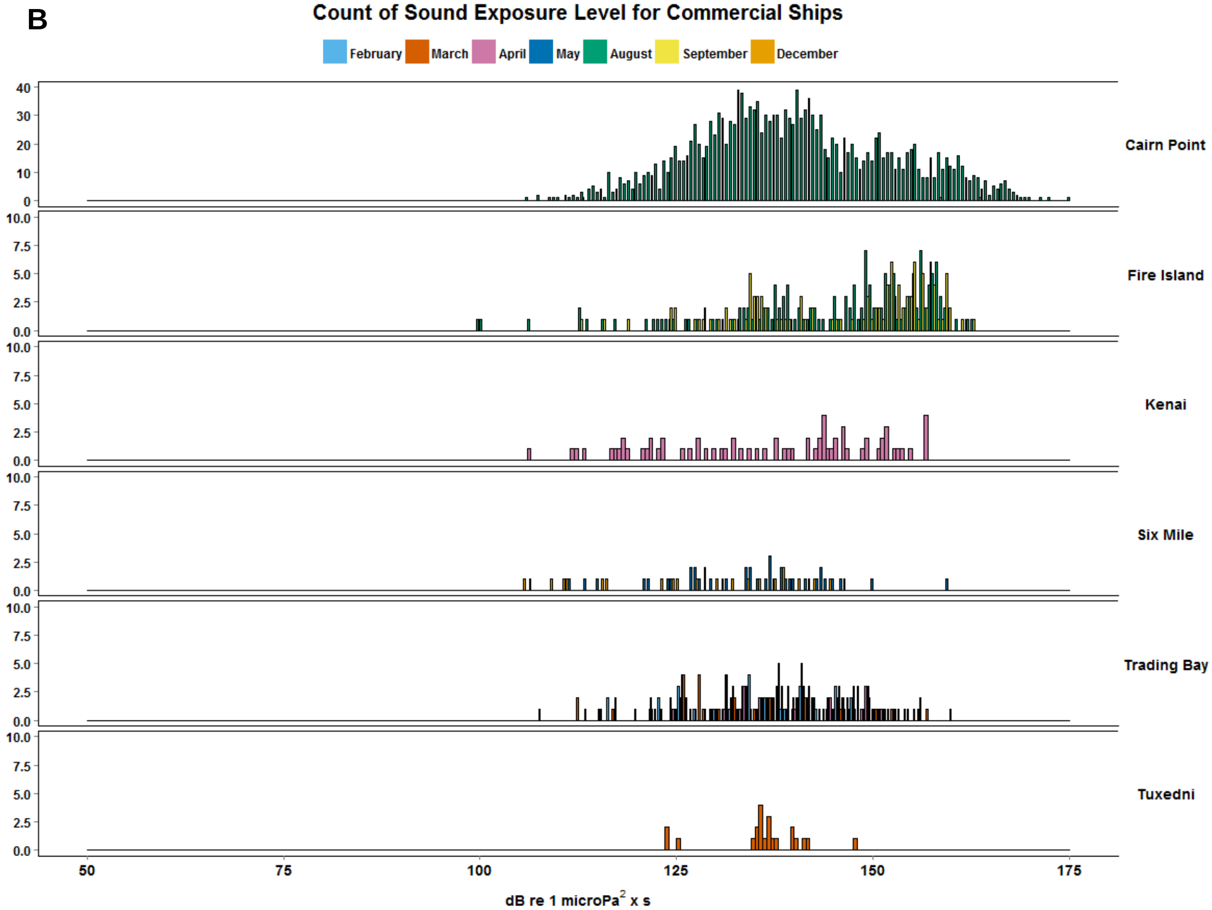
[5] Julie Anderson. Port of Anchorage operations project manager for the U.S. Army Corps of Engineers. Pers. Comm. Nov 25th 2014.

4.4.b SEL histograms

This metric represents the acoustic energy flux from detected events, which considers both the loudness (acoustic pressure) and the duration (time) of the event. Sound pressure is measured over the duration of each event on a case by case basis. Energy flux is given by the time integral of the pressure squared. The figure below shows the distribution of SEL for all the events of each noise class and for each location and month, across a dB scale spanning from 50 to 175 dB. In this case, the upper limit presented in this figure exceeds the 144 dB rms technical limitation because of the cumulative effect of events of long duration (i.e. events that did not reached 144 dB rms at any single time but lasted long enough to increase the SEL value above 144 dB). Note that y-axis scale is different across panels.

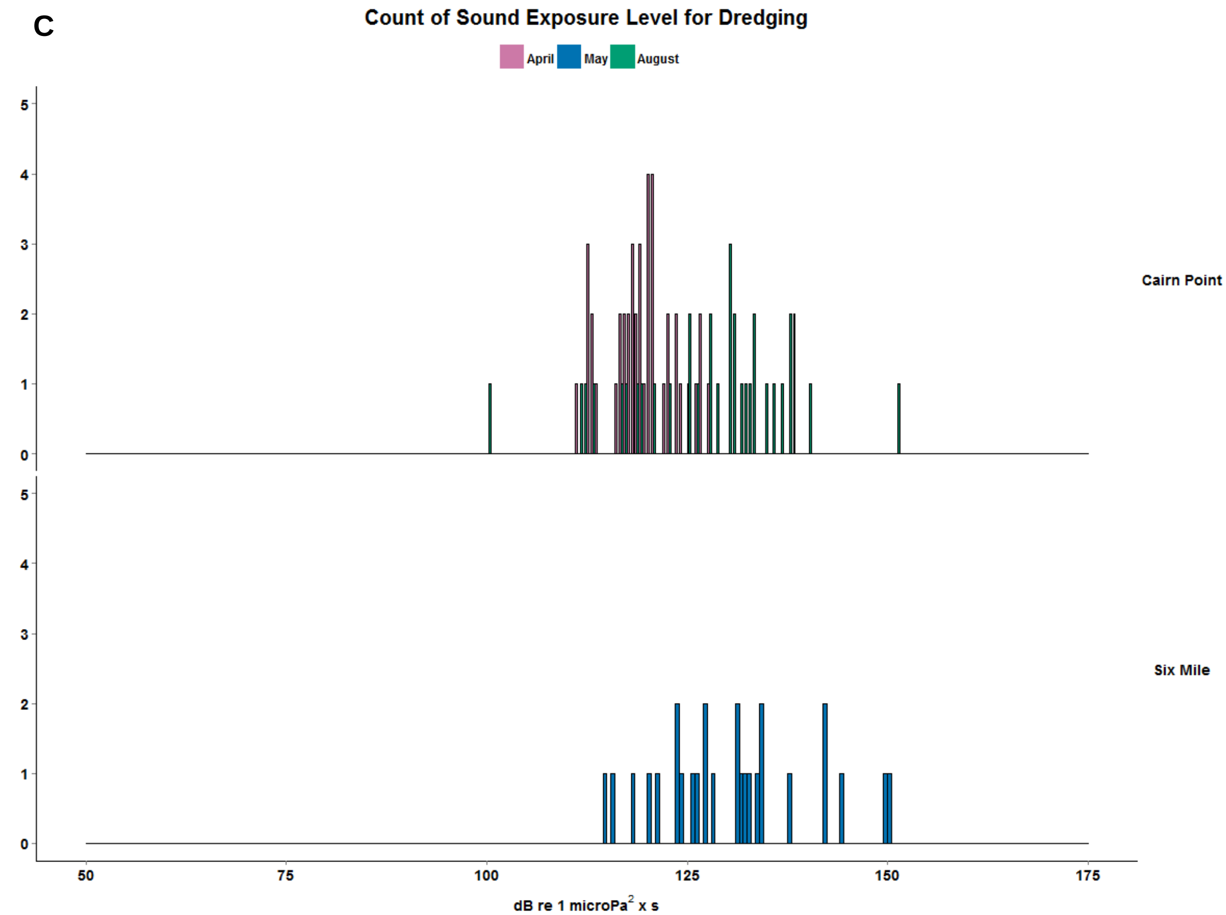


Jet aircraft (commercial or military non-fighter) noise, although short in duration (Fig. 4), presents relatively high SEL values for Cairn Point, which is the closer mooring location to an airport. When compared to SPL (Fig. 8A), it is interesting to note that levels at Fire Island and Six Mile are similar when measured as SEL, but lower at Six Mile when measured as SPL. This difference highlights how the longer duration of the events at Six Mile (Fig. 4) has a stronger weight in the SEL metric than for events at Fire Island.

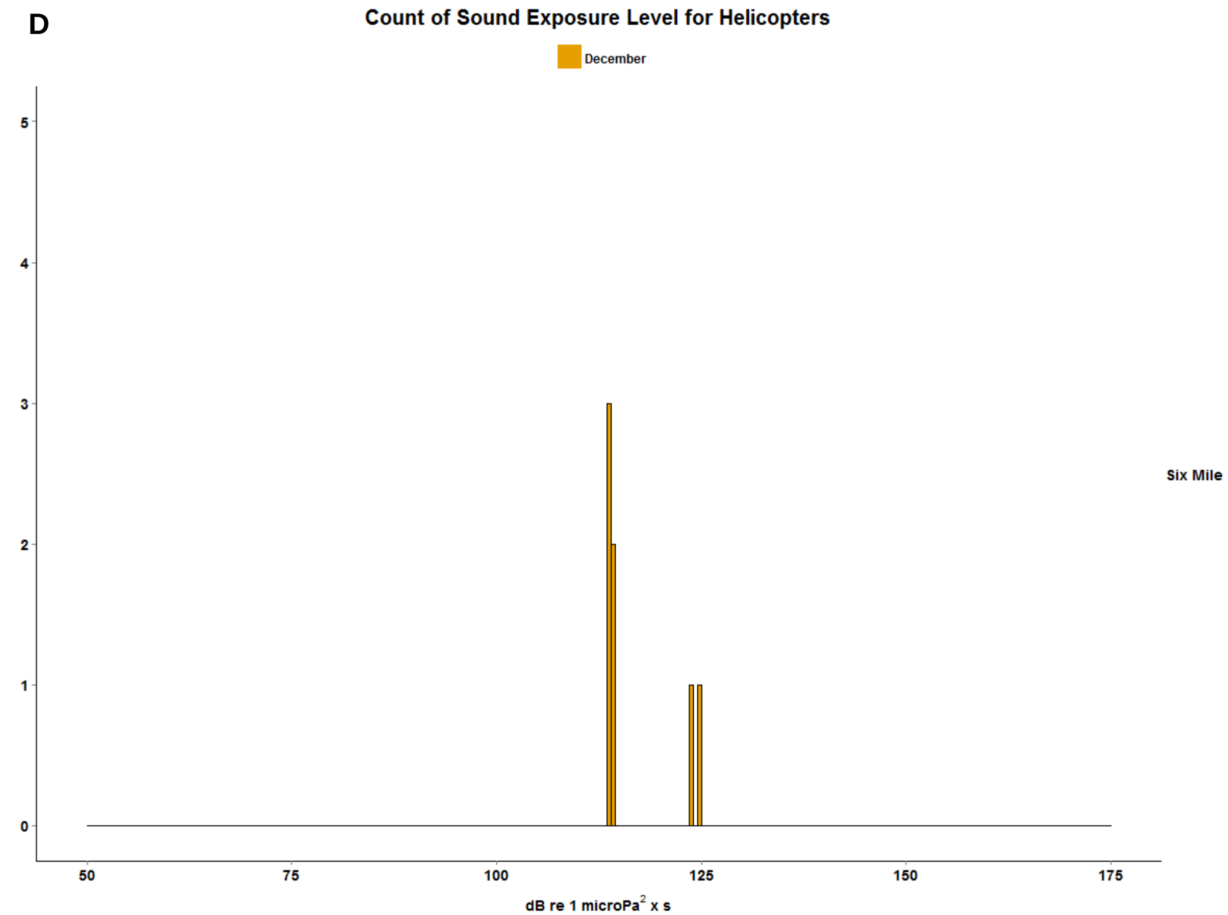


Commercial ship noise, when considering the duration of the events, balances out the loudness differences across sites (Fig. 8B). This panel shows how SEL for most commercial ship noise events in Cook Inlet falls within approximately 125 to 150 dB in all locations and months where it was measured.

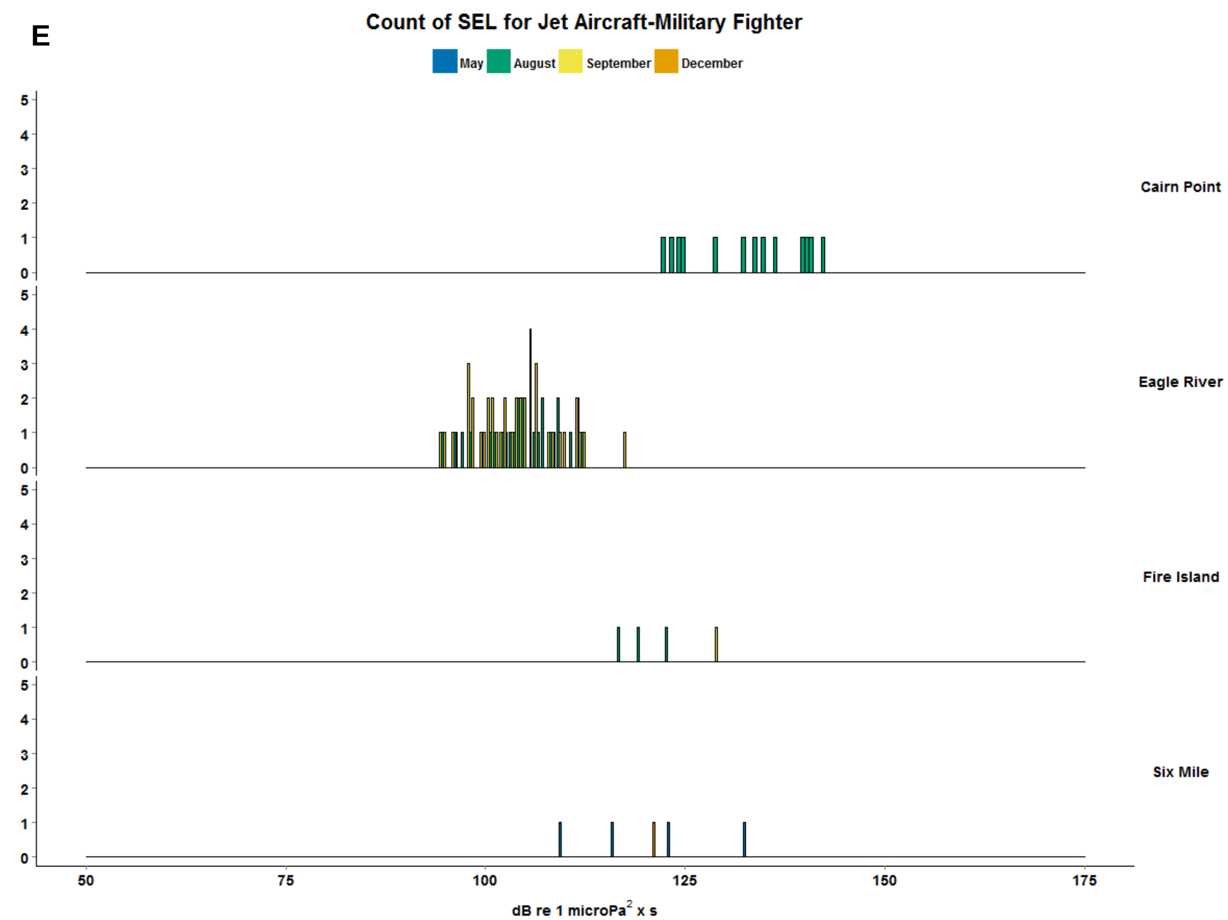
Although SPLs for commercial shipping at Six Mile were lower than at Cairn Point, when considering the cumulative effect over time, the levels are closer between locations. This suggests that commercial ship noise exposure to belugas in either side of the lower Knik Arm might not be very different, as discussed earlier.



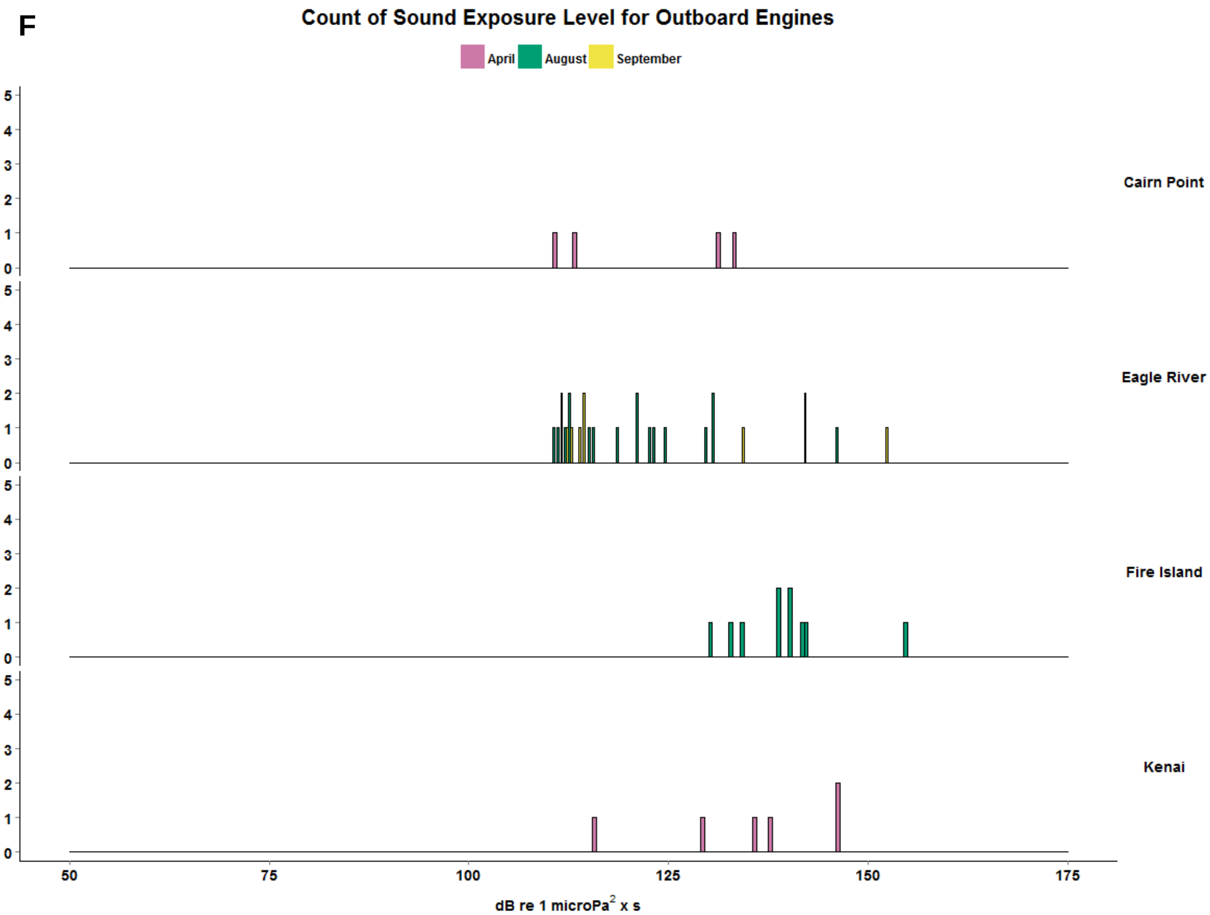
Dredging noise loudness measurements also show slightly different results when considering the duration of the events. SPL values indicated that this noise class was louder, particularly in August, at Cairn Point than at Six mile. However, SEL values presented here indicate the opposite. Six Mile dredging noise, although very similar in dB distribution has louder events. Because dredging activities occurred at different locations between the sampled months, and different dredging methods were used (clam shell vs. hopper)(J. Anderson *pers. comm.* Nov 2014), received levels at both Cairn Point and Fire Island were expected to be different. Further understanding of the differences in dredging radiated noise, spectra and its source levels would be desirable to better address potential negative acoustic effects to Cook Inlet belugas.



Although very small sample, SELs ranged in the 110-125 dB. This small variability could be related to a recurrent path followed by helicopters over Six Mile. Due to the proximity to the Elmendorf Air Base, these could be military helicopters; however we have not attempted to identify helicopter types.

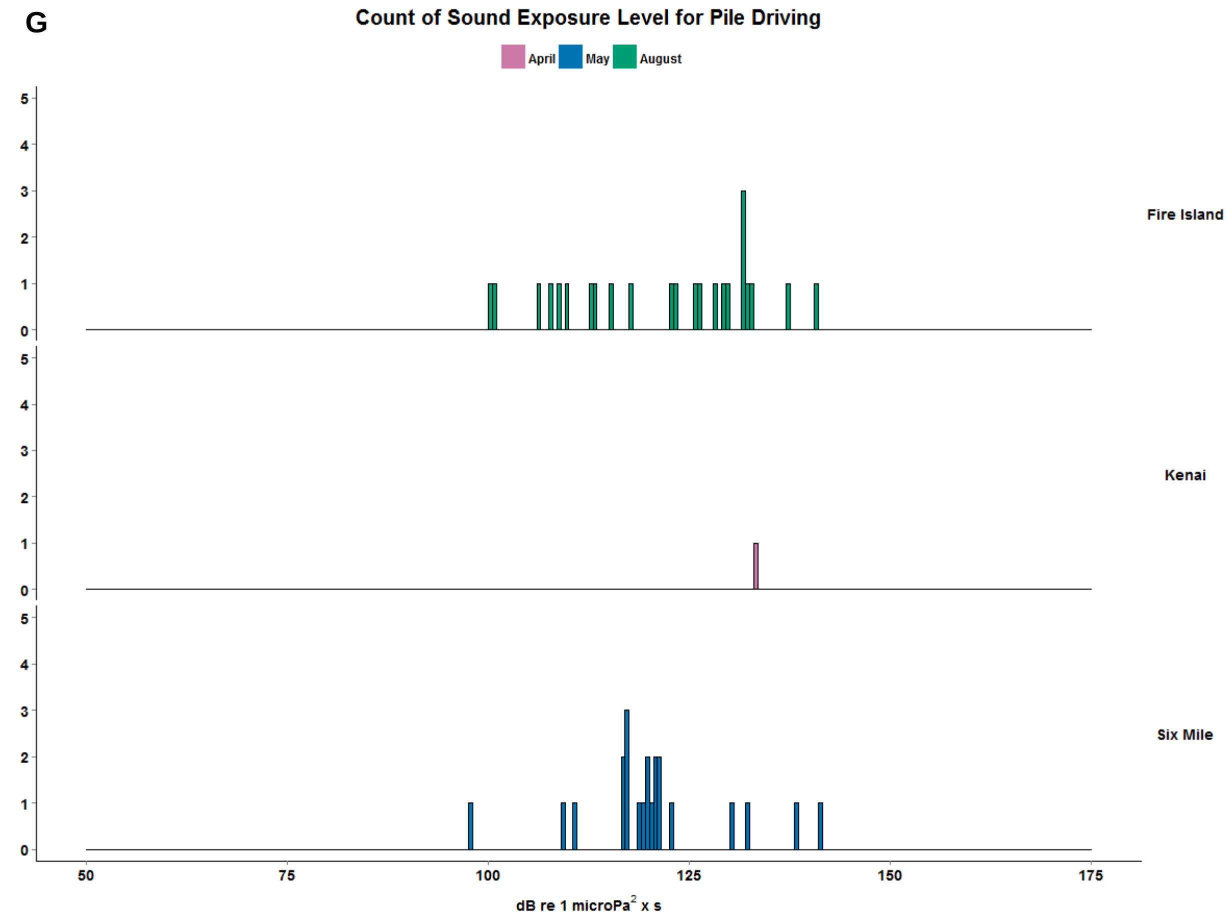


When comparing jet fighter aircraft noise measured as SEL, values are higher but differences across sites are similar to SPL. This suggests that duration of these events is similar across sites.

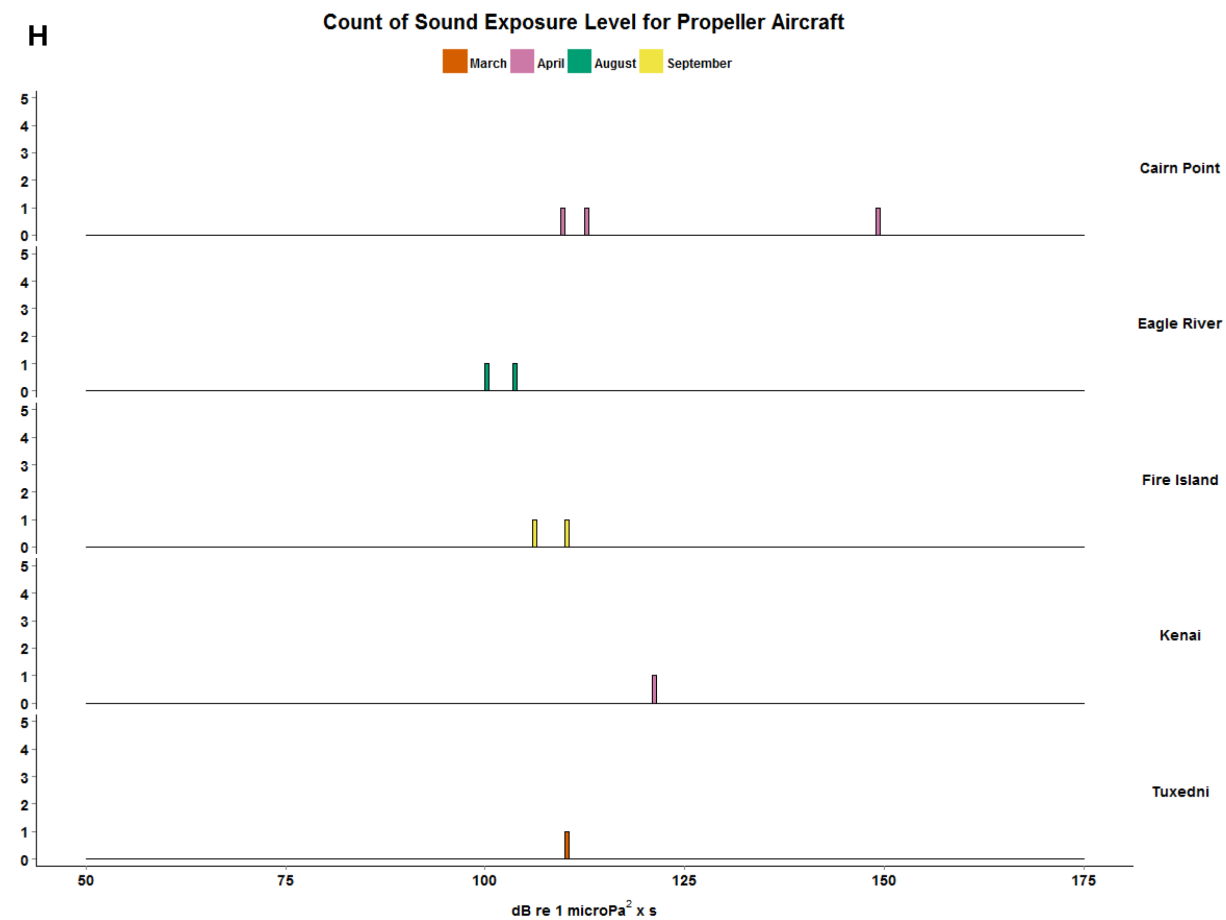


Outboard engine noise was variable in SELs but never lower than 110 dB.

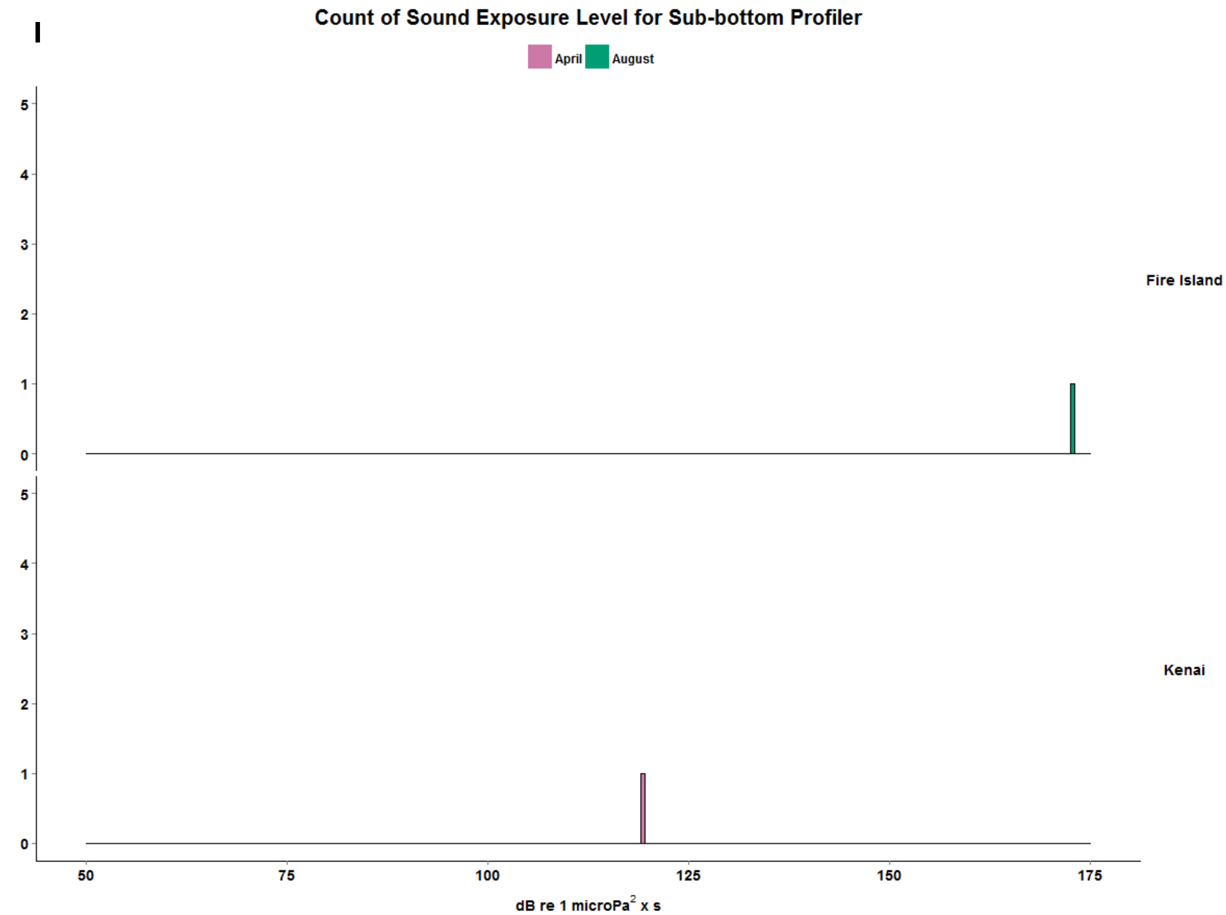
G



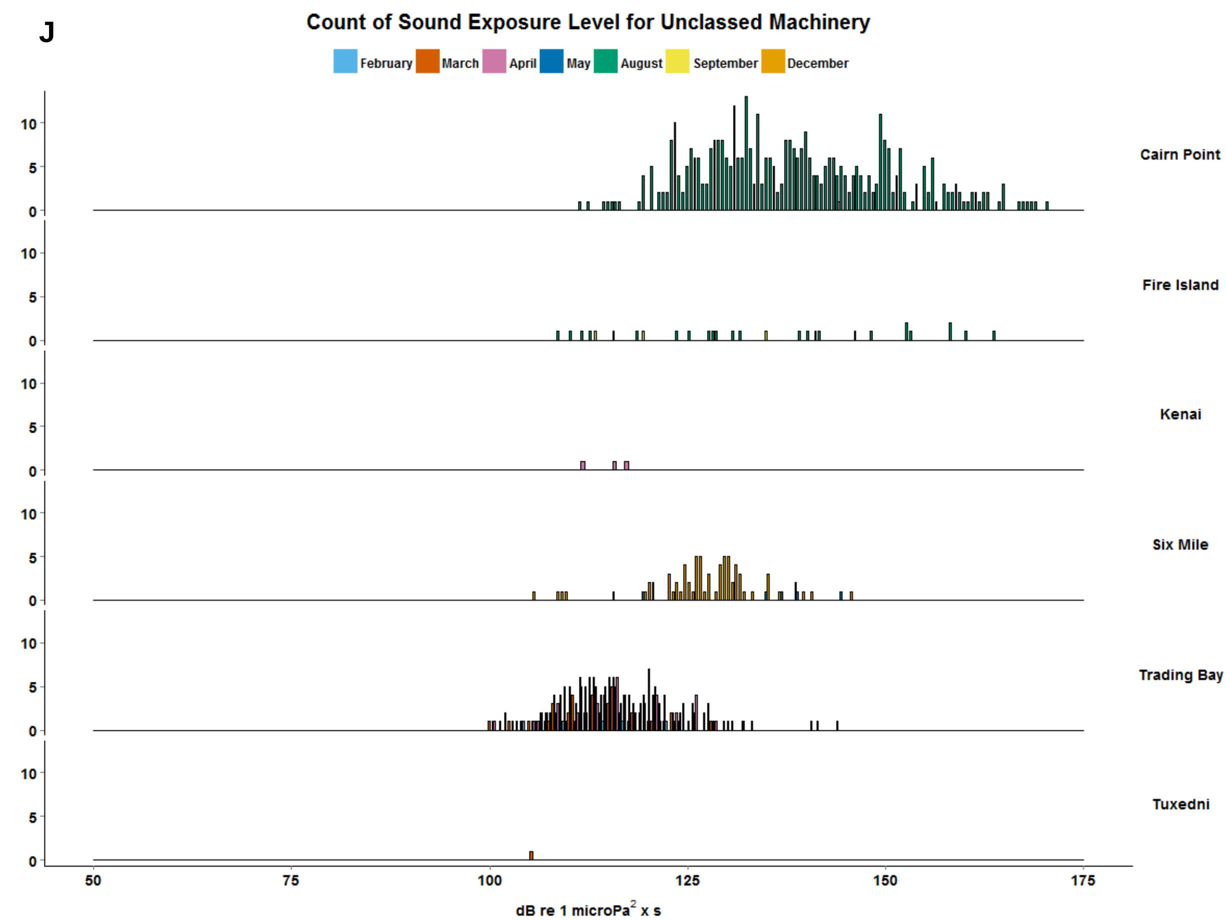
Pile driving noise, when measured as SEL highlights the loudness of this activity. Even if the source was presumed to be several miles away, received SELs ranged in the 90-140 dB. Because pile strike sequences tend to last long periods of time, noise is accumulated over time generating higher SEL values than when measured without considering the temporal domain (e.g. single pile impact measurement). These results support the notion that POA's pile driving exposure to belugas is very similar no matter if they are displaced towards the west side of the arm when accessing or exiting Knik Arm.



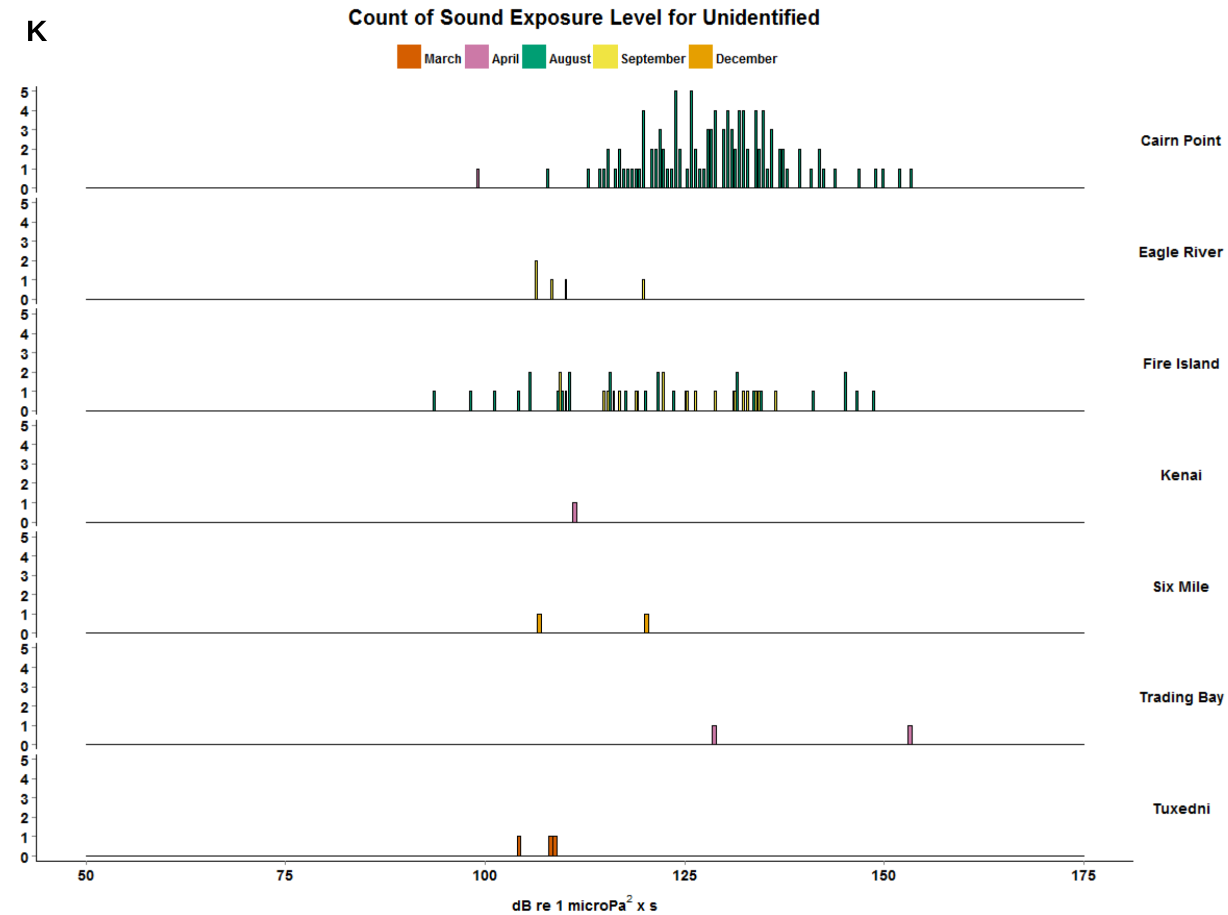
Propeller aircraft SELs predominantly ranged in the 100-125 dB, but one instance from Cairn Point was 150 dB, which could be related to a low flight overpass.



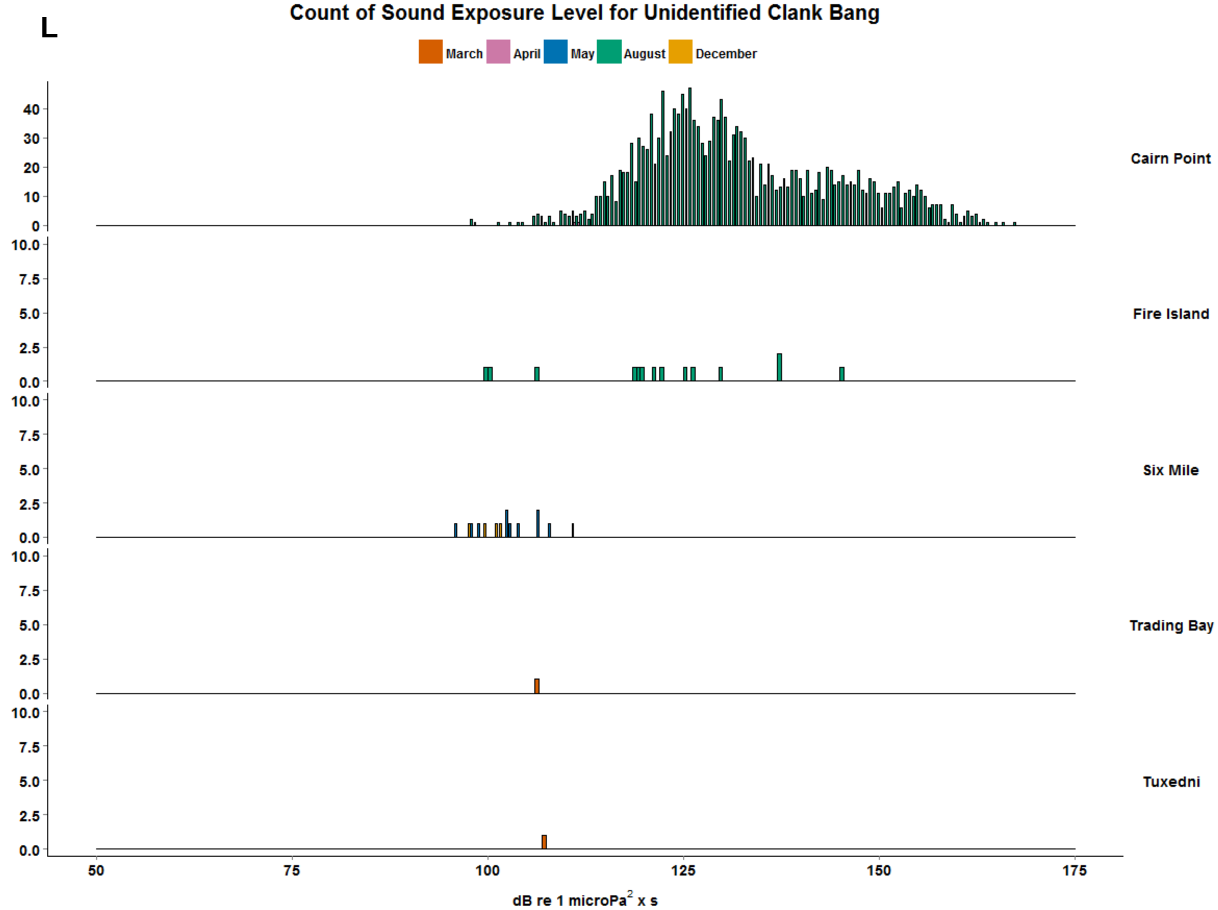
As mentioned in figure 8M, sub-bottom profiler noise occurs in long sequences. When considering the cumulative effect of the duration of these sequences, the received levels are much higher than SPL. This is reflected in Fire Island, where the SEL was close to 175 dB. Furthermore, clipping occurred in this noise class (Fig. 2), indicating that the loudest events have been omitted in the SEL measurement, therefore the reported SELs here should be considered conservative. SEL obtained in Kenai suggests that this operation occurred further away than the detections in Cairn Point. This noise class, together with some events of commercial ship noise, are the loudest anthropogenic noises detected throughout the data analyzed in this study.



Unclassed machinery events in Six Mile appear to be closer in SEL to the other locations in the Upper Inlet than when comparing SPL (Fig. 8J). As with commercial shipping, when considering the duration of these events, loudness differences across sites are become smaller.

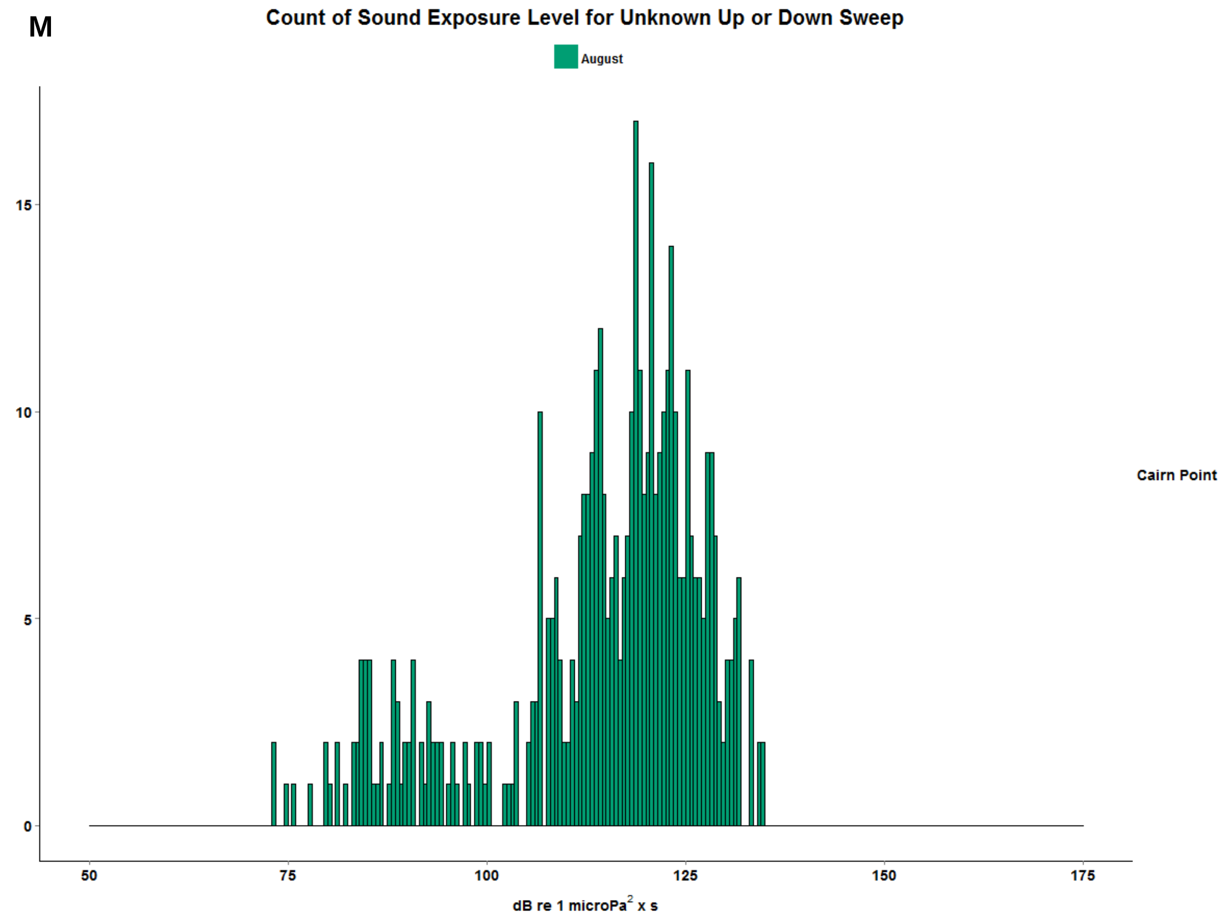


Unidentified noise SEL shows a wide range of loudness as expected because this class probably includes multiple noise sources. There are not evident differences between SPL and SEL other than higher levels due to the cumulative effect of events lasting considerable time.



Similar to unidentified noise class, clank or bang noises show a wide range of SELs and there are not evident differences between SPL and SEL other than higher levels when considering the duration of these events.

M



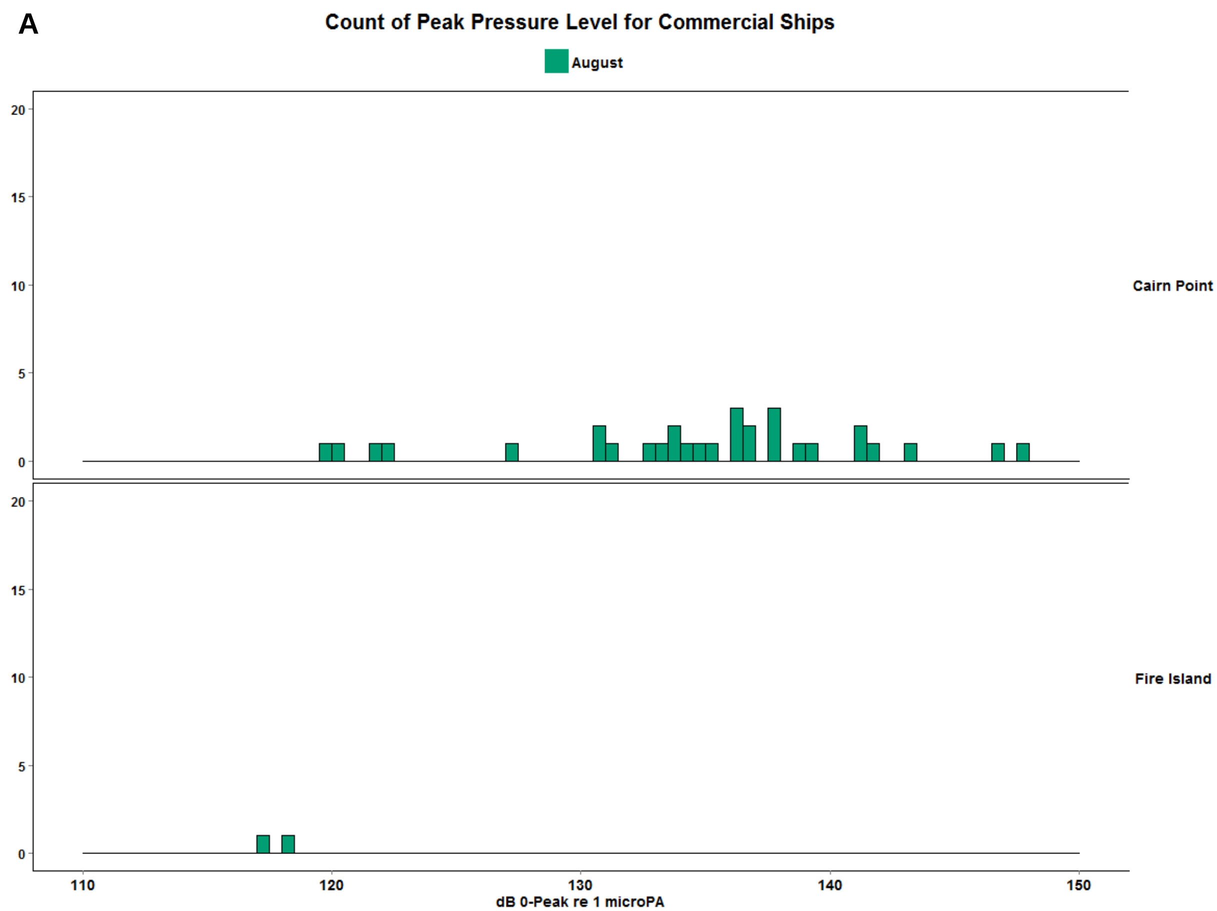
There are no major differences between SPL and SEL for this noise class.

Figure 9: SEL by noise class, month and location from all the anthropogenic noise events detected in the sampled locations in Cook Inlet, Alaska. Noise classes included are A- jet aircraft (commercial or military non-fighter), B- commercial ship, C dredging, E- helicopter, F- outboard engine, G- pile driving, H- propeller aircraft, I- sub-bottom profiler, J- unclassed machinery, K- unidentified, L- unidentified clank or bang, and M- unknown down or up sweep.

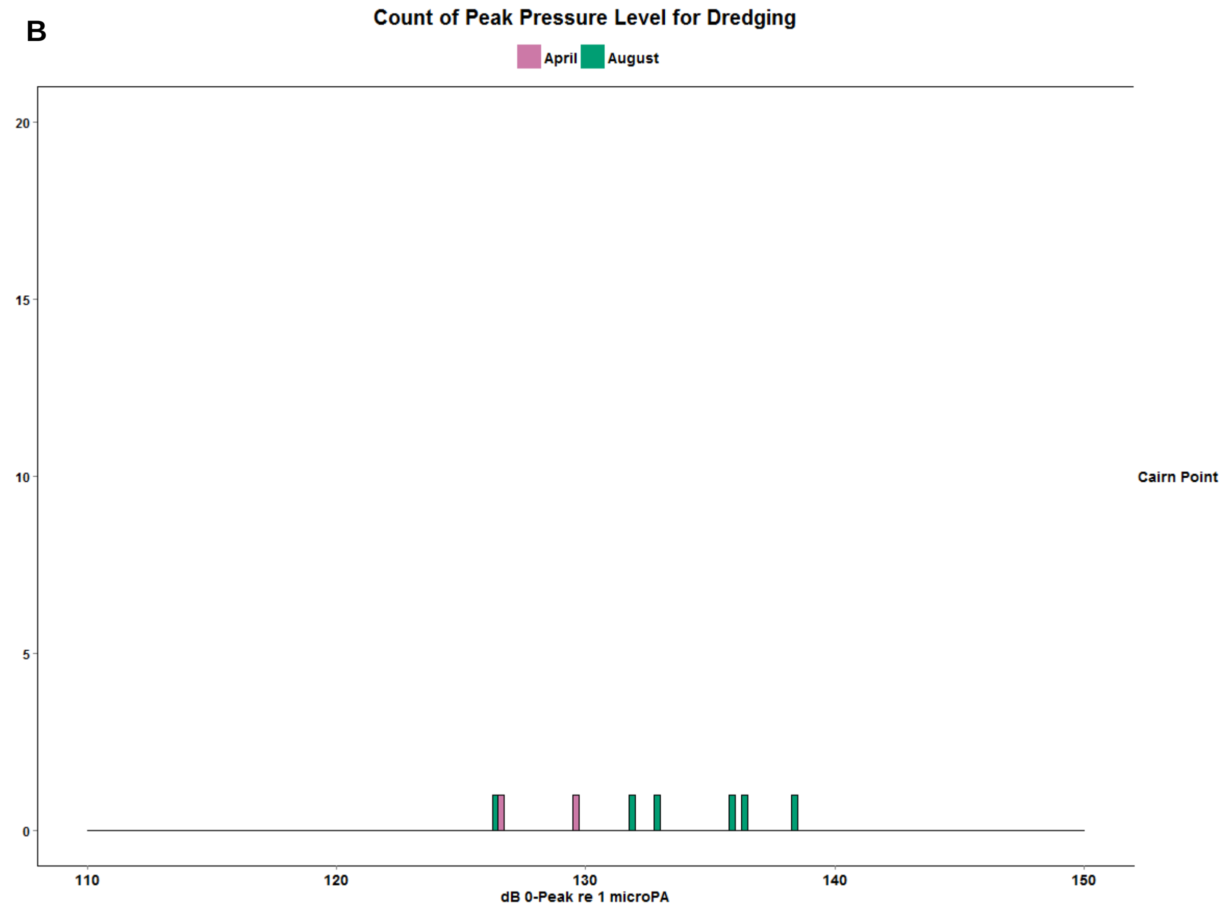
4.4.c dB 0-peak histogram

Peak pressure accounts for the acoustic energy measured at its highest level within each event, thus this metric does not consider the duration of the event. It is a relevant metric for impulsive signals as these are not well characterized by metrics that consider the duration of the event (e.g. SEL) or are dependent of a fixed duration to calculate loudness (e.g. SPL).

Peak pressure levels were only measured in noise events that were classified as impulsive (see methods). This section includes figures for noise classes that included impulsive events, and the values presented here are only for impulsive events, thus a much lower number than continuous events. The next figures show the peak pressure distribution over an axis of 110-150 dB that is fixed in all figures to allow a direct visual comparison across noise classes.

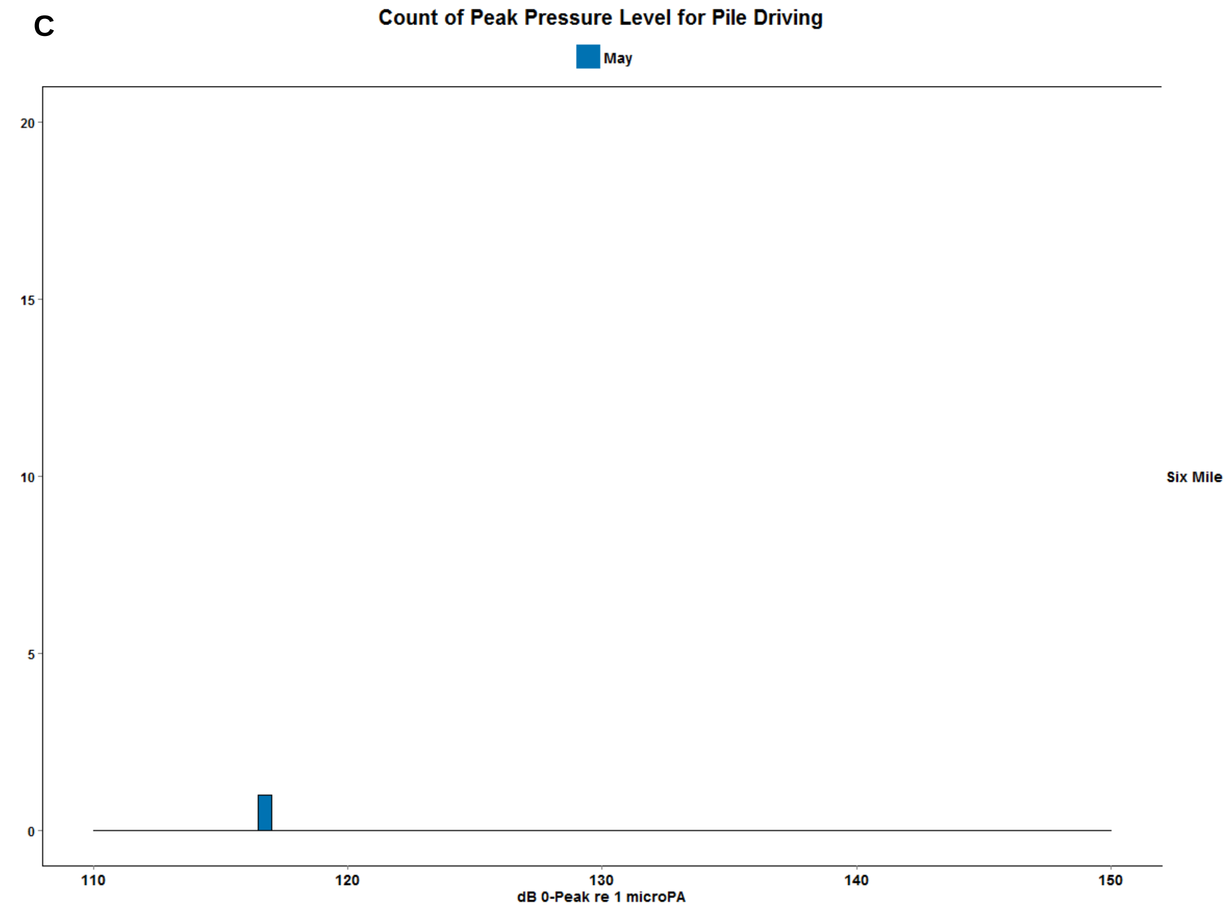


Some commercial ship noise events, while longer than typical impulsive signals (i.e. >1s), where classified as impulsive because they presented fast energy rise time at the onset of the signal. This occurred in Cairn Point and for two occasions in Fire Island, and it is probably related to the start of vessel engines. In these cases, peak pressure could reach levels close to 150 dB.



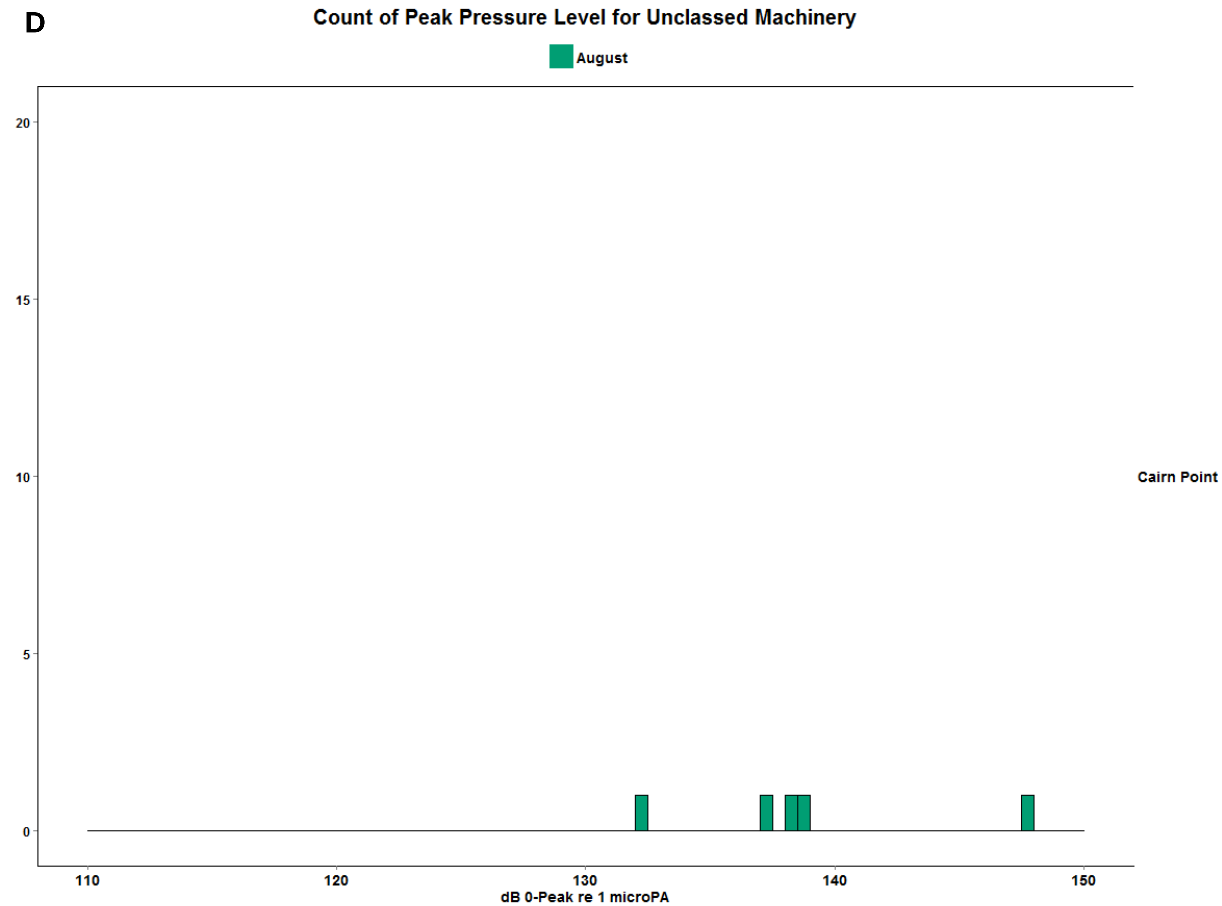
Dredging in Cairn Point included impulsive events that could be related to the nature of the dredged material or the mechanical properties of the dredge. However this only happened 8 times in 2 month and they all lasted less than 1 second, therefore they are unusual noise events.

C

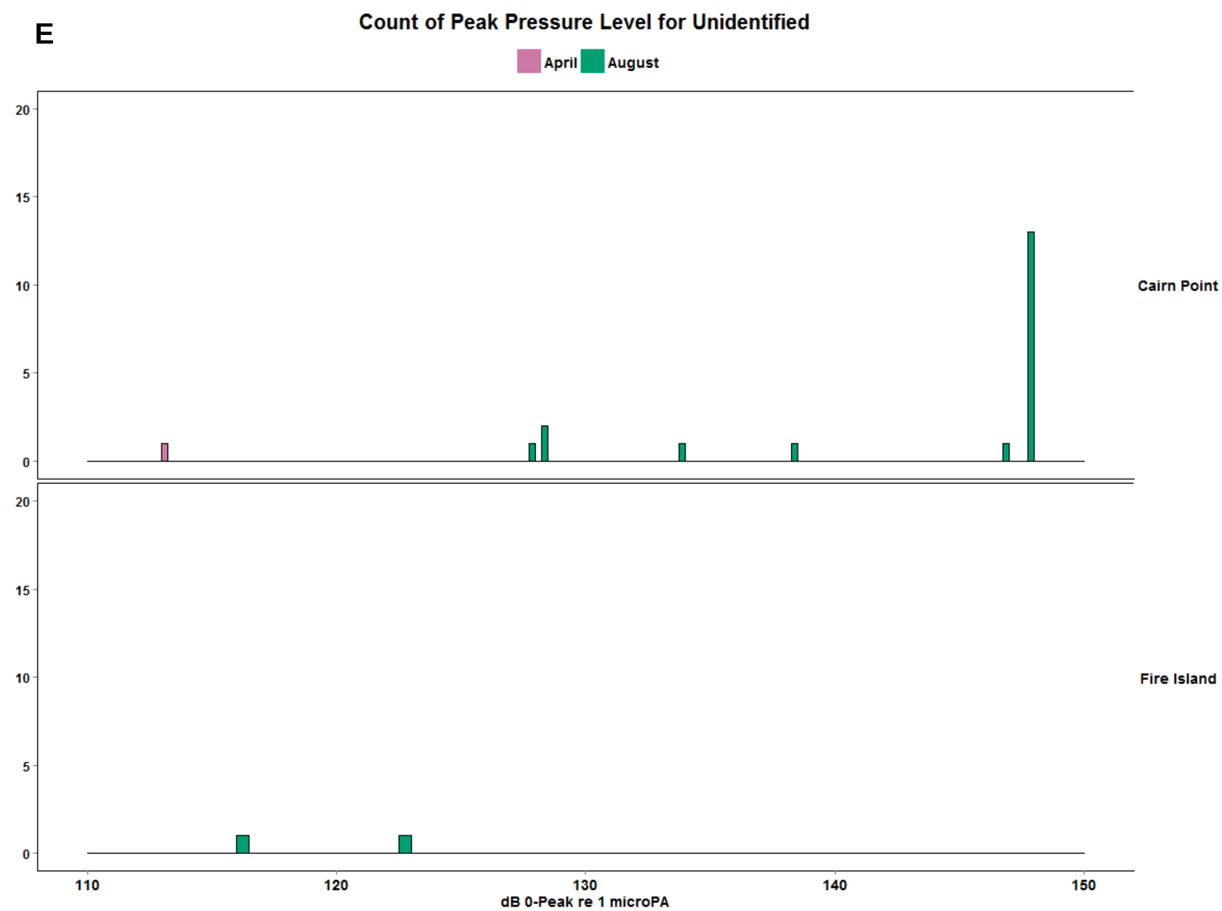


Because this activity was logged as a single event for each sequence of pile strikes instead of logging every pile strike as an event, all the events of this noise class lasted more than 1 second, except the instance included in this figure, which was a single strike, probably during hammer set up procedures. No other pile strike event was classified as impulsive, even if they all lasted less than 1 second (see table 2) and potentially had rapid rise-times (see criteria for impulsive classification in methods). To appropriately characterize this noise source, single strikes would need to be selected and measured to report SPL rms over 90% of the acoustic energy as well as dB peak levels. However this fine resolution analysis was outside the scope of this study.

Even if the single value presented here is at 117 dB peak, and SPLs range in 95-120 dB, it is SEL in the range 100-145 dB what provides a better perspective of the loudness of this activity detected in Six Mile, Fire Island and Kenai, because of its considerable duration (Fig. 4).

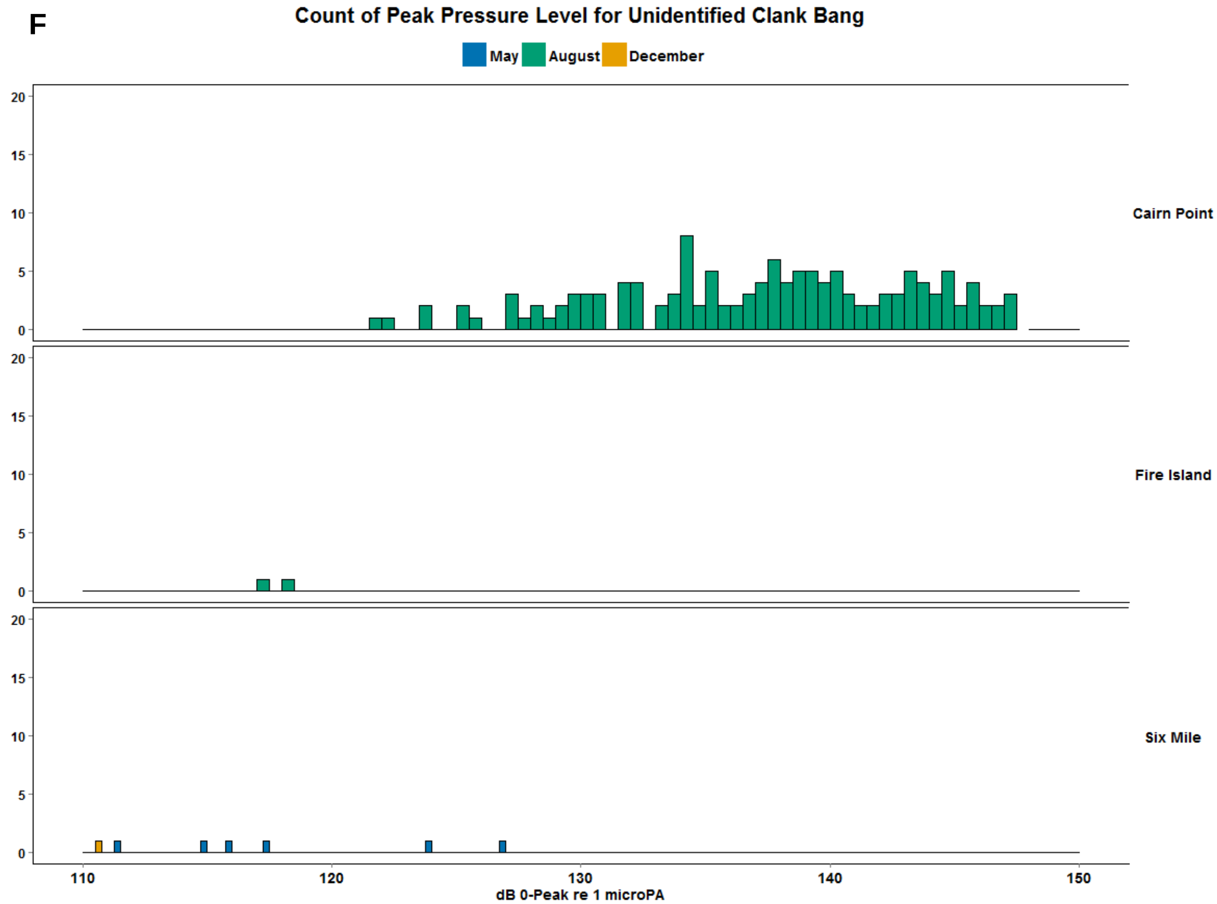


Few unclassed machinery events were classified as impulsive. Their peak pressure levels ranged between 132 to 148 dB. However, unclassed machinery often had banging noises concurrent with continuous machine noise. But because they overlapped with continuous noise they were not classified as impulsive. Further analysis of these events would be required to discern between the amount of impulsive noise and continuous noise in these recordings.

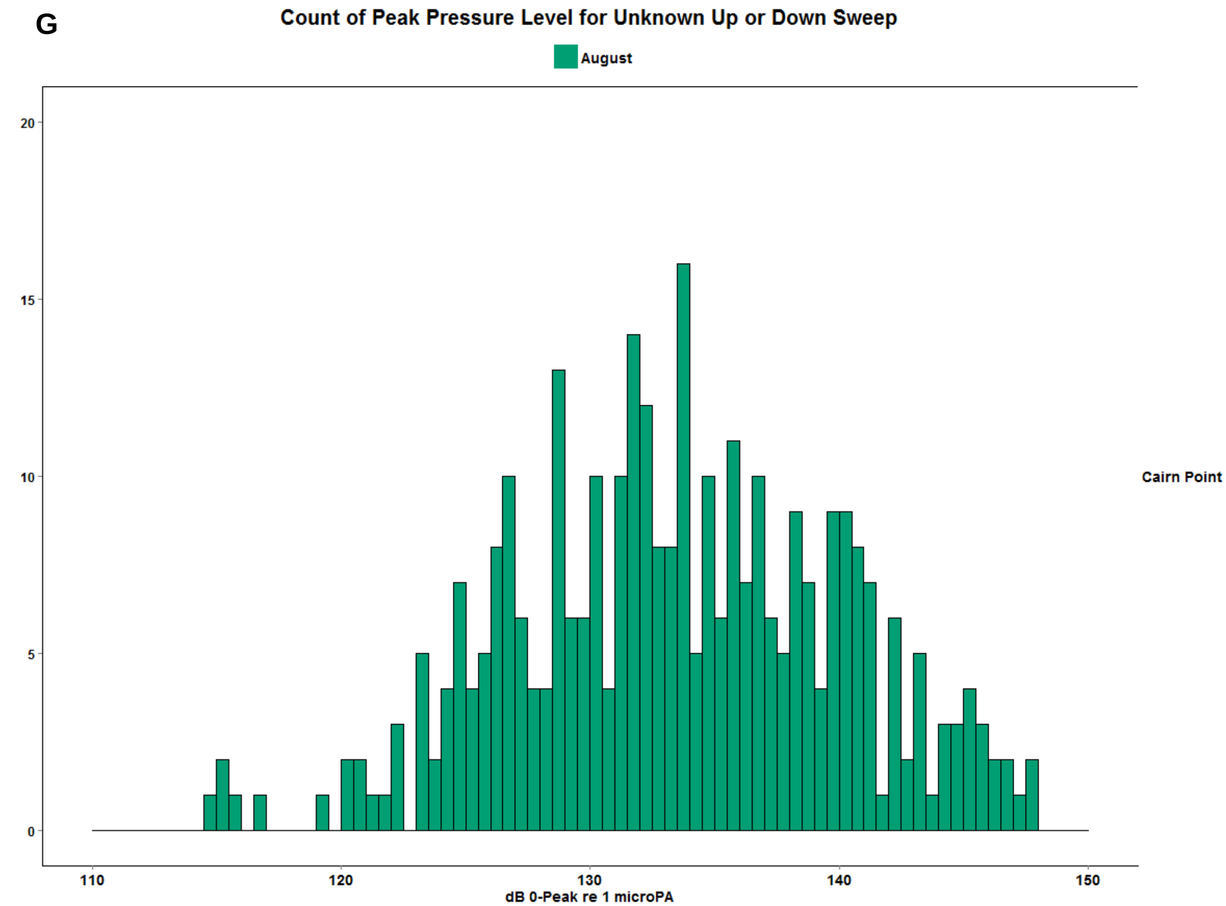


Unidentified events included impulsive noises, some near 150 dB at Cairn Point.

F



Approximately 9% of all the events of this noise class were classified as impulsive. When comparing peak pressure and SPLs (Fig. 8L) across locations, peak pressure values for Fire Island are slightly lower that what it would be expected.

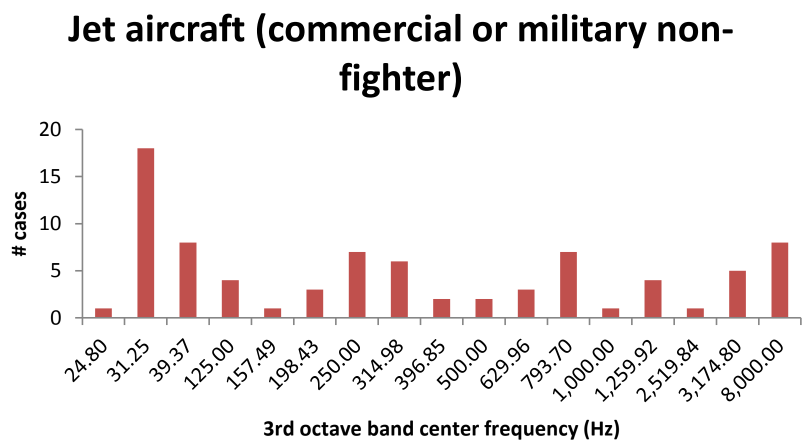


Approximately 29% of all the events were classified as impulsive for this noise class. When comparing these results with SPLs (Fig. 8M), peak pressure levels are lower than what would be expected, suggesting that the loudness of these signals is relatively constant across its duration.

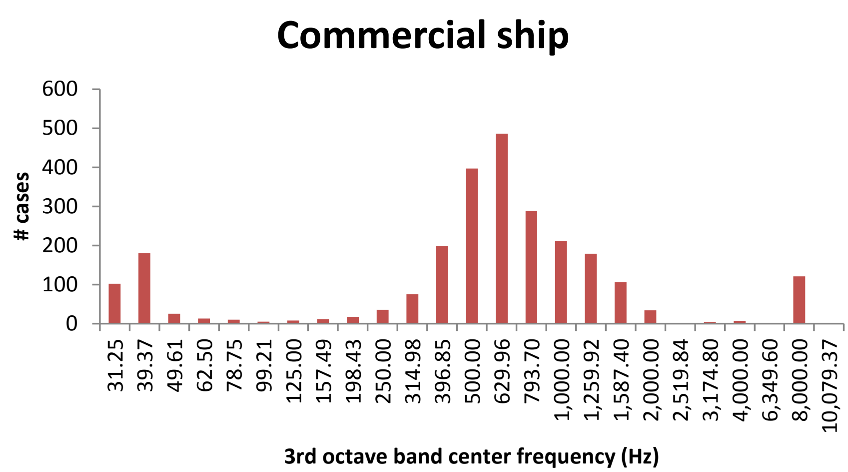
Figure 10: Peak Pressure for impulsive events by noise class and month from all the impulsive anthropogenic noise events detected in the sampled locations in Cook Inlet, Alaska. Noise classes included are A- commercial ship, B dredging, C- pile driving, D- unclassed machinery, E- unidentified, F- unidentified clank or bang, and G- unknown down or up sweep.

4.4.d 3rd octave band peak histogram

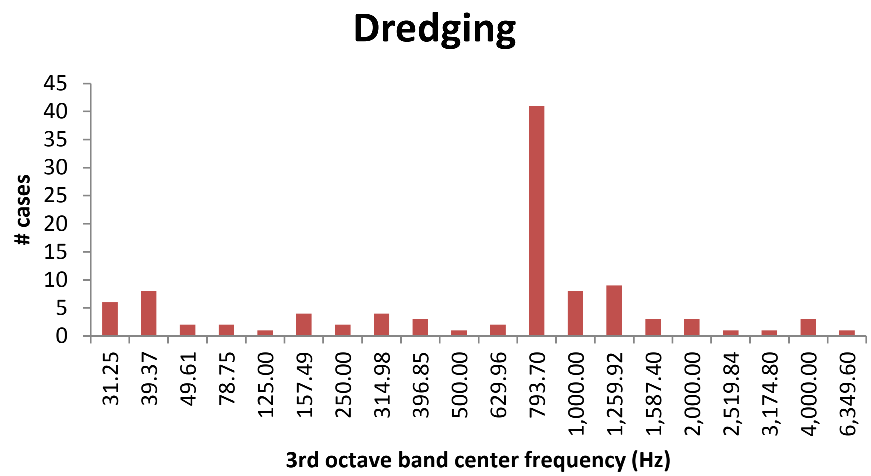
The next figure includes panels for each noise class, independently of when or where they were recorded. Each panel shows how many times each of the 3rd octave bands included the highest acoustic energy for each detected event. Each panel is a histogram with the distribution of peak energy across frequencies in 3rd octave bands for each noise class. This figure is useful to evaluate for each noise class, how concentrated or disperse in the frequency domain is the peak acoustic energy, as well as to identify which 3rd octave bands are more often affected in each noise class.



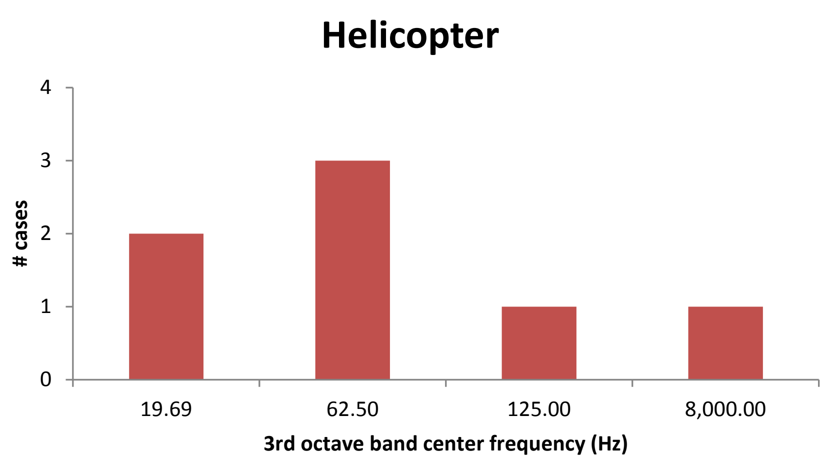
Non-fighter jet aircraft noise shows a very broad dispersion of peak 3rd octave bands. This is probably explained by the directional nature of this noise source and the great variability in distances and altitudes where it was recorded.



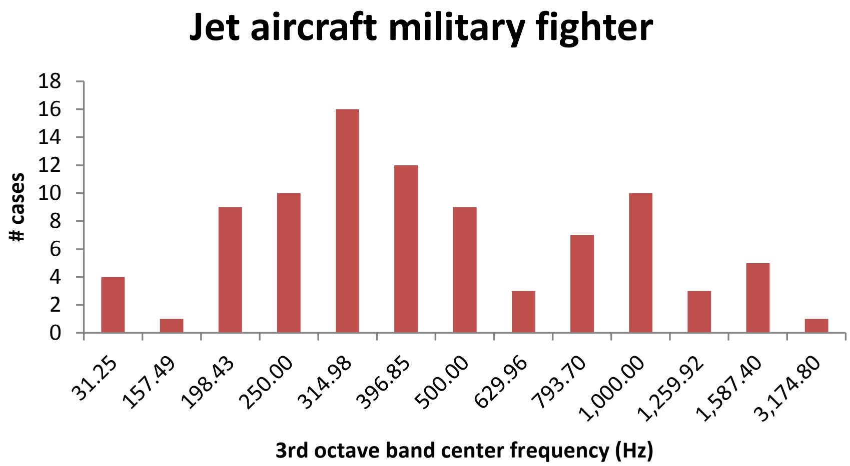
Commercial ship shows peak frequencies concentrated around 630 Hz. Lower frequencies, which are typically affected by ship noise might have been affected by the shallow water conditions of Cairn Point.



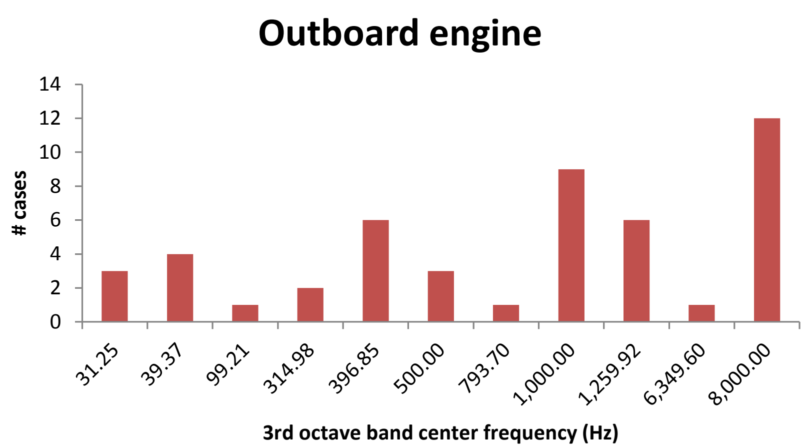
Dredging noise shows a distinct peak in energy at 794 Hz.



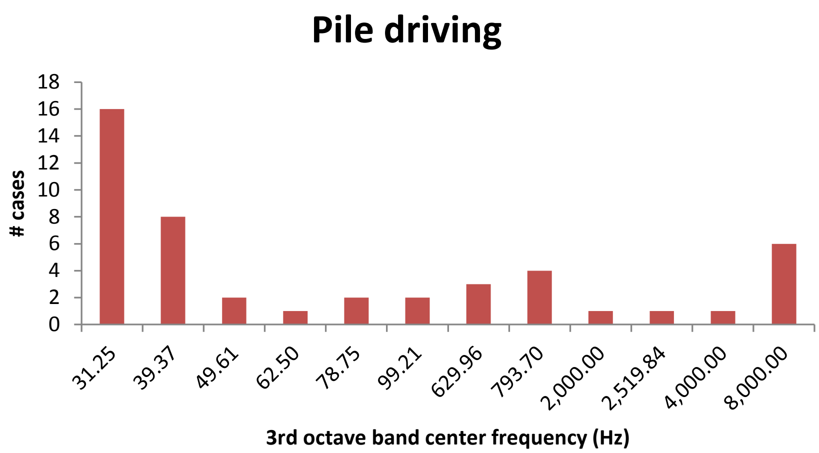
Helicopter noise seems to affect lower frequencies, as expected, but also one event had its peak energy at 8000 Hz. Due to the small sample size, this histogram might not be a good representation of this noise class in Cook Inlet.



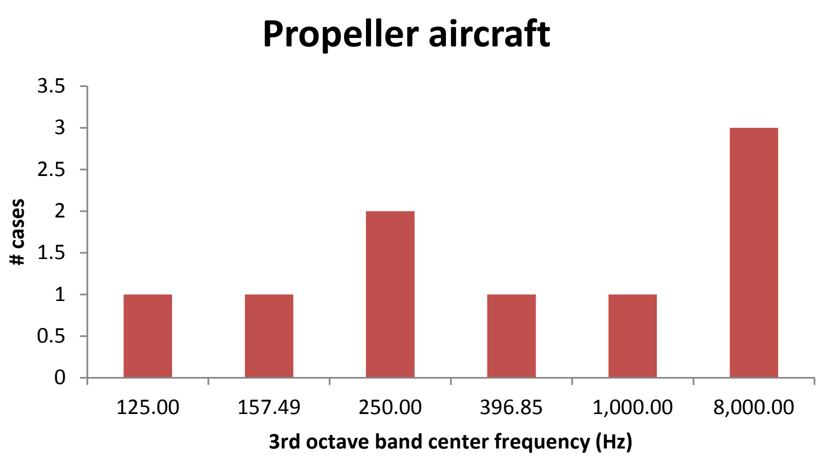
Despite the high variability in received levels (Fig. 9E and 10E), most fighter jet events show peak energy in the range 198-500 Hz.



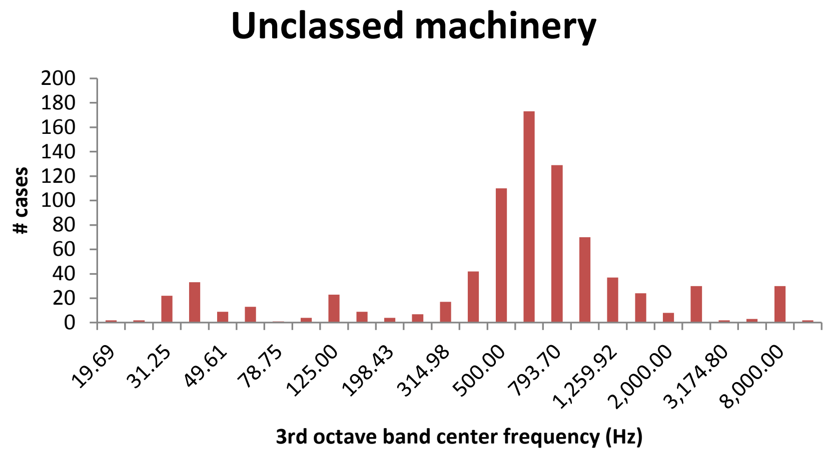
Outboard engine noise typically presents strong harmonic contents. This is reflected by the higher number of energy peak values in the bands 397, 1000 and 8000 Hz. This histogram suggests that higher frequencies are more often affected by outboard noise. Beluga hearing is more sensitive at higher frequencies, therefore this noise source might affect beluga communication at further ranges when higher frequency harmonics predominate the spectrum of this noise class.



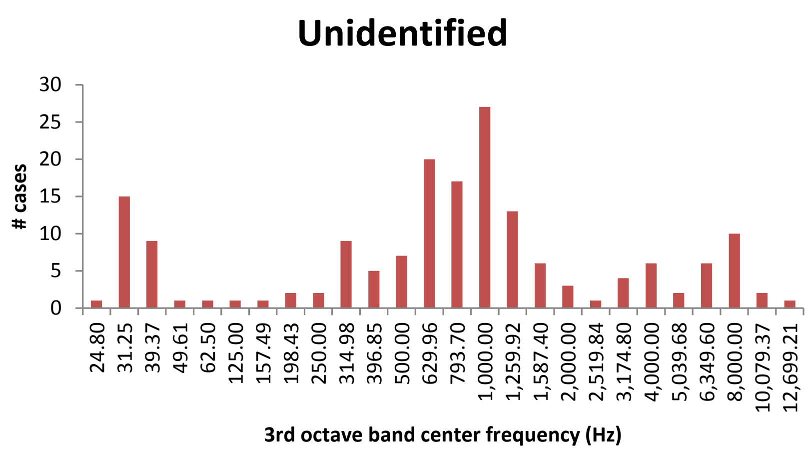
Pile driving noise is more pronounced in the lower frequency bands, as expected for impact noise sources, and in particular when the noise source is far from the recorder, as in this case.



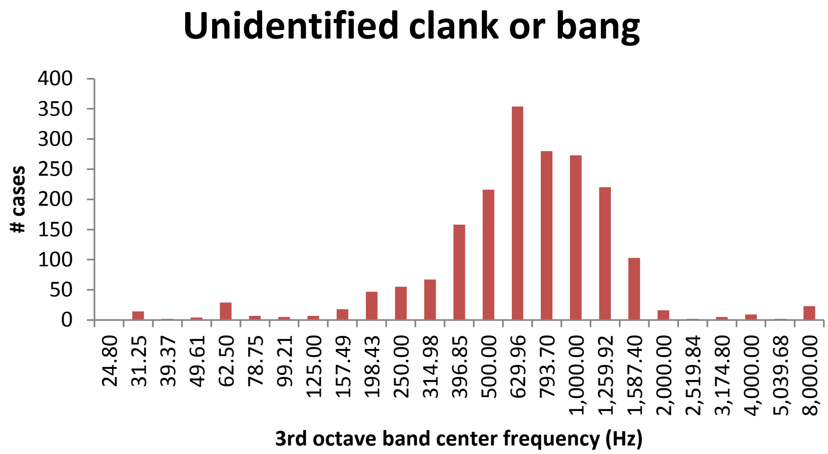
Propeller aircraft shows highest number of peaks in the 8000 Hz band. However due to the low sample size for this noise class, this histogram might not show a complete frequency distribution of peak energy for this noise class. These results suggest that, at least for these events, propeller aircraft noise in these locations of Cook Inlet might be substantial at higher frequencies than expected, because generally propeller aircraft noise peaks below 1000 Hz and energy decreases with increase in frequency (Richardson et al. 1995).



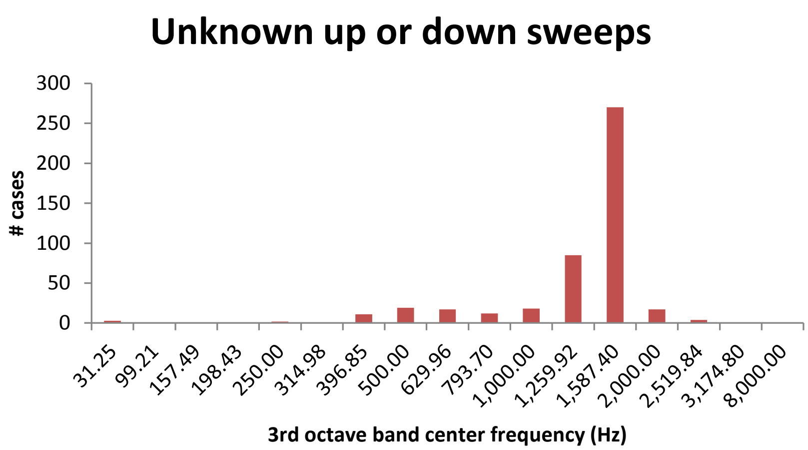
Unclassed machinery shows a high concentration of peak energy in the 500-1260 Hz band range. This is similar to what was obtained for commercial shipping, which suggests that many events classified as unclassed machinery might in fact be related to commercial shipping.



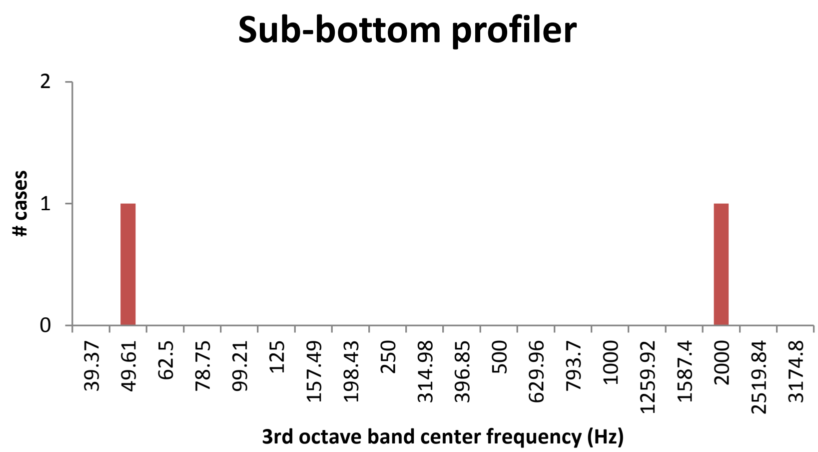
Unidentified class shows peaks in energy concentrated in 630-1000 Hz bands. Similar to unclassed machinery, many events in this noise class could be related to commercial shipping.



Unidentified clank or bang noise also has most of its energy peaks concentrated in the same bands as unclassed machinery, unidentified and commercial shipping. Results presented in section 1 for this noise class also suggest that it might be related to commercial shipping.



Peak energy for unknown up or down sweeps was very concentrated in the 1260 and 1587 Hz bands. Sweeps were loud but short, thus covering only a small range of frequencies.



Sub-bottom profiler was only detected in two locations (Kenai and Fire Island). In Fire Island this signal was very loud (Fig. 6I) and its peak was concentrated in the 2000 Hz band. However, in Kenai, because it was faint (Fig. 9I), peak energy is much lower because it probably corresponds to the vessel noise that operated the profiler, thus the low frequency peak in 50 Hz should not be considered as part of the sub-bottom profiler signal. This signal is synthetized and can be programmed at different frequencies; the signals detected in Fire Island covered the range 1000-4500 Hz. Only one event was logged in each location, although it was detected for many hours, because this noise class was logged from start to end and not each independent sweep (thousands of sweeps were detected per event).

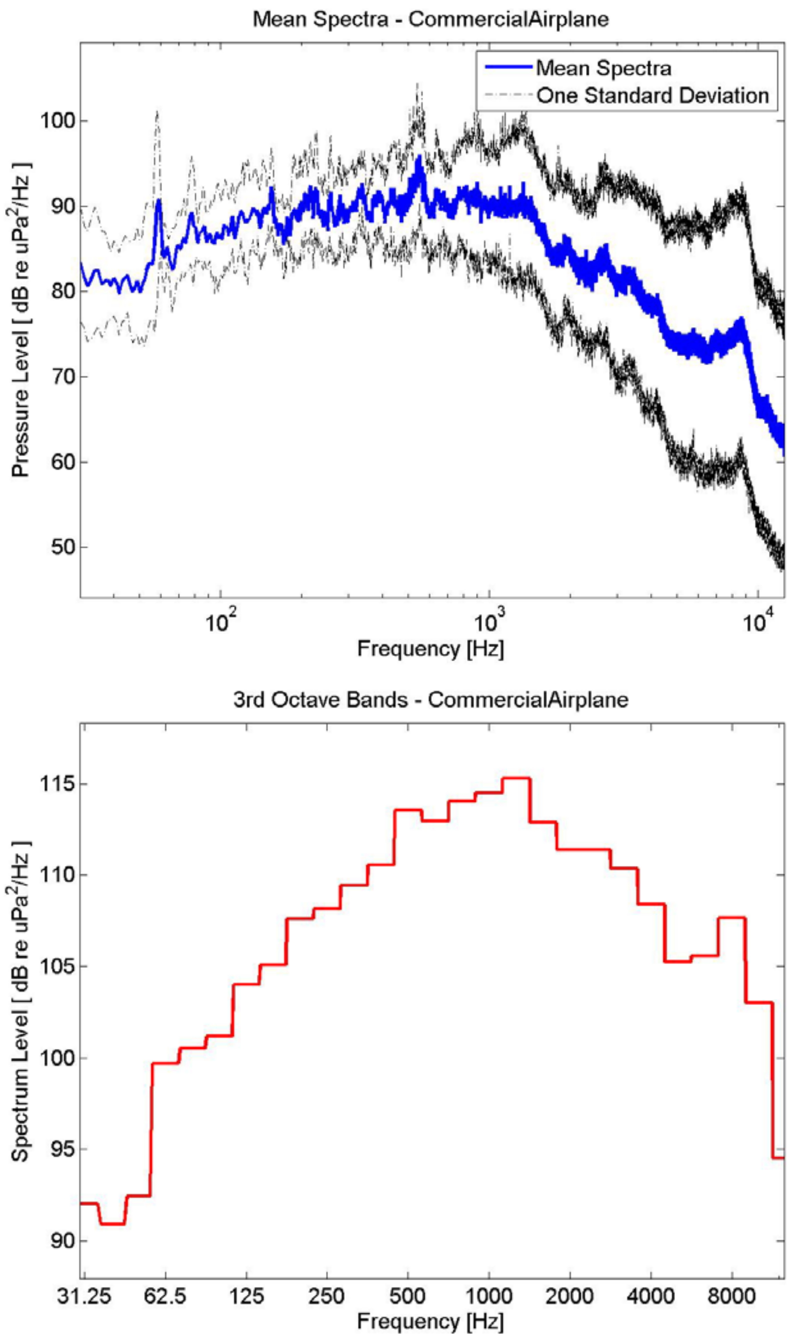
Figure 11: Histograms of acoustic energy peak distribution across 1/3 octave bands for each noise class.

4.4.e Averaged spectra and 3rd octave per noise class

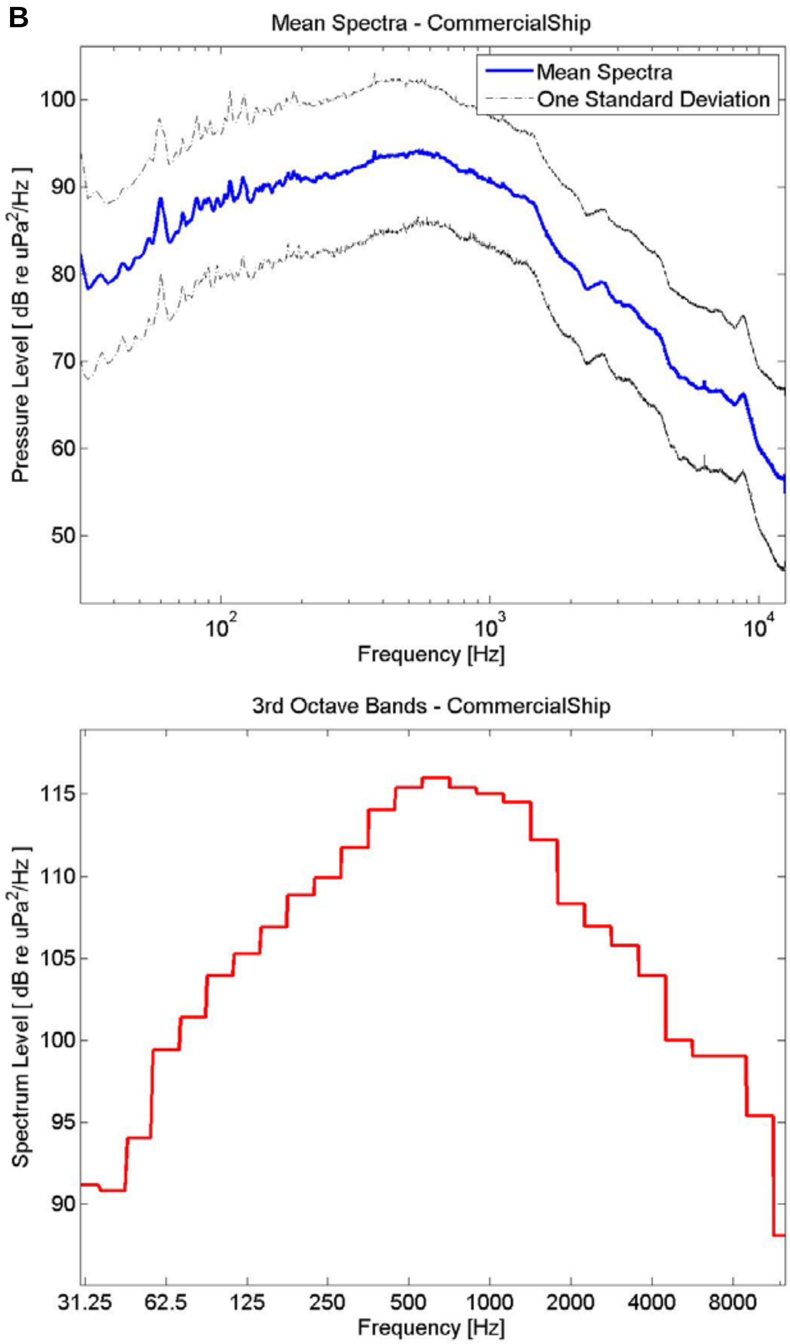
The next series of figures present the averaged spectra (upper panel) and 1/3 octave band analysis (lower panel) for each of the noise classes identified in this study. Average values are based on all the events for each noise class detected in each location and month. Instead of presenting results for each location and month, we have selected one representative spectrum and 3rd octave band results for each noise class based on where and when they are more prevalent (Fig. 3).

3rd octave levels for each noise class are compared to beluga hearing data from all the available studies (White et al. 1978, Awbrey et al. 1988, Klishin et al 2000, Mooney et al. 2008, Castellote et al. 2014) and the potential for communication masking is discussed.

A

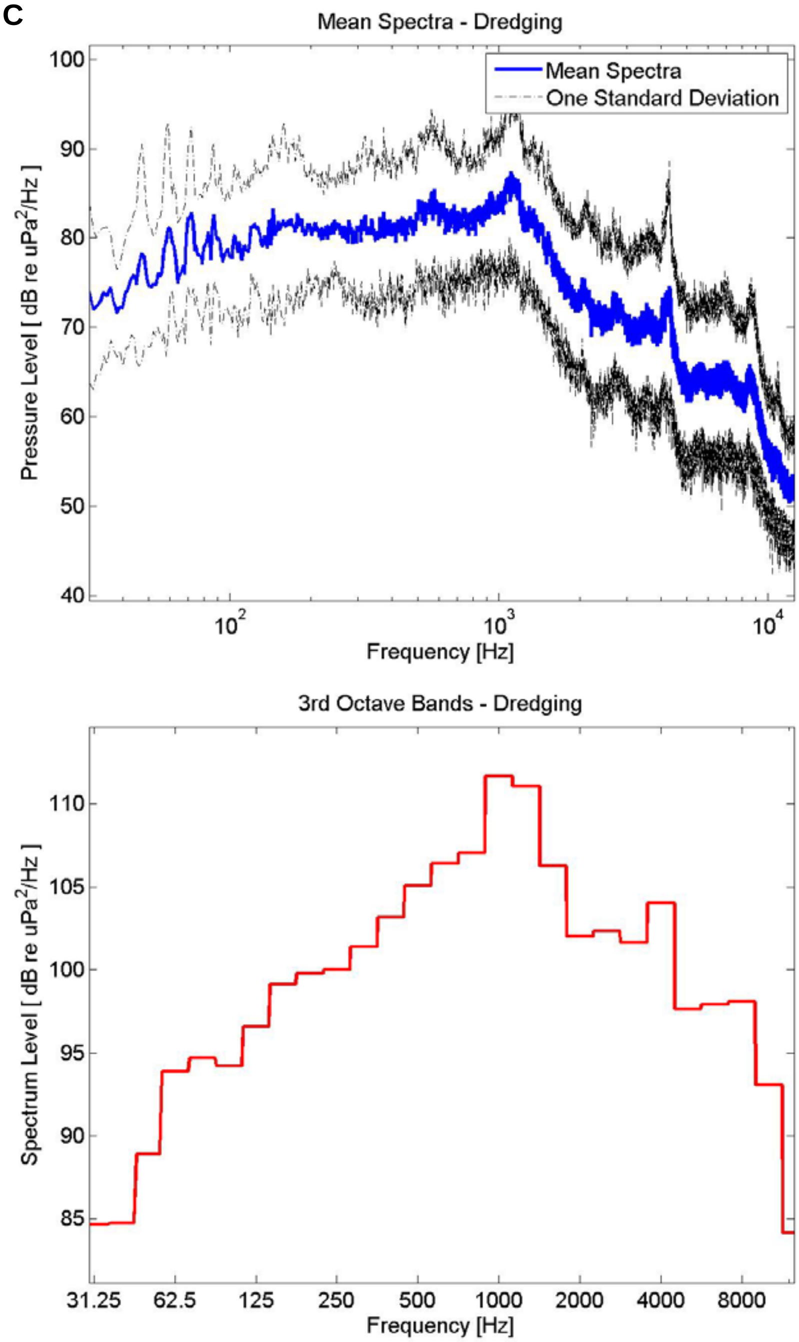


Jet aircraft (commercial or military non-fighter) averaged spectrum and 3rd octave band analysis show a relatively uniform increase in acoustic energy up to 1000 Hz followed by a rapid decrease through higher frequencies, consistent with the peak histogram shown in figure 11. Variability is higher in higher frequencies. Averaged peak energy is slightly above 115 dB re 1 micro Pa^2/Hz, which is above beluga hearing thresholds for that frequency band, thus beluga can hear jet aircraft (commercial or military non-fighter) noise when this happens and has the potential to generate masking of their communication signals. But because jet aircraft events are short (Fig.4), occur in moderate numbers (table 3) and for low % of time (Fig. 3) at Cairn Point, Fire Island and Eagle River which were the monitored areas closest to airports, this noise source might not be problematic for belugas.

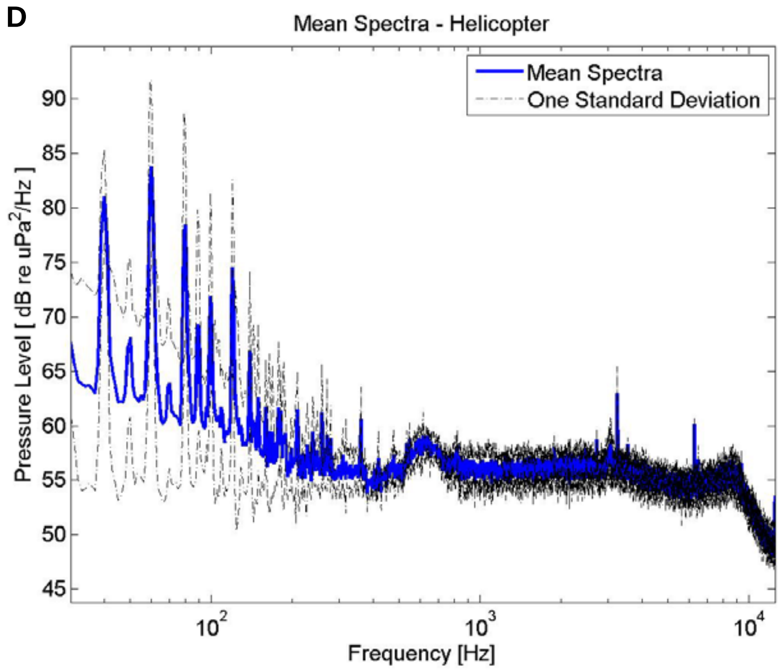


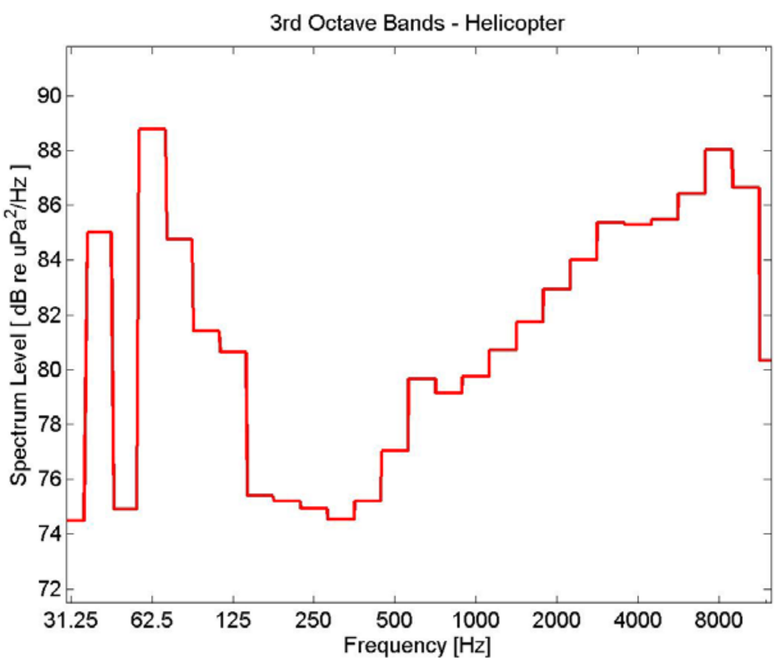
Commercial ship averaged spectrum and 3rd octave band analysis show a steep increase in energy up to 600 Hz followed by a steep decrease in higher frequencies resulting in a peaky spectrum reaching levels above 115 dB. Variability is uniformly distributed across frequencies. This 3rd octave band analysis results are consistent with the peak histogram presented in figure 11. Hearing threshold for belugas at these peak frequency bands is approximately 108 dB. Al other 3rd octave bands above 600 Hz show received levels that are above hearing thresholds too. Therefore, commercial ship noise is easily heard by belugas. Because this noise class is recurrent in all the locations sampled except in Eagle River (Table 2), covers an important % of time (Fig. 3), can last many hours (Fig. 4) and received levels are most of the time above hearing thresholds (Fig. 8), it might have an important negative effect in their communication (e.g. masking of social signals).

C



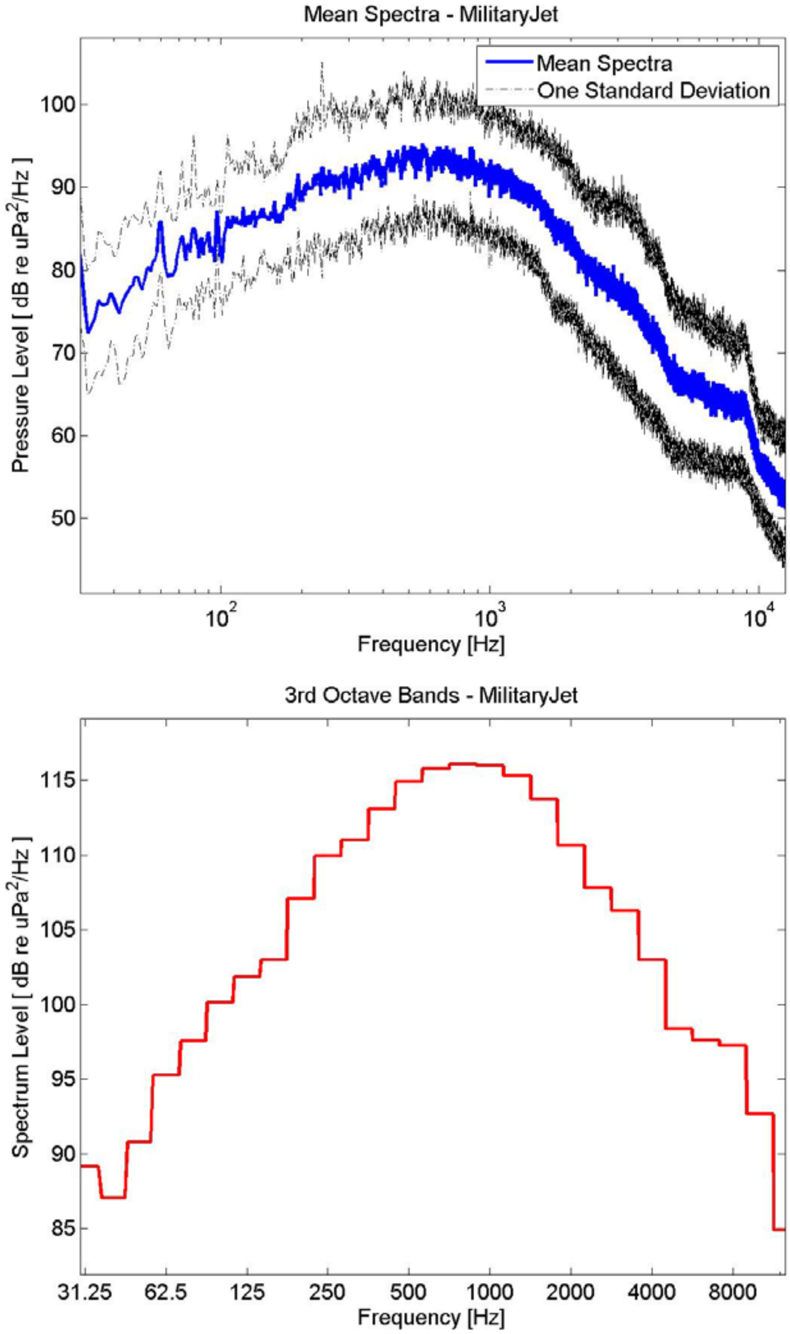
Averaged spectrum and 3rd octave band analysis for dredging is similar to commercial ship, which is expected because of the similarity in the nature of the engine noise produced, but includes peaks across the spectrum which are most probably related to pump noise. Peaks can be observed in the spectrum at both the lower and upper ends, which are translated in higher levels for the respective 3rd octave bands. This averaged 3rd octave band analysis is consistent with the peak histogram presented in figure 11, where peak energy occurs n frequency bands centered in the range 793-1260 Hz. Peak 3rd octave band centered in 1000 Hz exceeds 110 dB which is above the beluga hearing threshold, and all the 3rd octave band levels above this frequency are also above the hearing thresholds, therefore beluga hearing is masked by dredge noise at the locations and months sampled. This noise class was only detected at Six Mile and Cairn Point, and even if the number of events detected are high (Table 3), the mean duration (Fig. 3) and % of time (Fig. 4) for these events are small in Cairn Point and moderate in Six Mile. Therefore this activity's noise might affect beluga communication moderately and only at Six Mile.



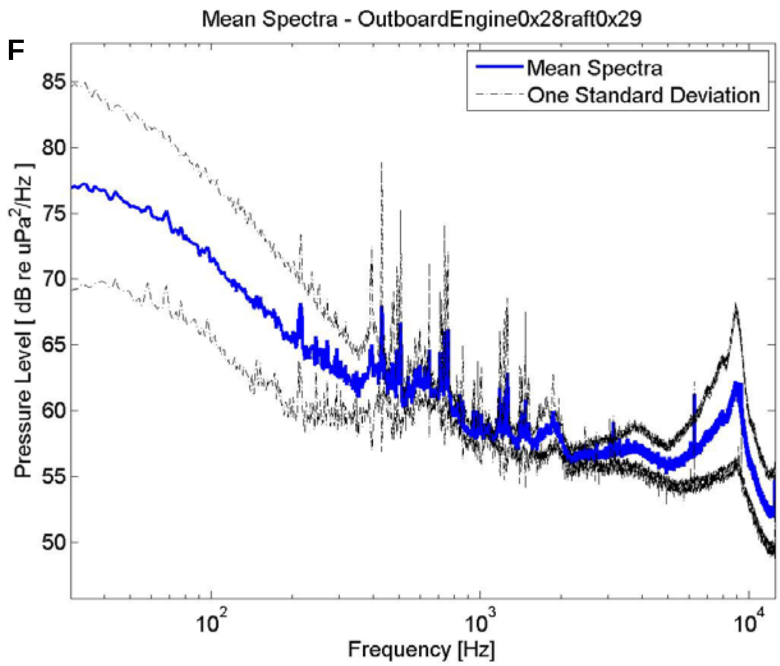


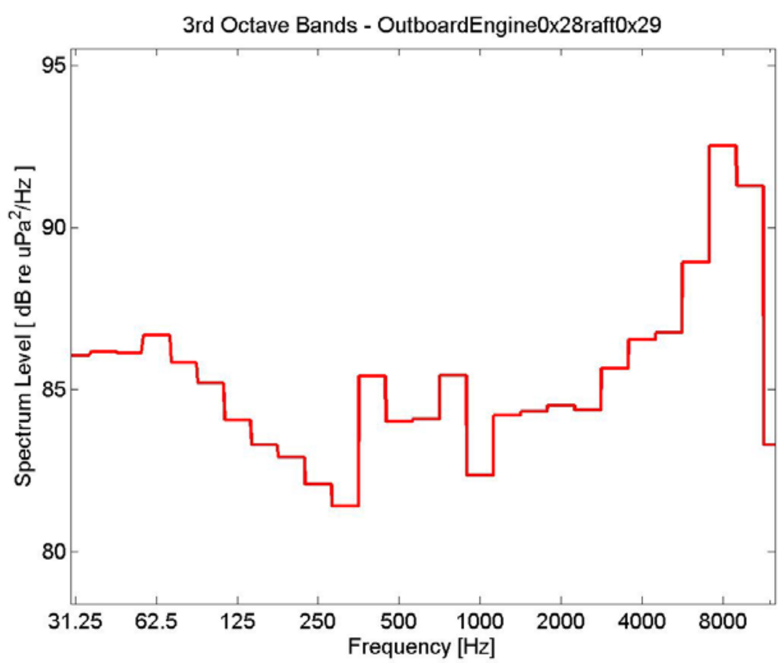
Averaged spectrum for helicopter noise show typical acute peaks in the first 200 Hz related to the harmonic content of noise generated by propeller or rotor blade rate. This averaged 3rd octave band analysis is consistent with the peak histogram presented in figure 11. Received levels for these peaks are below beluga hearing thresholds, but 3rd octave band levels above 4000 Hz exceed hearing thresholds. And thus belugas can hear this higher frequency helicopter noise component. Because the occurrence of helicopter noise was very small and only at Six Mile (Table 1) and its mean duration is short (Fig. 3) and % time insignificant (Fig. 4), this noise source should not be considered a concern in the months and locations sampled.

E



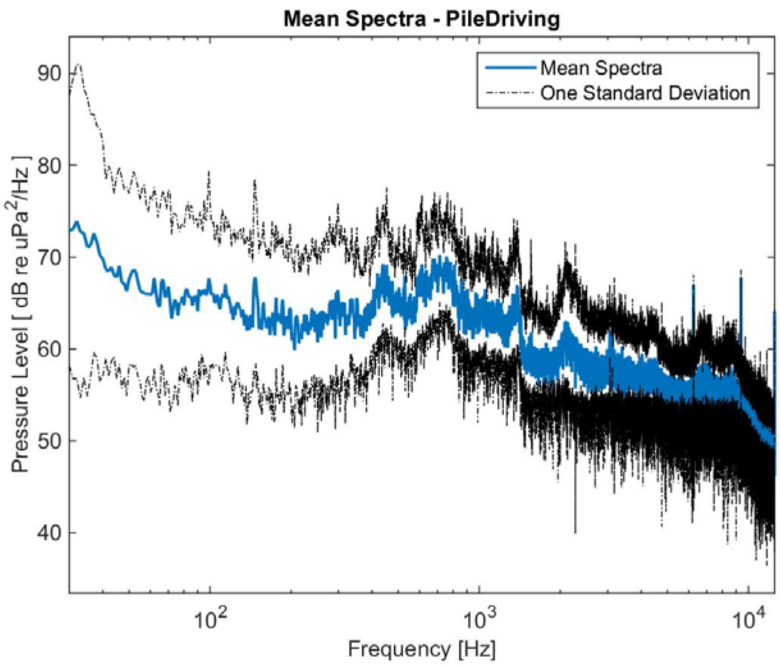
Jet fighter noise averaged spectrum is less variable than commercial or non-fighter jets. The spectrum contour is more concave than commercial or non-fighter jets, emphasizing the acoustic energy in central frequencies around 500-1000 Hz. However, when comparing these results with the peak histogram presented in figure 11, peak energy generally occurs at slightly lower bands (centered at 315 Hz) than the ones observed here (centered at 900 Hz). Lower variability in the spectrum reduces peak levels in the 3rd octave band analysis, which barely exceeds 115 dB in the 900-1000 Hz bands. Beluga hearing is exceeded by all bands above 500 Hz, therefore, this noise source can easily mask beluga communication. This noise class was detected in several locations but was only relevant in Eagle River (Table 3). However, its % time in Eagle River was very small (Fig. 3) and its mean duration was around 10 seconds (Fig. 4), therefore, even if this signal normally occurred at high enough levels to mask beluga communications (Fig. 8E), its occurrence within the sampled months was very limited and thus of low concern.

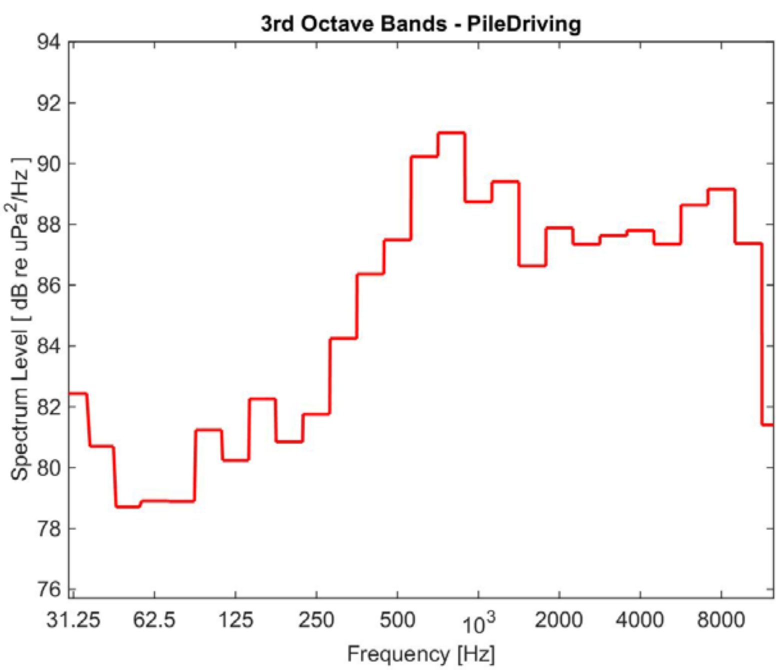




Outboard engine averaged spectrum shows multiple peaks up to 1100 Hz which are typical harmonic bands found in this type of noise, but the stronger contribution was at higher frequencies, around 8000 Hz, as observed in the 3rd octave band analysis, and for most events (Fig. 11). Peak 3rd octave band levels only exceed beluga hearing at 8000 Hz and higher, thus potentially masking beluga communication. This noise class was detected in 4 locations in moderate numbers (Table 2), and both % of time (Fig. 3) and mean duration of these events were small except in Kenai where duration was exceptionally long. However, all the detected events for this noise class were probably above hearing thresholds (Fig. 8F). Therefore, while the prevalence of this noise class was not very high, its acoustic properties can clearly affect beluga communication and thus, should be considered as potentially problematic. In particular, in areas or periods where outboard engine use is concentrated should be properly monitored (e.g. wider band recordings, non-duty cycled, etc.).

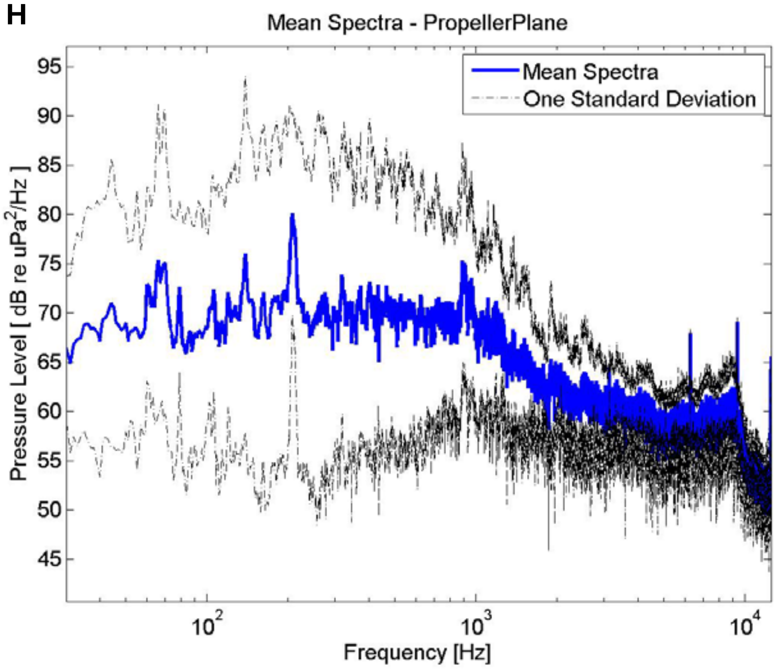
G

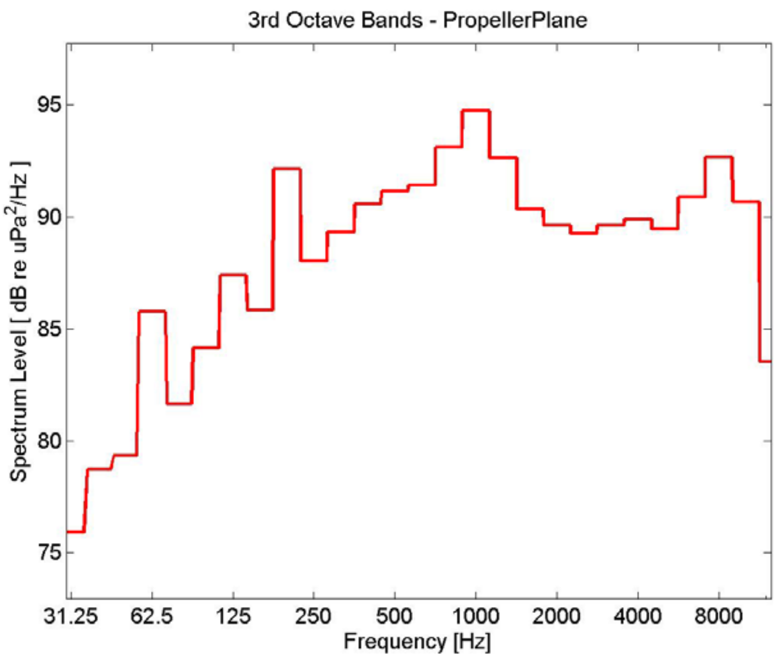




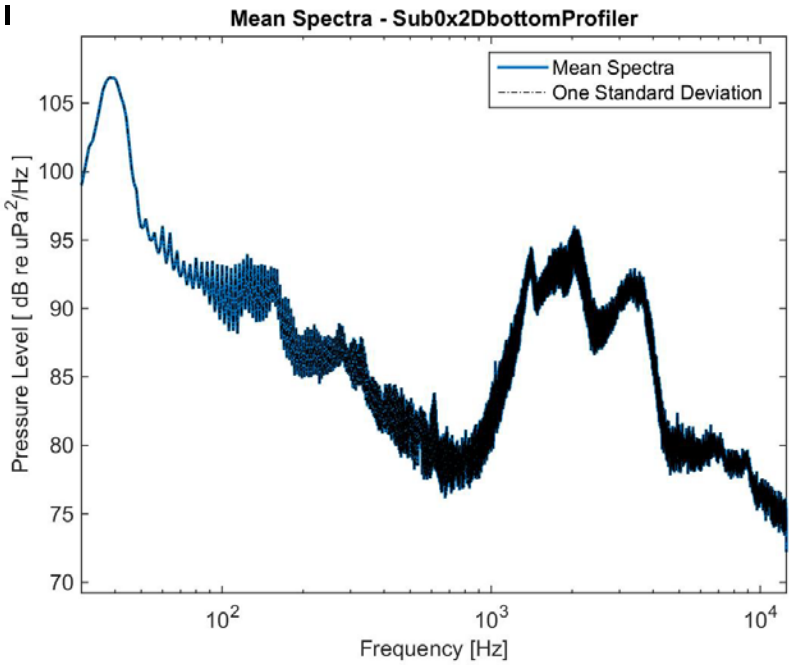
Pile driving noise detected in Fire Island shows stronger components in mid frequencies exceeding 90 dB, in the 500-1000 Hz range. There is an unexpected low amount of energy in the lower frequency bands which are the typically affected by pile driving, as also shown in Fig. 11. This feature could be a particularity of the noise propagation conditions when this source is detected from considerable distances in Fire Island. Received levels at Fire Island are above beluga hearing thresholds only at the 4 kHz band and higher. Received levels at Six Mile and Kenai are also above hearing thresholds for several 3rd octave bands (data not shown). Even after several miles of propagation through shallow waters, this noise still has the potential to mask beluga communication. These results are in accordance with the concern for the potential acoustic effects from pile driving operations to marine mammals, and our results highlight that these concerns should also be in place for Cook Inlet belugas. The similitude in levels received at Kenai, Fire Island and Six Mile from a source that was presumably at very different distances (Fig.9G), the highly varied distribution of peak pressure among 3rd octave bands (Fig. 11) and the fact that received levels for some bands were above beluga hearing thresholds in all three locations indicates that sound propagation for this source is particularly complex in Cook Inlet, that sound source verification should be considered an important part of the mitigation plan for this activity and that this source of noise could affect a large area of the beluga acoustic space in Cook Inlet.

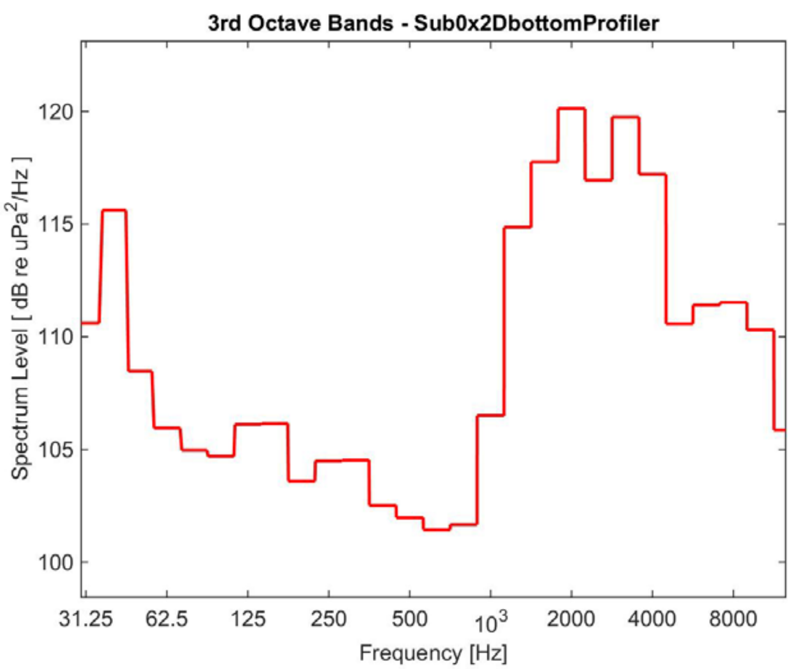
H





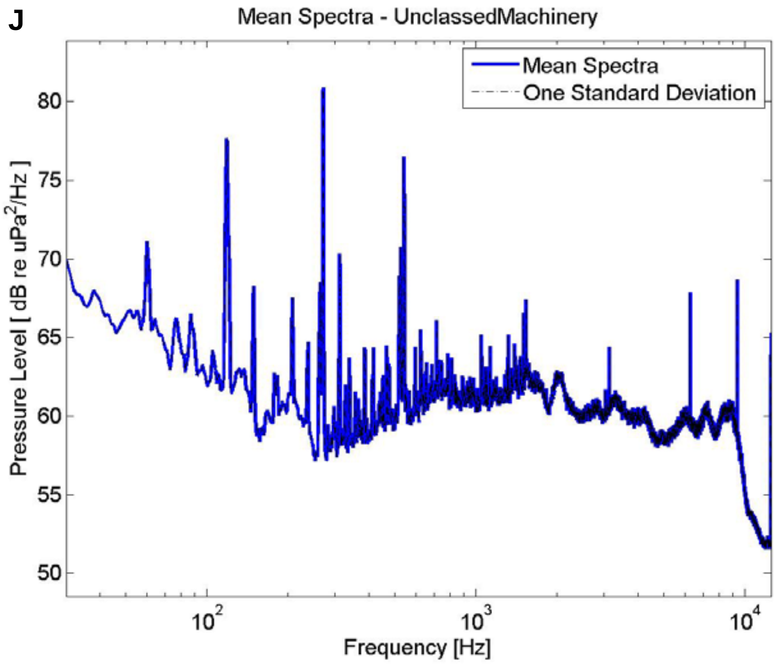
Propeller aircraft normally presents peaks in the spectrum due to the harmonic contents related to the blade's rotation rate. The averaged spectrum shows energy peaks up to 1000 Hz. The 3rd octave band analysis indicates that the peak at 1000 Hz is the one with highest acoustic energy, reaching 94 dB. Other peaks are observed in the spectrum at higher frequencies but of lower intensity, these are reflected in the 3rd octave band analysis with a secondary peak in 8000 Hz. Nevertheless, this 8000 Hz peak seems to be the most prominent when considering all the propeller aircrafts detected (Fig 11). Beluga hearing thresholds are exceeded by the 3rd octave bands centered at or above 4 kHz. Therefore, while the strong peaks at lower frequencies, typical of propeller planes, are not heard by belugas, its higher frequency components clearly are. These occur in all 9 events detected in the sampled data. If these events are representative of the acoustic footprint of propeller aircraft noise in Cook Inlet, this source of noise might affect beluga communication, although its masking effect might have short duration (Figs. 3 and 4) and thus might not be of concern.

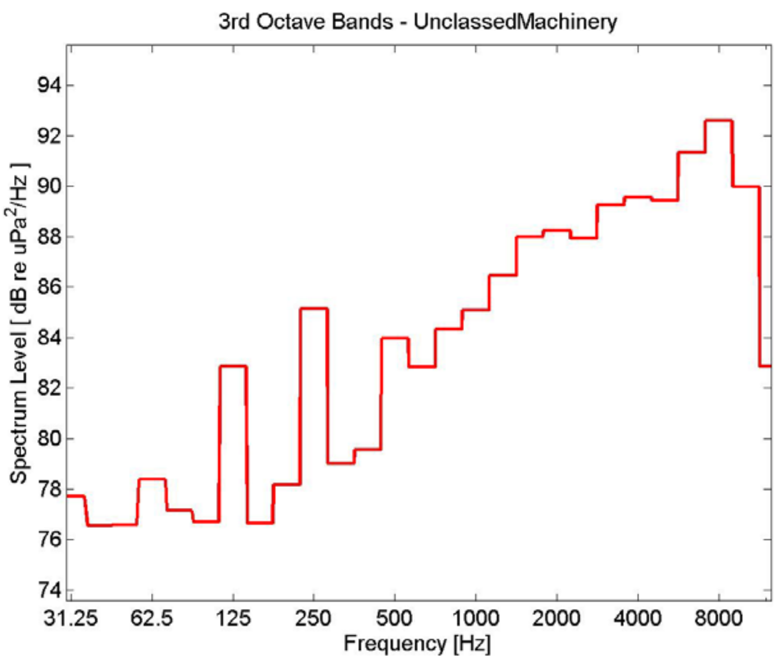




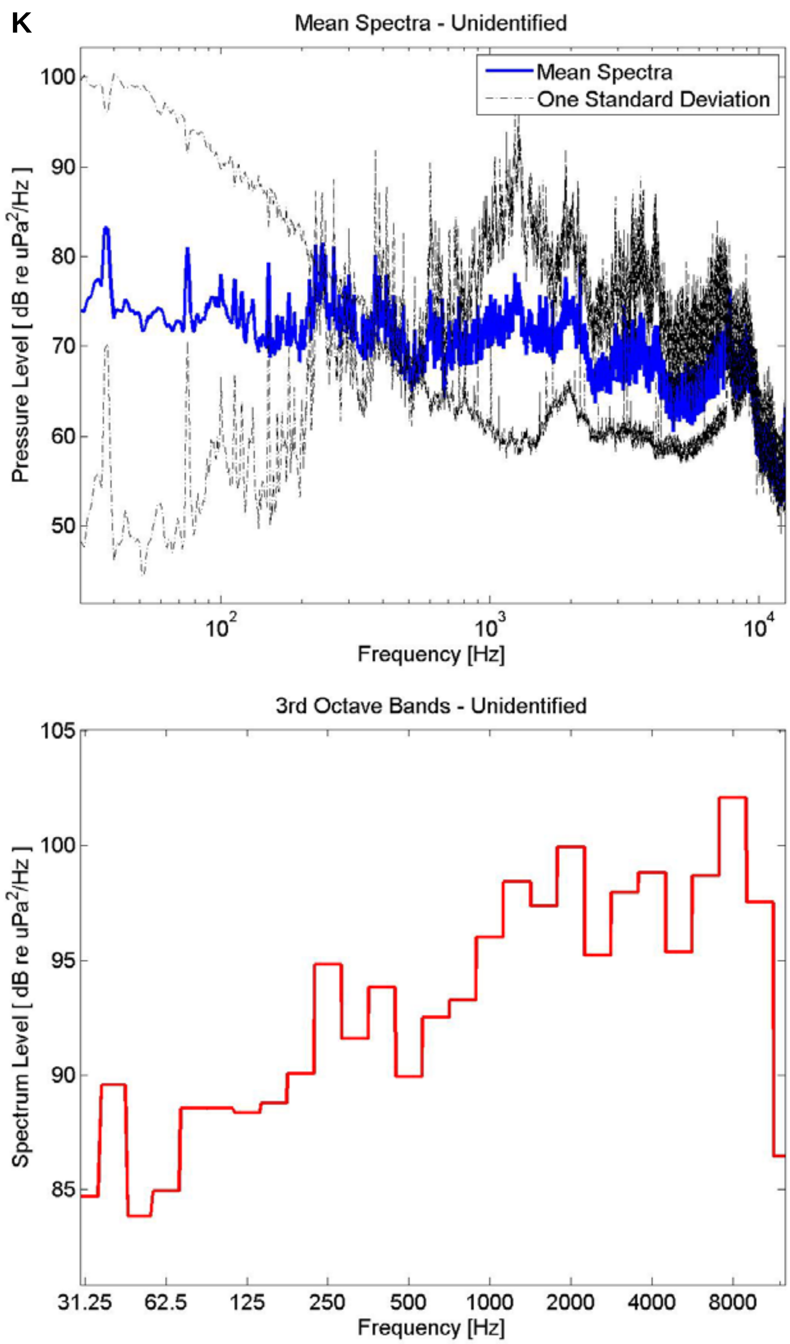
The averaged spectrum for sub-bottom profiler signals show very little variability as expected because this is an intentionally synthetized signal. Most of the energy below 1000 Hz is not related to the profiler signal and probably related to the vessel towing the profiler. Thus, peak energy for this sound source is in the 1000-4000 Hz bands, exceeding 120 dB, which is well above the hearing threshold of belugas at and above the 1000 Hz band. This activity was only detected during one day at both locations, and in the case of Cairn Point it was present for over 9 continuous hours. This suggests that when a survey is ongoing, it generates an acute acoustic disturbance both on noise levels and on its continuous presence. The event at Cairn Point occurred on August 19th 2009 and at Kenai on April 1st 2012, both dates within the peak occurrence of belugas in both locations (CIBA unpublished). This noise source can easily disturb beluga communication because of the loudness of this source in important frequency bands for belugas, where hearing is sensitive. This was not a common noise class, and its occurrence was limited to a single day in each of the two locations, but the occurrence of these types of surveys should be avoided in areas and periods of concentrated beluga presence, as was the case for Kenai in Spring and the Susitna area in summer, across Fire Island where these signals were detected with highest received levels.

J



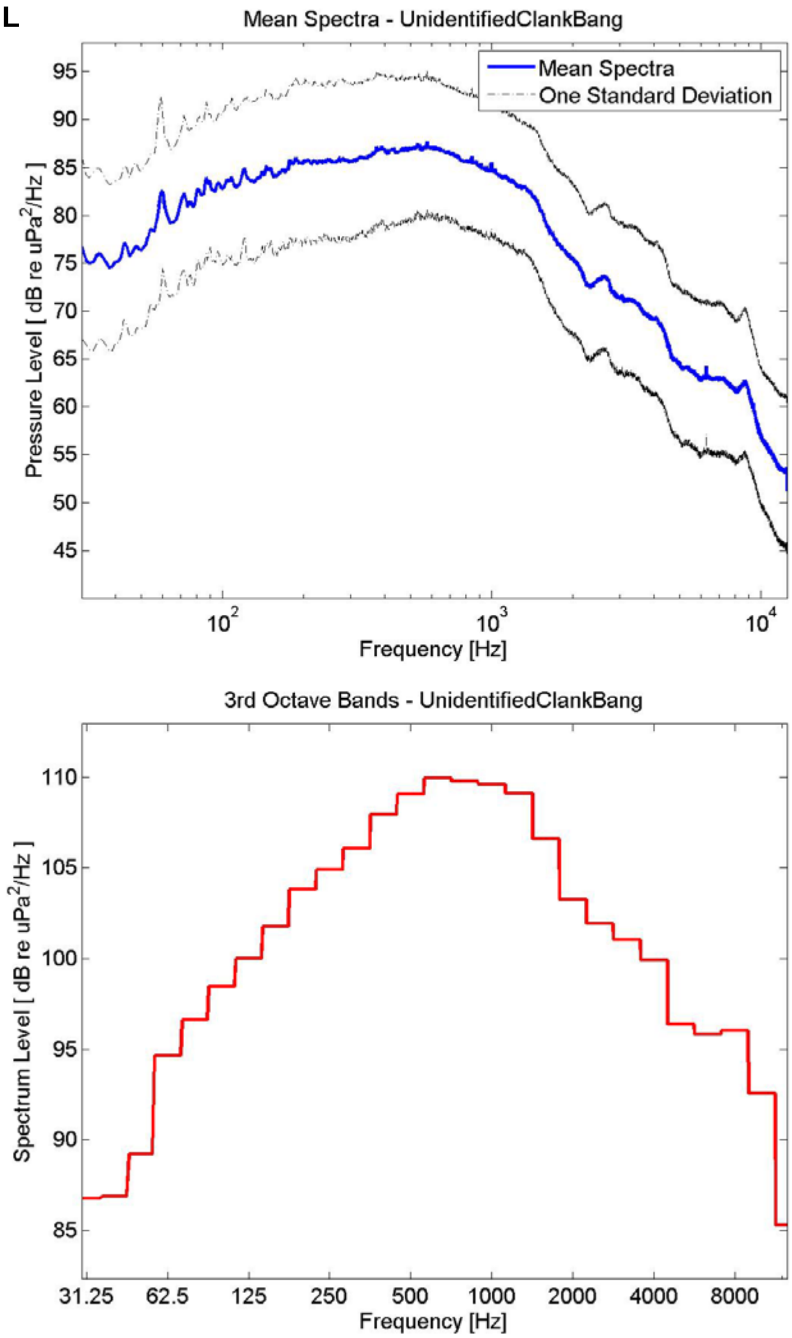


Unclassed machinery averaged spectrum shows intense peaks in the 100-500 Hz range which could be related to some sort or rotatory machinery or resonant frequencies from impulsive noise. Higher frequency peaks, around 6000-8000 Hz contain highest acoustic energy. Beluga hearing thresholds are exceeded in 3rd octave bands centered at or above 3000 Hz. This noise class was very common at Cairn Point, Six Mile and Trading Bay (Table 3), generally loud (and Fig. 8J) and probably related to the shipping and industrial activities occurring, particularly in summer, around the POA, and year round in Trading Bay in connection with the presence of oil and gas platforms. Because of the occurrence and received levels of this noise class it would be recommended to further explore which are the sources that have not been identified in this study.



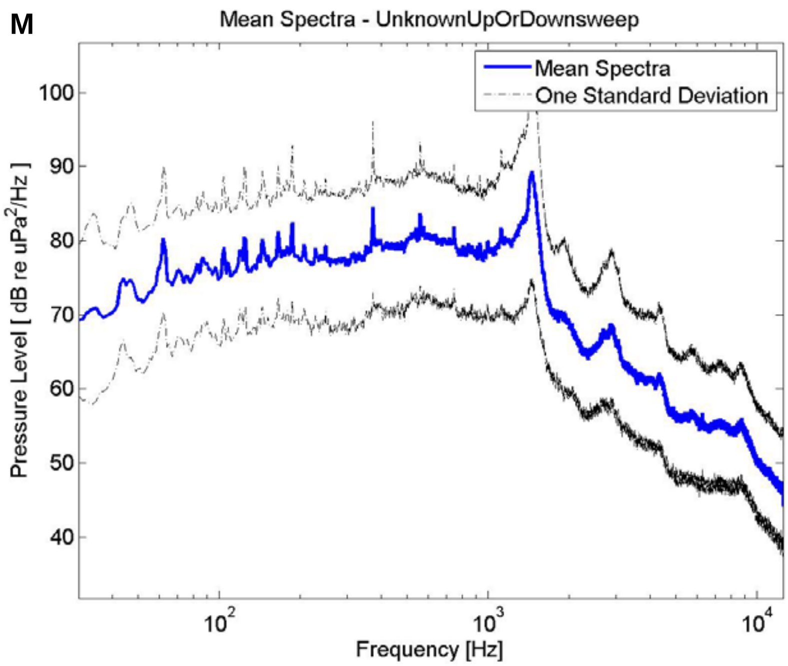
Unidentified noise shows high variability in the averaged spectra, especially at lower frequencies, highlighting the different nature of noise sources included in this class as well as the variety of acoustic energy content across events. 3rd octave band analysis suggests that most of the energy is concentrated in the upper frequency bands, between 1000 and 8000 Hz, although most events show peaks around 1000 Hz (Fig. 11). Received levels for these bands are well above beluga hearing thresholds, therefore these unidentified noises have the potential to mask beluga communication. This noise class was particularly relevant at Cairn Point in August (table 3). Further efforts to distinguish unclassed machinery in this area in summer might also elucidate the origin of these unidentified noises.

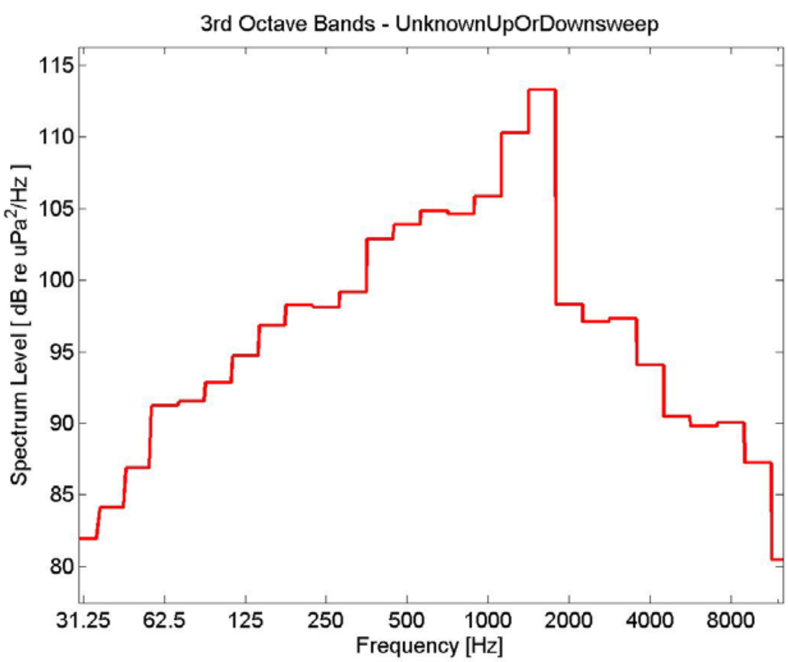
L



Unidentified clank or bang averaged spectra shows a gradual and homogeneous increase in energy from the lower frequencies, peaking at 500-800 Hz and gradual decrease to higher frequencies. Variability remains constant across the spectral domain. 3rd octave band analysis suggests that most of the acoustic energy for this noise class is concentrated in the mid frequencies, around 500-600 Hz, and most events peak in these bands (Fig. 11). Beluga hearing thresholds are reached at 3rd octave bands centered in 500 Hz and all the above, thus this unidentified noise has the potential to mask beluga signals. Its occurrence seems to be related to shipping activities which are widespread throughout Cook Inlet, and in particular at Cairn Point in August this noise class is detected over 25% of the time (Fig. 3). Therefore, at least for Cairn Point in summer, this noise class is of concern for beluga communication, and should be further investigated to identify its source.

M





Unknown up or down sweep averaged spectra shows acoustic energy with series of small peaks in the lower frequency range 0-500 Hz that probably corresponds to the unknown machinery related to the source of these signals, but the highest energy is concentrated in the 1500-2000 Hz range, where the up or down sweeps were detected. The fact that the peak in energy is centered in the 1500 Hz band, suggests that acoustic energy is stronger at the beginning of the down sweep or the end of the up sweep. These results match the histogram shown in Fig. 11L. 3rd octave bands centered at 600 Hz or above exceed beluga hearing thresholds, thus these up or down sweeps can mask beluga signals. However these were only detected at Cairn Point in August (Table 3) and their mean duration and % time present were very small (Fig. 3 and 4), thus the concern for beluga communication is negligible. Nevertheless, in context of the amount and diversity of anthropogenic noise occurring at Cairn Point in summer (unidentified, unclassed machinery and unidentified clank or bang noise classes all are of particular importance in summer at Cairn Point), this noise class adds to the potential for negative cumulative effects.

Figure 12: Averaged spectrum and 3rd octave band analysis by noise class from all the events detected in the location and month where they were most prevalent. Nosie classes included are A- jet aircraft (commercial or military non-fighter) from Cairn Point in August, B -commercial ship from Cairn Point in August, C- dredging from Cairn Point in August, D- helicopter from Six Mile in December, E- jet aircraft (military fighter) from Cairn Point in August, F- outboard Engine from Kenai in April, G- pile Driving from Fire Island in August, H- propeller aircraft from Cairn Point in April, I- sub-bottom profiler from Fire Island in August, J- unclassed Machinery from Cairn Point in April, K- unidentified from Trading Bay in April, L- unidentified Clank or Bang from Cairn Point in August, and M- unknown Up or Down Sweep from Cairn Point in August.

5. CONCLUSIONS

The series of results presented in this report document the highly varied nature of anthropogenic noise in the waters of Cook Inlet. Specifically, there is strong variability in source diversity, loudness, distribution, and seasonal occurrence of noise, which reflects the many different activities within the inlet. Background noise levels obtained on the quietest days of the sampled locations and periods were always below the hearing thresholds for beluga whales; this indicates that during such quiet periods beluga hearing is limited by their intrinsic hearing sensitivity and not by the amount of masking caused by natural noise. Natural masking might occur during high current velocity in certain areas of the upper inlet, yet only for their lower hearing range, as opposed to the common belief that Cook Inlet is a naturally noisy environment. Further assessment of natural masking of beluga communication and hearing in Cook Inlet is needed. However, the temporal prevalence and levels of anthropogenic noise we measured and have reported on above indicate that beluga communication and hearing is largely masked by anthropogenic noise in most of the locations and periods sampled.

Noise from commercial ships was widespread and at elevated levels (well above heavy traffic noise reported by Richardson et al. 1995), indicating such noise may have a negative effect on beluga communication. Ship noise levels in Saguenay Fjord, St. Lawrence estuary, Canada, were reported in the range 102.1 – 114.1 dB rms (Gervaise et al. 2012). These authors estimated beluga potential communication and echolocation range reduction to be less than 15% of its expected value under natural noise conditions when ship noise was highest. More than 79% of our reported SPL values for commercial ship noise were above 114.1 dB rms (Fig. 8B), therefore the potential communication and echolocation range reduction for Cook Inlet belugas is even more extreme than in the Saguenay Fjord. Due to the clipping of commercial ship noise events at high levels, our data preclude an accurate description of highest received levels. However, the results presented here are sufficient to highlight the potential for the acute masking of beluga communication at a wide temporal and spatial scale within their critical habitat. Cairn Point was the location where the loudness and duration of commercial ship noise events were most concentrated, due to activities at the POA. This specific source of anthropogenic noise was present in the recordings from all months we analyzed, with highest levels in August.

In addition to the concentrated shipping noise at Cairn Point, a combination of unknown noise classes occurred in this area, particularly during summer. Specifically, unknown up or down sweeps, unidentified, unclassed machinery, and unidentified clank or bang noise classes were all of particular importance and collectively add to the potential for negative cumulative effects on beluga communication and hearing. Events from these noise classes were detected at levels that cause beluga signals to be masked, and, probably originated at levels that could reach physiological impact if belugas were nearby (e.g. within hundreds of meters from the source). Because the methodology of our study does not permit an estimate of the distance from the noise source to our acoustic moorings, source levels cannot be estimated. However the documented occurrence of high noise levels (i.e. received levels >170 dB SEL or >140 dB SPL) and the accumulation of noise events at Cairn Point during a period when relatively large numbers of belugas are known to regularly move through the area is of concern and should be further evaluated.

Unclassed machinery contributes substantial anthropogenic noise, both in loudness and prevalence, to the waters of Cook Inlet. Further efforts to identify more of these unknown noise sources should be considered a priority, particularly noise sources that may be relatively easy to identify; e.g., up or down sweeps, and clank or bang noises. In this regard, Trading Bay is an interesting location because recurrent very stereotypic unknown machinery noises where detected, presumably related to oil and gas operations in that area.

Other anthropogenic noise results are worth summarizing. Pile driving could affect a large area of the beluga acoustic space in Cook Inlet, and thus temporal and spatial distribution of this noise source should be considered to avoid cumulative impacts. Dredging might affect beluga communication moderately, and only at Six Mile, at least based on our sampled periods and locations. Outboard engine noise should be considered as potentially problematic because of its high frequency harmonic content and broadband elevated loudness. In particular, in areas or periods where outboard engine use is concentrated (e.g. high fishing or hunting periods, river mouths) this noise source should be properly monitored to better understand its noise contribution and potential acoustic impact to beluga critical habitat. The occurrence of surveys involving the use of sub-bottom profilers, by far the loudest noise source detected in this study, or other active transducers, should be avoided in areas and periods of concentrated beluga presence.

Future research should expand the locations and months sampled in this study and improve the classification of unknown anthropogenic noise sources easily distinguished by their stereotypic acoustic properties. In particular, comparisons between summer and winter should be addressed in locations where anthropogenic noise is expected to be high and input from operators of machinery (e.g. tug boats, dredges, pile driving, etc.) should be collected to facilitate noise sources recognition.

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