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Killer Whale (Orcinus orca) pulsed calls in the Eastern Canadian Arctic

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Killer whale (*Orcinus orca*) pulsed calls in the Eastern Canadian Arctic

A Thesis submitted in partial satisfaction of the requirements for the degree in Master of Science

in

Marine Biology

by

Jessica Jeanne Sportelli

Committee in charge:

John Hildebrand, Chair
Lisa Ballance
Simone Baumann-Pickering

2019

The Thesis of Jessica Jeanne Sportelli is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California San Diego

2019

DEDICATION

This thesis is dedicated to all the strong female figures in my life who have shown me how to be the best that I can be. Thank you for paving the way, and for inspiring me to keep going.

EPIGRAPH

In nature's infinite book of secrecy

A little I can read.

~ William Shakespeare

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A huge thank you goes out to my fellow graduate students in the Scripps Whale Acoustic Lab and Scripps Acoustic Ecology Lab. I literally could not have done this without your help, guidance, and friendship. I hope I get the chance to work with you all in the future. Thank you to Josh Jones who took me under his wing during my senior year of undergrad, and who has provided me with advice and opportunities I couldn't imagine. Thank you, Josh, for all of your guidance and enthusiasm surrounding this project and for making time for me in your busy life. Thank you to Kait Frasier who sat with me on MATLAB for hours and whose intelligence and kindness shines so bright.

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To my friends, thank you for always being there for me, for supporting me through the hard times, and celebrating the good times. My experience here would be very different if each one of you were not in my life. I couldn't imagine my life without you.

Finally, thank you to my parents. Mom and Dad: your unwavering support has meant so much to me. You never questioned my jump from the arts to science, and always found ways to allow me to explore this new career path. I appreciate everything you have done to help me continue my education and to shape me into the person I am today. Love you.

ABSTRACT OF THE THESIS

Killer whale (*Orcinus orca*) pulsed calls in the Eastern Canadian Arctic

by

Jessica Jeanne Sportelli

Master of Science in Marine Biology

University of California San Diego, 2019

Professor John Hildebrand, Chair

Killer whales produce pulsed calls, which are used for communication. Calls are highly stereotyped and repertoires are unique to individual pods. Discrimination amongst these calls and comparison of call repertoires between pods can help determine population structure in killer whales and can be used to track pod movements. Calls were detected in underwater acoustic recordings in August and September 2017 in the Arctic waters of Eclipse Sound, in Nunavut, Canada. We present a repertoire of killer whale calls recorded. Eleven stereotypic call types, three biphonic and eight monophonic, were identified using manual call organization and manual whistle contour extraction. A higher diversity of calls was detected in the hydrophone located in

the known narwhal aggregation site in Milne Inlet, than at the second hydrophone deployed at the mouth of Eclipse Sound which is the proposed entrance and exit point for the killer whales.

The potential for increased killer whale presence and magnitude of predation on narwhals is a source of concern for management of the population and by Inuit subsistence hunters who rely on narwhals for food and economic benefit. Describing the acoustic repertoire of killer whales seasonally present in the Canadian Arctic may help understand their behavior and seasonal movements. The results presented may provide a basis for future acoustic comparisons across the North Atlantic and aid in characterizing killer whale ecotypes making seasonal incursions into Arctic waters.

Introduction

Killer whales (*Orcinus orca*, Linnaeus, 1758) have a cosmopolitan distribution and live in familial pods with distinct physical markers, specialized prey selection, and unique vocal repertoires, placing them in respective "ecotypes" (Ford and Fisher 1986; Pitman et al. 2010; Higdon et al., 2011). They produce a variety of vocalizations, including echolocation clicks for hunting and navigating, single toned whistles, and discrete pulsed calls for pod communication (Ford & Fisher 1986; Simonis et al. 2012; Shamir et al. 2014). Pulsed calls can be complex, are stereotyped, and are characterized by "a high repetition rate of sound pulses" (Wellard et al. 2015; Rice et al., 2017). Pulsed calls can be composed of either a single fundamental frequency, referred to as monophonic calls, or two independently modulated fundamental frequency contours with a low frequency contour (LFC) and a high frequency contour (HFC). These are referred to as biphonic calls (Filatova et al. 2009). The stereotyped nature of discrete pulsed calls allows them to be placed into "call types". These call types make monitoring killer whale migrations and behavior relatively straight-forward, especially in areas like the Pacific Northwest where databases of vocal repertoires are well established (Rice et al. 2017). Matriarchal pods of killer whales have their own unique pulsed call repertoires, specific to that pod, that is believed to be used as pod markers (Ford 1991). This is described as the pod's dialect, and is believed to be a long term and well-established vocal mechanism for maintaining intra-group communication and group cohesion (Ford & Fisher 1986; Filatova et al. 2009; Shamir et al. 2014).

Dialects can identify a pod down to their respective region, as shown in captive killer whales who produce vocal differences related to their locations of capture, and can be linked to prey specification, as seen in the three ecotypes found in the Pacific Northwest; the residents, transients, and offshores who have different dialects and prey choices respectively (Dahlheim

1982; Ford & Fisher 1986; Rice et al. 2017). Dialects can be recognized by both human and prey species. Human analysis and the ability to discriminate dialects both visually and aurally have been shown to be a reliable way to collect and report data on this species (Danishevskaya et al. 2018). It has also been shown that harbor seals (*Phoca vitulina*) in the Pacific Northwest can distinguish between fish and mammal-specialist dialects, and will respond with an escape behavior to a Transient mammal-specialist call playback (Shamir et al. 2013; Shamir et al. 2014). This body of work on discriminating killer whale pulsed calls recorded in the Eastern Canadian Arctic aims to describe the acoustic behavior of this species, and contribute to the growing effort of monitoring their seasonal migration patterns.

The pod(s) of interest in this study are the killer whales in the Eastern Canadian Arctic, in the waters of Eclipse Sound in Nunavut, Canada (72º 41’57” N, 77º 57’33” W). While historical whaling records from the 1800s show killer whale presence in the area, local Inuit knowledge and acoustic evidence show that killer whales are prolonging their stay, and presence of individuals has been reported to have increased exponentially since the 1950s (Reeves & Mitchell 1988; Laidre et al. 2006; Higdon et al. 2011; Higdon, Westdal, & Ferguson 2014). The prolonged stay is hypothesized to be coupled with the overall decrease in sea ice in the area; as areas that were historically covered in pack ice are now open, exposing new water habitats (Higdon et al. 2011). Killer whales in the North Atlantic are understudied, and their basic ecology and distribution is poorly known (Laidre et al. 2006; Higdon 2011; Higdon, Westdal, &Ferguson 2014) They have been documented to be pagophobic, or ice avoiding, and have been seen to leave the Eastern Canadian Arctic waters before ice formation in mid to late October. They have also only been visually observed in ice free conditions, although this can be contributed to observer effort and feasibility of being outside and on the water in the summer months (Higdon et al. 2011). Their presence in open water is supported by acoustic recording efforts in ice free summer months versus recordings when ice coverage is present in the winter (Matthews et al. 2011; Higdon et al. 2011). They have been observed predating on local narwhal (*Monodon monoceros*), bowhead whale (*Balaena mysticetus*), beluga whale (*Delphinapterus leucas*), and many phocid populations. These "prey" animals have predictable spring and fall migrations and well-established summer aggregation sights within the Eastern Canadian Arctic (Higdon et al. 2011).

The narwhal is of special concern, not solely because narwhal have been the most common prey species for killer whales in Eclipse Sound, but because heavy narwhal predation is a concern for Inuit communities that subsistence hunt the narwhal and place socio-economic and cultural importance on them. (Higdon et al. 2011; Higdon, Westdal, & Ferguson, 2014). Understanding the basic ecology of the killer whales here is crucial for monitoring population structure and predicting future impacts and ecological changes killer whales will induce on the marine mammal community in the area. This species is known to exert top-down control on ecosystems (Ferguson et al. 2012). Through predation of narwhals or as competitors to Inuit, the implications of their prolonged stay here are unknown.

For this study, I focused on describing the discrete pulsed calls of the killer whales detected through Passive Acoustic Monitoring (PAM) methods. Recordings of killer whales were made during late summer and early fall of 2017 in the northern waters of Nunavut, Canada, 58.9 km East and 99.5 km West respectively from the town of Pond Inlet, on the coast of Eclipse Sound (Jones et al. 2014). Here, I discriminate 11 killer whale pulsed call types, containing both monophonic and biphonic structure, from those recordings in August and September of 2017.

Location of Acoustic Recording Devices in the Eastern Canadian Arctic

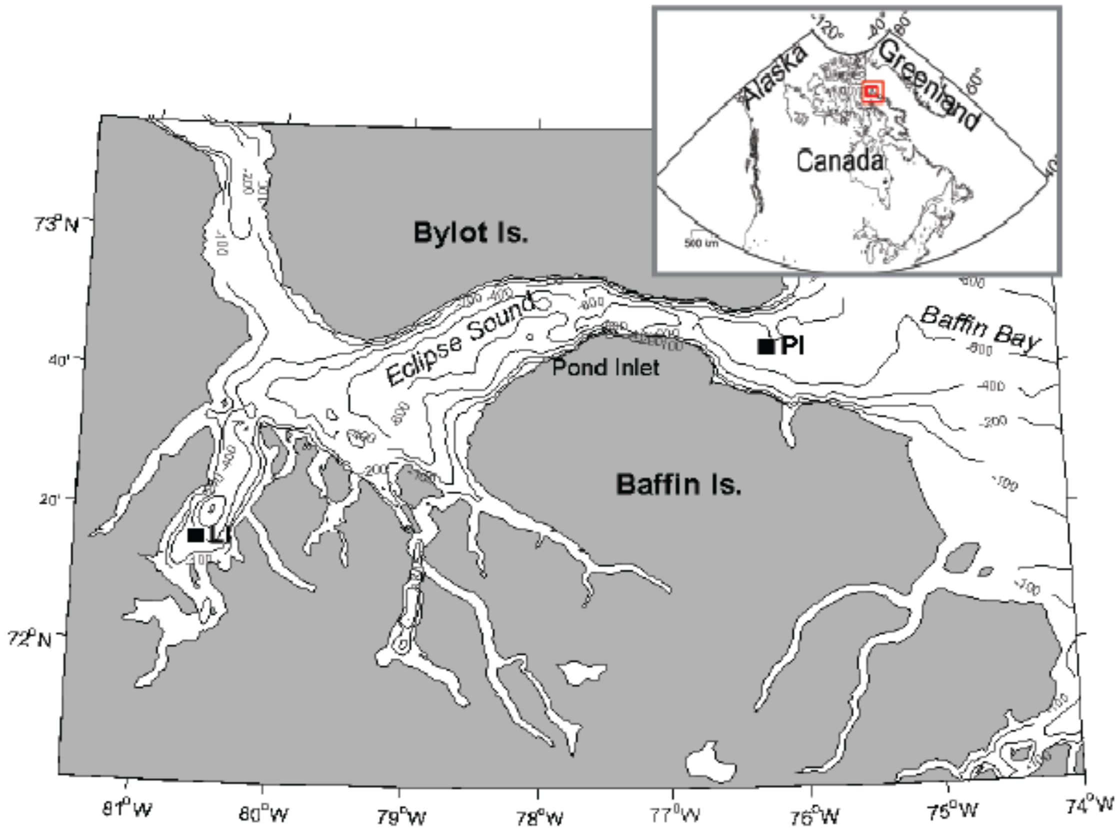


Figure 1: Location of acoustic recording devices deployed in Eclipse Sound and Milne Inlet in Nunavut, Canada. 'PI' refers to the HARP and 'LI' refers to the SM2M+ Deep Water Mooring. Contour intervals in meters. Inset shows study location in regards to Canadian arctic.

Passive Acoustic Monitoring

Passive Acoustic Monitoring (PAM) is a beneficial way of studying whales for a variety of reasons. First, cetaceans are highly vocal animals, as sound travels faster and farther in water, which aids in group cohesion and communication, especially when visibility in the water column is low. Visual observations from land or vessel can be extremely helpful when determining population size, species identification, and animal behavior, but is limited by daylight, good water and weather conditions, and willingness of observer. PAM provides long-term, day and night, monitoring of an animal's acoustic activity and can be deployed to the sea floor and left in a location for months (Wiggins & Hildebrand 2007). The ability to gather data on animals at night is highly beneficial when aiming to describe the whole vocal repertoire. Second, PAM is a non-invasive way of gathering acoustic data, as the instrument sits on the seafloor and has low risk of impacting the whales' natural behavior (Širović & Hildebrand 2011). Finally, the Arctic can be a challenging environment to work in, with harsh winters that include periods of 24-hour darkness and below freezing conditions. Placing an instrument in the water and retrieving it after a prolonged period of time relieves the need for an individual stationed there for the study period. However, PAM only provides relevant data when the animals are actively calling. Whales may be in the area but not vocalizing, so monitoring whale presence around a hydrophone is limited to their active vocalization.

The Scripps Whale Acoustic Lab (SWAL) and Oceans North Canada (ONC), deployed two underwater recording devices in two locations in Eclipse Sound. One, near a known narwhal aggregation site called Low Island (LI) in Milne Inlet, and the other just East of the town of Pond Inlet (PI), at the mouth of Eclipse Sound and Baffin Bay (Figure 1). The use of long-term acoustic recording devices has enabled investigation of the acoustic behavior and seasonal occurrence of marine mammals in places that are remote and at times where travel to a remote location has not been feasible, as is often the case in the High Arctic (Jones et al. 2011).

Goals

Ground work is needed to start describing dialects and repertoires of killer whales in Eclipse Sound. I aim to do this by manually organizing calls into subjective categories and manually contouring the tonal components of each call. Contouring tonal components give us an understanding on the call's subunits, to "better identify call structure and to further understand call complexity of odontocetes" (Frasier et al. 2016). Motivation for this study comes from the limited knowledge we have on North Atlantic killer whale populations and their use of the Arctic, as well as the concern of native Inuit people regarding the new threat and competition that increasing numbers of killer whales pose on narwhal stock. Additionally, by quantitative discrimination of individual tonals and components within each call type, future analysis based on automatic detection can be established. These acoustic studies can provide details on species identification, distributions, and movements. Here, I have compiled 11 call types to begin building a call repertoire.

Methods

Data Collection

Two autonomous passive acoustic monitoring hydrophones were deployed in Eclipse Sound; one High Frequency Acoustic Recording Package (HARP; Wiggins & Hildebrand 2007), and one Wildlife Acoustics SM2M+ Deep Water mooring. Comparison of specifications and recording effort for each instrument can be found in Table 1. The HARP, developed at Scripps Institution of Oceanography, is a low-powered, high-data-capacity, and high-speed digitizing instrument that provides continuous long-term monitoring of vocalizing marine mammals underwater. The HARP has an effective bandwidth of up to 100kHz which is necessary for studying odontocete calls, whistles, and clicks (Wiggins & Hildebrand 2007). This HARP (labeled 'PI' on Figure 1) was deployed at the mouth of Eclipse Sound and Baffin Bay, East of Pond Inlet, located at 72°43'30" N, 76°13'48" W at a depth of 670 m. The instrument recorded continuously from August 14th, 2017 through January 30th, 2018 with a sampling rate of 200 kHz. For the purposes of this project, only the first of three disks that were created out of the entire 5-month PI HARP recording effort was used and surveyed. This is because no killer whales were further detected past the first disk. This makes the analysis effort for this particular HARP range from August 14th, 2017 to October 29th, 2017, the end of the first disk, for a total of 76 days.

The Wildlife Acoustics' Song Meter SM2M+ Deep Water hydrophone, owned and operated by Oceans North Canada, has an effective bandwidth up to 48kHz. Sample rate of this instrument was set at 96kHz and recorded for 45 min at the start of every hour (Wildlife Acoustics, Inc. 2013). The SM2M+ Deep Water Mooring was deployed in Milne Inlet, West of Pond Inlet, located at 72°15'25.2" N, 80°34'44.4" W at a depth of 400 m. This hydrophone (labeled 'LI' on Figure 1 for Low Island, an island close to the hydrophone) recorded from August 1, 2017 to September 24, 2017. Data was provided by Oceans North Canada. The two recording devices are approximately 173 km away from each other, so overlap of vocal detections is not of concern. Acoustic recordings from both hydrophones were converted into an XWAV sound file format for analysis (Jones et al. 2011).

Table 1: A comparison of recording efforts and specs of the two autonomous acoustic recording instruments used in this study.

Recorder	Location	Depth	Recording Period	Sampling Period	Sample Rate
High Frequency Recording Package (HARP)	Lat.: 72.725 N Long.: -76.230 W	670m	8/14/2017 - 1/30/2018	Continuous	200kHz
Wildlife Acoustics SM2M+ Deep Water mooring	Lat.: 72.257N Long.: -80.579 W	400m	8/1/2017 - 9/24/2017	45 min beginning every hour	96kHz

Call Analysis and Contour Extraction

Long Term Spectral Averages (LTSAs) on the custom-built MATLAB program *Triton* were created with a 2-hour time frame and a maximum frequency of 10 kHz (Wiggins and Hildebrand 2007). Recordings were manually scanned for killer whale acoustic activity (encounters) and logged, regardless of specific call type. Encounters were periods of killer whale calls that ended after a 10-minute period of no killer whale calls (Rice et al. 2017). Once an encounter was detected in the LTSA, a corresponding 10 second spectrogram window with a 10kHz max frequency (5000 point FFT, Hanning windows, 70% overlap) was inspected for pulsed calls. Pulsed calls were complex, included rapidly repeating broadband pulses with frequency modulated tonals, and many harmonics (Wellard et al. 2015; Rice et al. 2017). Those with visually clear parameters (clear shape, start and end time, minimum and maximum frequency) were manually logged and sorted to create subjective call type categories based on visual and aural inspection. A call type was established when a call was repeated more than three times and stereotyped. JPEG graphic images and 10-75 second XWAV sound files were created for each logged call. Length of XWAV file depended on the continuous repeated nature of the call in one stretch of time. Calls were logged at the same position on the spectrogram; at the one second mark. Only calls with good signal-to-noise ratio (SNR), clear key parameters, and were visibly conspicuous on the spectrogram were included for the contour extraction and analysis.

Tonal contours, including fundamental frequency and harmonics, were manually traced using the custom software *Silbido* in 5 second time windows with a 10dB threshold (Roch et al. 2011). Contours of a call type were saved as annotation files. Individual contours within the annotation files were extracted and a feature file was written for each contour respectively, providing a shape of individual tones. A corpus (vocal data set) for each call type was simultaneously created (Frasier et al. 2016). Extracted contours for a call type were plotted two ways; the first to compare duration (milliseconds) and frequency (kHz), the second normalized the frequency of the tonals by a z-score transformation to compare subunits and overall shape of tonals, regardless of frequency (Figure 5.2). Normalizing the tonals allows for comparison of distinct contour shapes, which aids in call type identification on a qualitative, visual scale (Frasier et al. 2016).

For further quantitative analysis, calls were broken down to their component's fundamental frequencies (Figure 2). A matrix of call parameters was built for each call type, containing the average bandwidth, duration, start and end frequencies, and maximum and minimum start frequencies of the fundamental frequencies, along with corresponding standard deviations (Table 2). If a call type was biphonic, and therefore had more than one fundamental frequency, they were broken up into their respective tonal categories. Call type ES4 was the only call where the fundamental frequency was not always the most conspicuous, therefore the 2^{nd} harmonic was traced as it was always the most visible on the spectrogram. The goal of creating a matrix for each fundamental frequency of a call type was to begin building a set of parameters for future development of an automatic detector tool for future detections within large data sets.

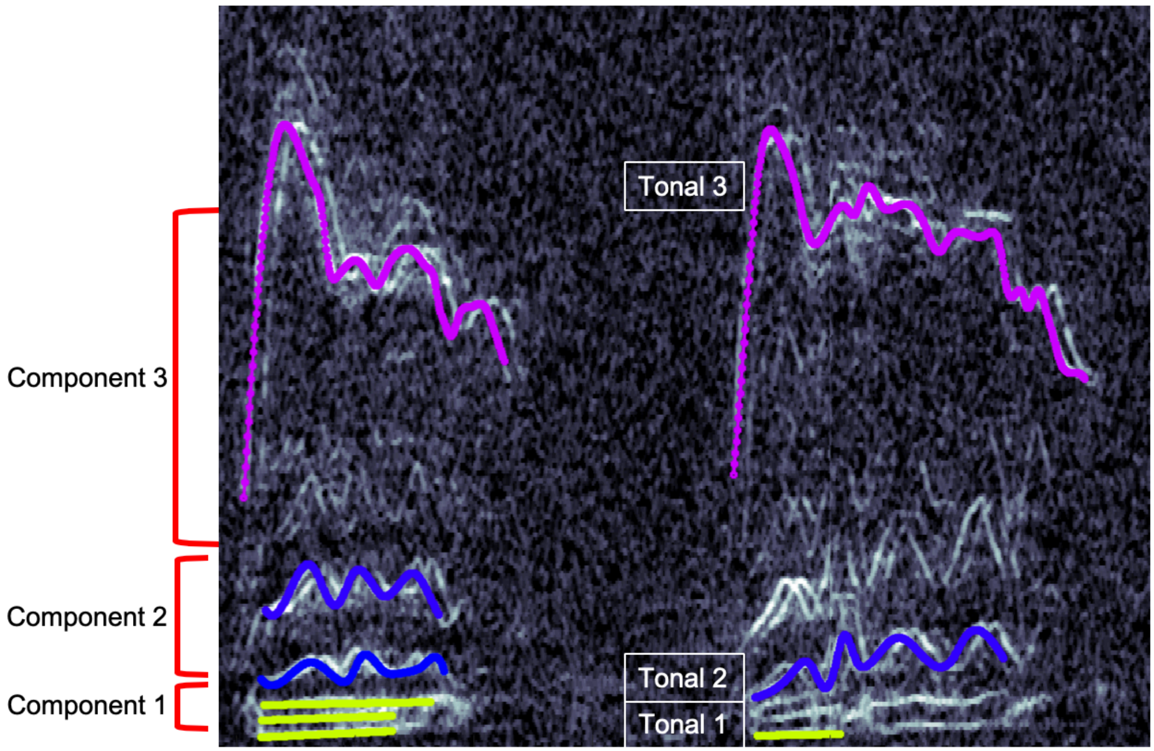


Figure 2: ES1 call type showing the components on the left, and the fundamental frequencies (tonals) on the right. The fundamental frequencies were analyzed for bandwidth, duration, and start frequency.

Results

Killer whale calls were detected on the 'PI' HARP starting on 08/23/17, followed by a 29-day period where no calls were detected. The killer whales were then acoustically present on 09/21/2017 until 09/30/2017. Calls on the 'LI' SM2M+ Deep Water Mooring in Milne Inlet were detected starting 08/22/2017, followed by a 9-day period of no vocal activity. Killer whales were detected again on 09/01/2017 and remained relatively detectable until 09/17/2017, with only 7 days of no vocalizations detected in between 09/01 and 09/17. A diel plot of killer whale vocal presence can be seen in Figure 3. Of the 38 killer whale encounters, 33 of them lasted less than an hour. The longest encounter was 3 hours 40 minutes and 49 seconds long. The shortest encounter was the length of one call: one second.

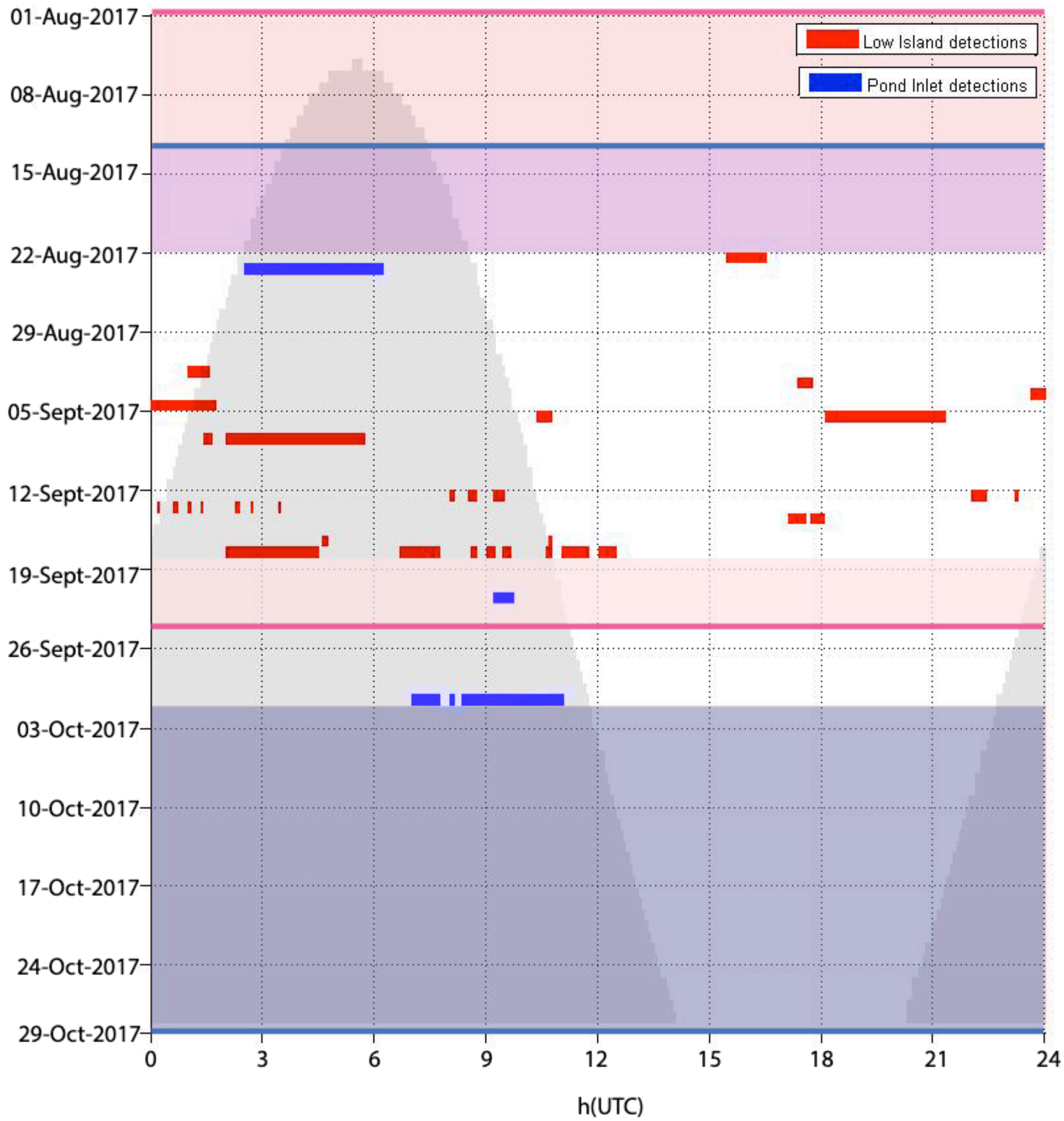


Figure 3: Diel plot showing killer whale pulsed call presence for both Low Island hydrophone (in red) and Pond Inlet HARP (in blue). Night is represented as the grey shadowing. Date on the x-axis refers to recording effort of both hydrophones combined. Time is in 24-hour on the y-axis. Pink and blue shading connotes times when hydrophone was recording but no detections were made.

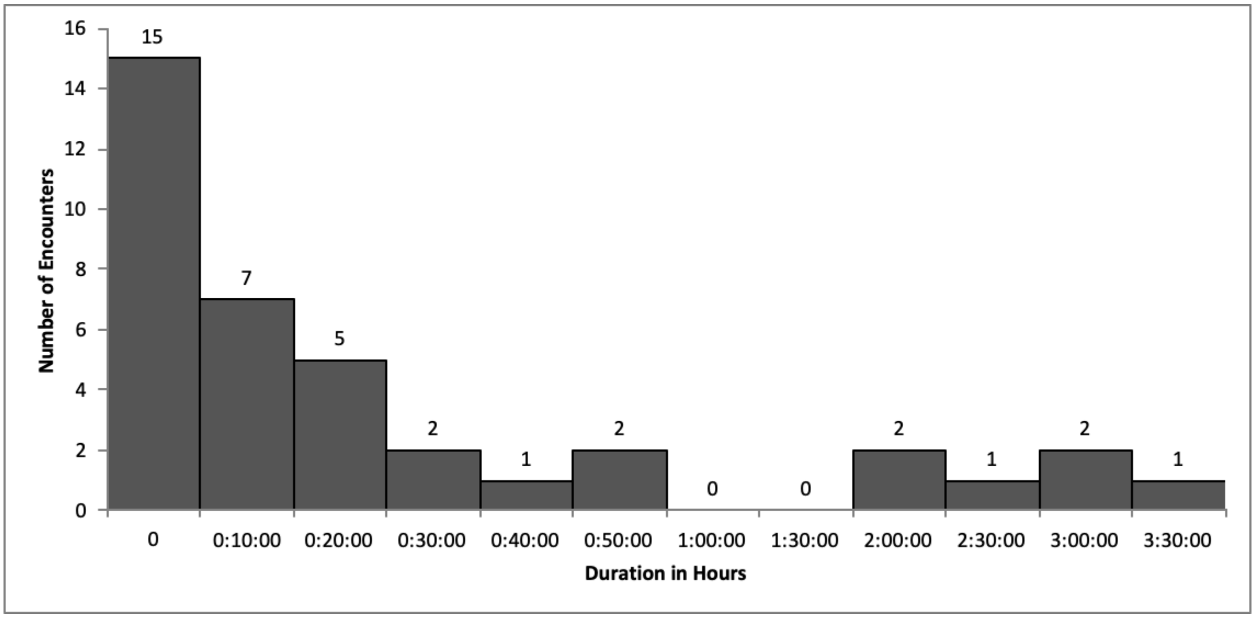


Figure 4: A histogram of the number of pulsed call encounters logged and the hours the encounter lasted. The majority of the encounters lasted less than ten minutes.

1,124 individual calls were manually logged from the 38 encounters. Those that had good SNR, were repetitive in the time series and stereotypic in physical structure were organized into 11 Eclipse Sound (ES) call types. A 12th possible call type was identified, however due to the side-band structure common in narwhal vocalizations, and the lower frequency component that is similar to killer whale call structure, this call type was not included in further repertoire analysis. This is due to the inability to confirm species source, as narwhals were acoustically detected sporadically during the day this call type was discovered. Moving forward for the purposes of this thesis, it will not be quantitatively described.

Presented in Figure 5.1 and Figure 5.2 are representatives of the 11 call types after contour tracing in "Silbido" and contour extraction, which includes fundamental frequencies and harmonics/side bands. These images give a clear picture of the call structure as a whole and its components. Color of tonal tracings from the "Silbido" program does not have significance, but is meant to show separate components of a call.

Of the 11 call types detected, three can be described as "biphonic", or, having more than one fundamental frequency that is made simultaneously in time (Filatova et al. 2015). ES1 and ES3 calls show this biphonic structure by having a LFC and a HFC produced simultaneously. ES5 shows a biphonic structure by having a "high" frequency whistle overlapping a short, low frequency click train, that is then followed by an overlapping harmonic pulse of low frequency whistles. The clicks were not included in analysis of this call type.

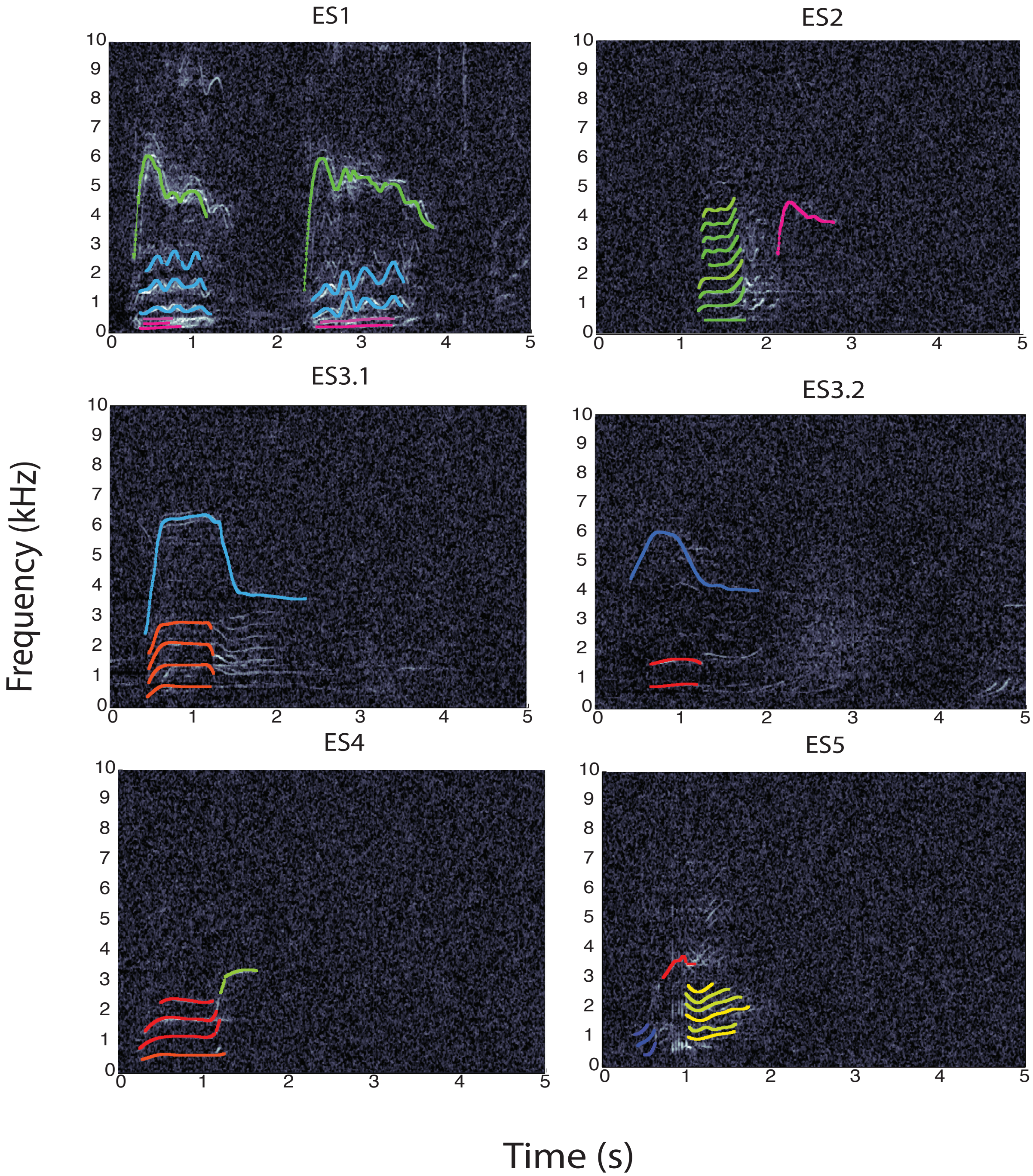
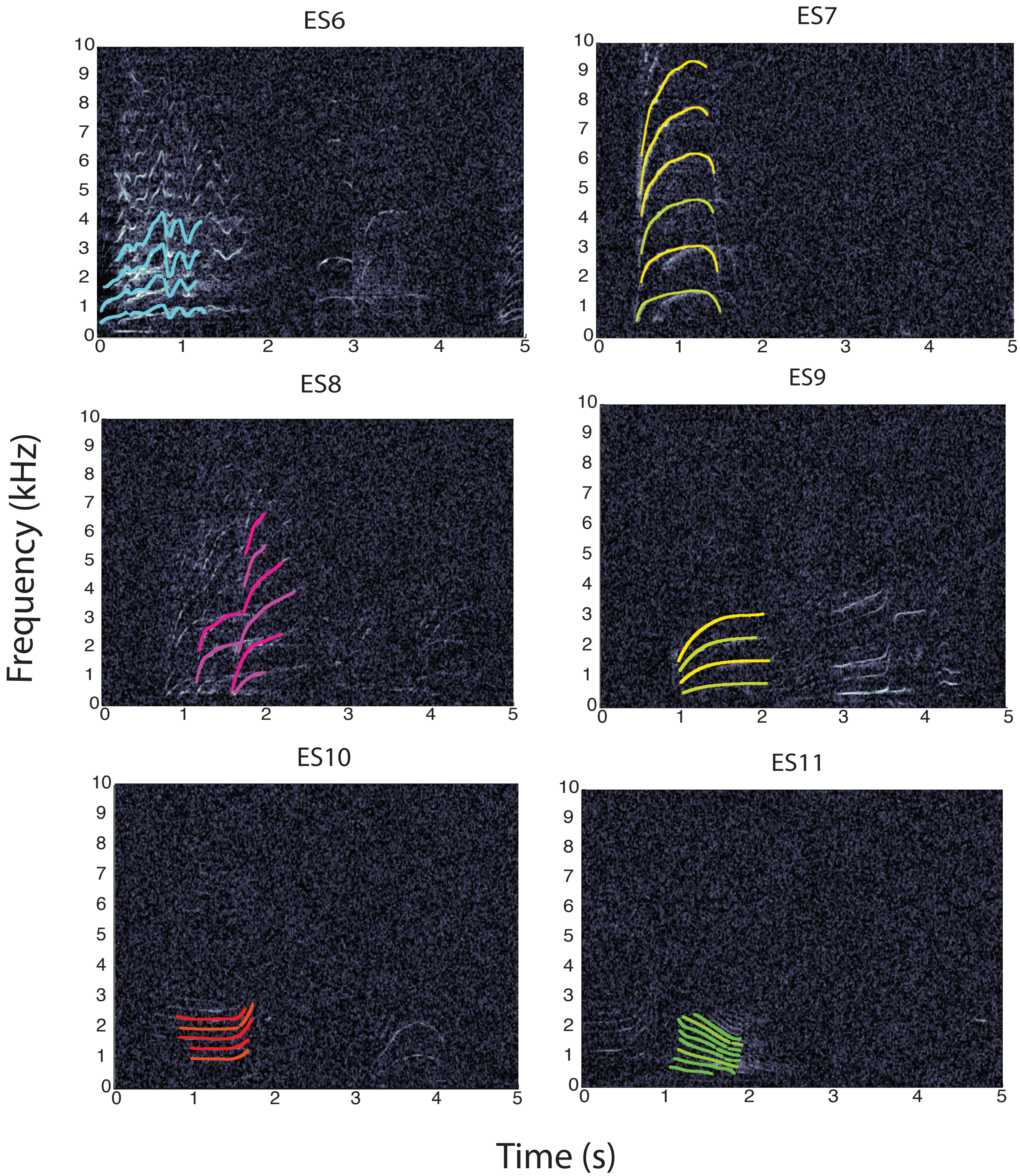


Figure 5.1: Silbido tracings of both fundamental freq. and harmonics in ES call types to show full structure of the calls. Colors of tracings have no meaning, and are only to show call components.

Figure 5.1 continued.



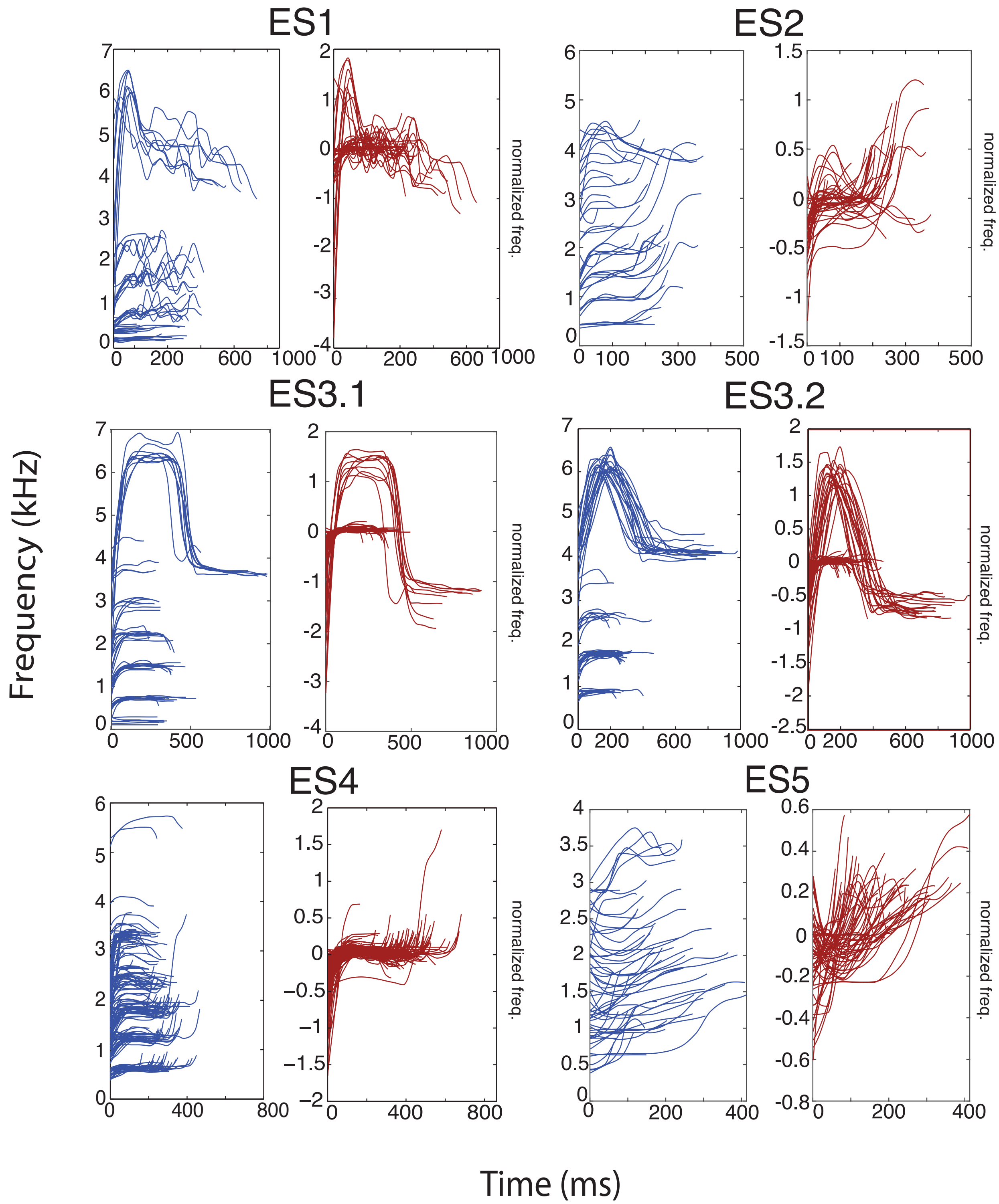


Figure 5.2: Contour extraction of both fundamental freq. and harmonics. Comparing both tonal frequency (Hz) and duration (ms) (blue), and the z-score normalization of the contours (red) to compare shape and duration (ms).

Figure 5.2 continued.

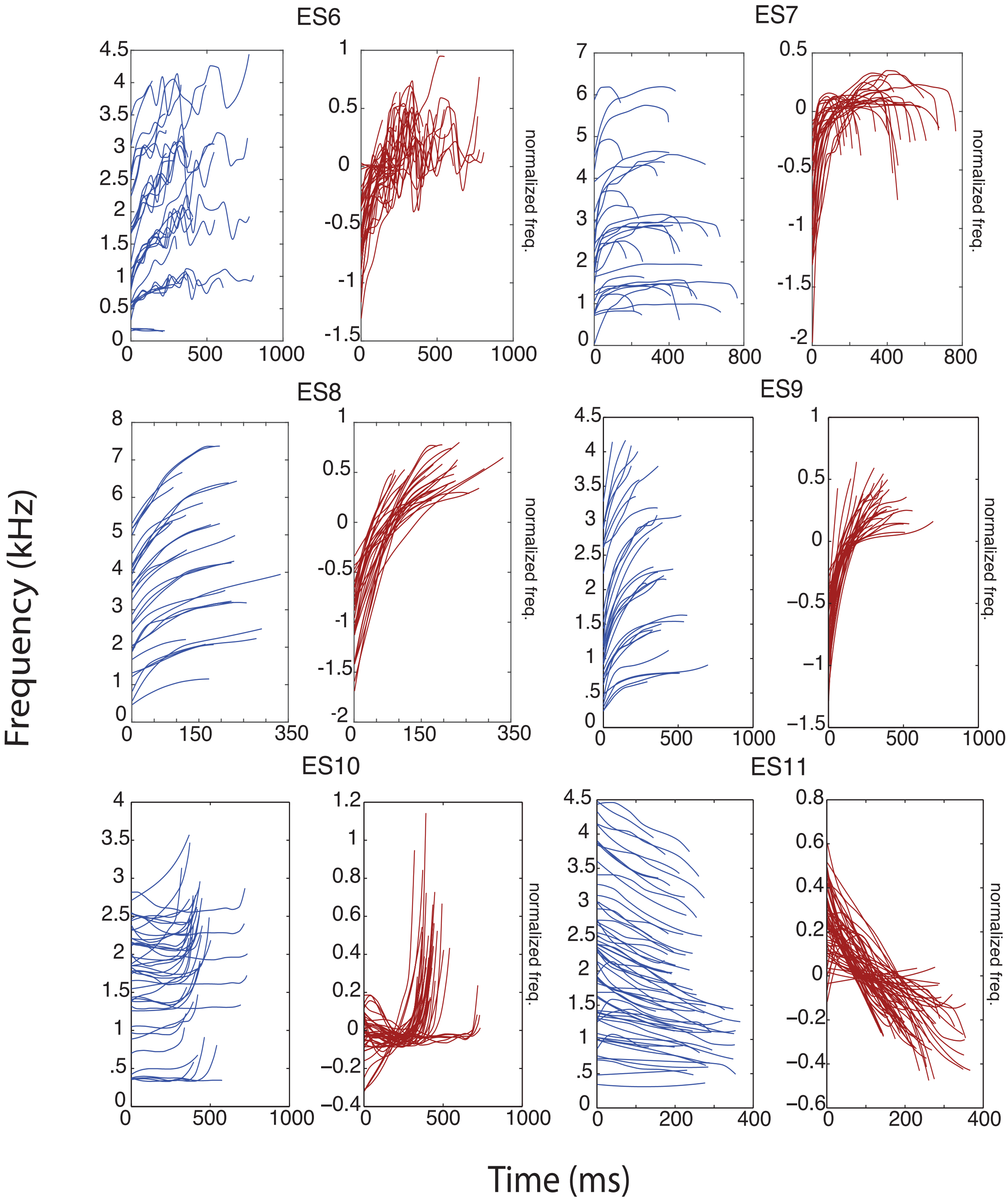


Table 2: Descriptive statistics for call type parameters based on individual fundamental frequencies 't1-3' from each component of the call.

Call Type	N	Bandwidth (kHz)	Start Freq. (kHz)	End Freq. (kHz)	Duration (s)
ES1					
t1	26	35 ± 33	153 ± 20	181 ± 31	0.6 ± 0.2
t2	25	612 ± 134	436 ± 97	948 ± 166	0.99 ± 0.3
t3	24	3863 ± 1129	2062 ± 1273	3910 ± 239	1.4 ± 0.2
ES2					
t1	9	861 ± 492	565 ± 165	1412 ± 535	0.7 ± 0.3
t2	10	1189 ± 480	3418 ± 467	3824 ± 222	0.7 ± 0.2
ES3.1					
t1	32	187 ± 94	518 ± 136	654 ± 164	0.8 ± 0.1
t2	26	3229 ± 497	3728 ± 993	3697 ± 371	1.5 ± 0.3
ES3.2					
t1	17	167 ± 122	747 ± 132	857 ± 77	0.5 ± 0.1
t2	21	2227 ± 364	4178 ± 474	4174 ± 181	1.5 ± 0.3
ES4					
t1	36	598 ± 199	1367 ± 189	1945 ± 180	0.8 ± 0.2
t2	33	959 ± 451	2355 ± 420	3292 ± 160	0.4 ± 01
ES5					
t1	15	451 ± 114	443 ± 29	894 ± 112	0.2 ± 0.1
t2	16	858 ± 266	2680 ± 292	3445 ± 259	0.4 ± 0.1
t3	16	155 ± 204	764 ± 168	1812 ± 1410	0.4 ± 0.2
ES6					
t1	7	733 ± 347	468 ± 96	1073 ± 418	1.1 ± 0.3
ES7					
t1	17	502 ± 337	697 ± 214	830 ± 228	0.9 ± 0.3
ES8					
t1	9	687 ± 141	1007 ± 670	1694 ± 732	0.4 ± 01
ES9					
t1	11	762 ± 387	664 ± 399	1422 ± 702	0.8 ± 0.3
ES10					
t1	16	395 ± 365	706 ± 451	1080 ± 758	0.8 ± 0.2
ES11					
t1	12	323 ± 111	1197 ± 216	925 ± 266	0.6 ± 0.1

Call descriptions

ES1: This "triphonic" call contains a low frequency component, a middle, frequency-modulated component, and a high frequency-modulated component produced simultaneously in time. This call was often coupled with the ES2 call type in a repeating pattern (Figure 6 spectrogram). For tonal extraction the lowest tonal was named t1 (tonal 1), the middle tonal t2 (tonal 2), and the high frequency tonal, t3 (tonal 3).

ES2: This call contained multiple, frequency-modulated harmonics, followed by a whistle. This call was coupled with the ES1 call types (Figure 6 spectrogram). The fundamental tonal of the harmonics was labeled t1, and the whistle was labeled t2.

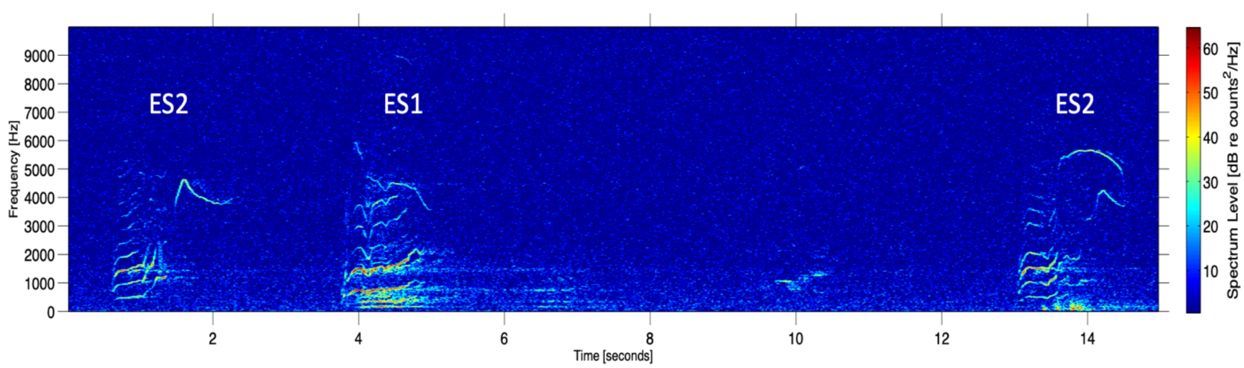


Figure 6: ES1 and ES2 call types are seen to be coupled with each other on the select dates that these called appeared in the recordings. In this figure ES2, ES1, and another ES2 are seen in a 15 second spectrogram window with an 8kHz max frequency, FFT of 5000, and %Overlap of 70%.

ES3.1 and ES3.2: These biphonic calls contain two components: one lower frequency harmonic tone (t1), and a higher frequency whistle (t2) that had a typical duration of one second. These two calls are similar both visually and aurally and are therefore variations of each other. ES3.2 makes a single, yet repetitive, appearance on 8/23/17, preceding the appearance of ES3.1 on the same day within the same encounter. ES3.1 becomes the only call represented for this call type for the remainder of the study period.

ES4: This call made up the majority of the call types on the PI HARP recordings, was highly repetitive, and primarily detected at night (Figure 8). The 2nd harmonic of the low frequency portion of the call was the most conspicuous in the spectrogram, and was labeled t1. The higher frequency whistle was labeled t2.

ES5: This biphonic call has a short, low frequency click train in the center, that is overlapped with a whistle at the beginning and end. While the clicks are an important characteristic of the call, they were not included for parameter analysis. Tonals 1-3 were labeled from left to right, and does not include the clicks. This call was detected on a single day; 9/4/17.

ES6: This call has a high rate of frequency-modulation within the fundamental and harmonic tones. This call was detected on a single day; 9/4/17.

ES7: Simple harmonic tonals that ranged in duration but had the similar concave shape. This call was seen amongst other calls, as seen in Figure 7.

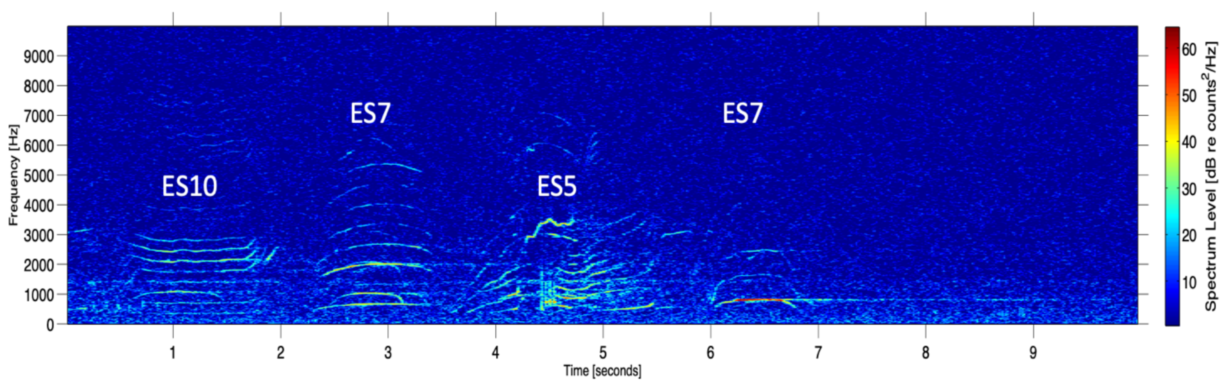


Figure 7: ES10, ES7, ES5, and another ES7 call types are seen to be produced in the same time window. The calls here are seen in a 10 second spectrogram window with an 8kHz max frequency, FFT of 5000, and %Overlap of 70%.

ES8: These upsweeping tonals came in pairs of two, overlapping with each other. It is unknown if this is one killer whale making the call or two.

ES9: Upward harmonic tonals that plateau.

ES10: Side banded call with an upward slopping end to the call.

ES11: Side banded call with a downward slopping tonals.

A visual representation of when each call type was detected can be found in Figure 8. The size of the dots represents the number of calls counted for that encounter, with encounter dates plotted on the x-axis and call type on the y-axis. Blue dots represent calls detected on the Pond Inlet HARP and red dots represent calls detected on the Low Island hydrophone.

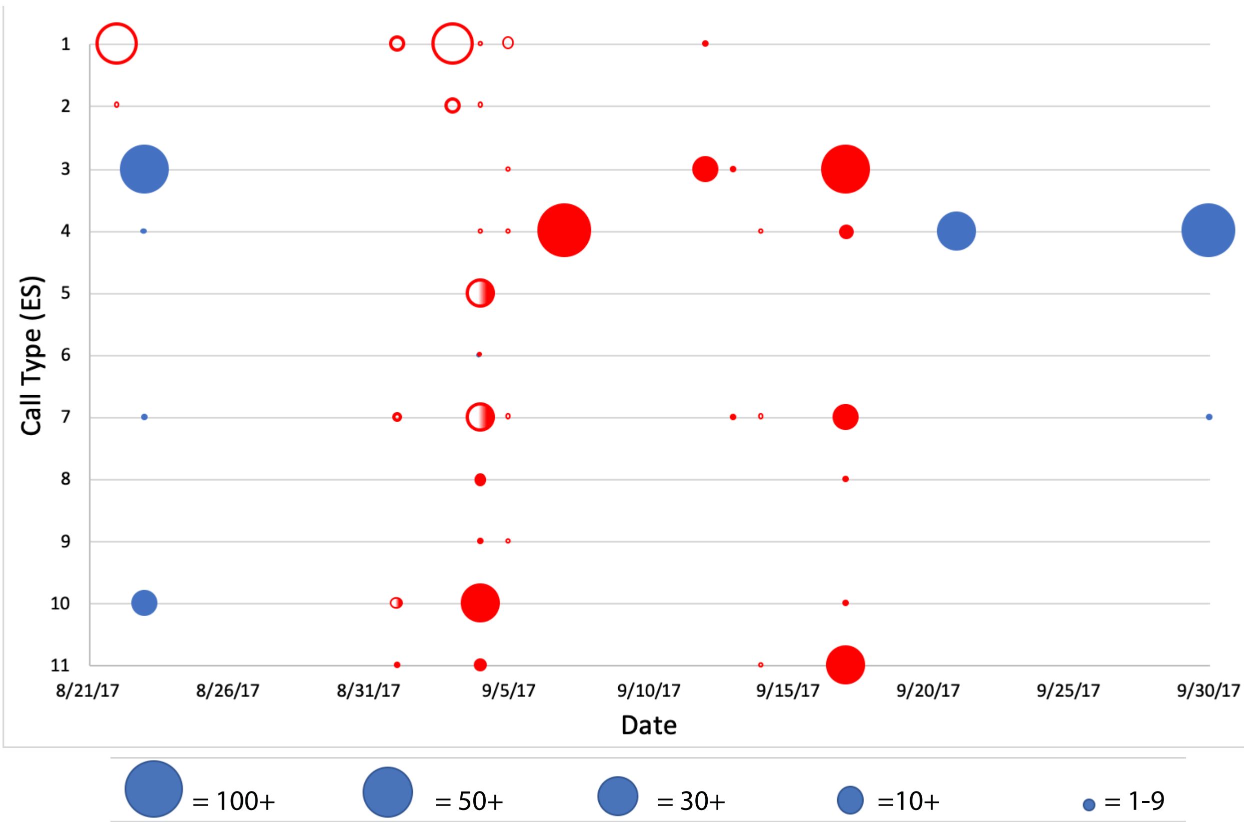


Figure 8: *Call types and when they were detected per encounter. Open dots represent calls detected during the day. Closed dots represent call detected during the night. Half open, half closed dots represent calls that were detected both day and night, as the encounter extended into the night. Size of dots represent number of calls counted per encounter, with larger dots representing a high number of calls counted.*

Discussion

While using autonomous acoustic instruments are highly beneficial for long-term recording, data shows cetacean presence only when the animal is actively calling. Cetaceans that are present in the area but are not vocalizing are not accounted for. Figure 3 shows the diel presence of killer whale call encounters around the Low Island hydrophone and the Pond Inlet HARP, but lack of "presence" in the data cannot conclude killer whales have left the area, especially between encounter times. Transients in the Pacific Northwest and fellow marine mammal prey specialists in Iceland are known to produce lower rates of clicks, whistles, and pulsed calls than their fish-eating conspecifics. This is because their prey species have a hearing range that overlaps with the typical frequency range of killer whale pulsed calls (Vongraven & Bisther 2014; Wellard et al. 2015). Therefore, it is energetically costly to produce higher rates of vocal behavior if eavesdropping by potential prey is a factor (Deecke et al. 2005). If we assume similar acoustic behavior to the Transients and Icelandic marine mammal specialists, then we can comment that these narwhal-hunting killer whales are quiet when travelling and hunting, and therefore a lack of call detection cannot conclude lack of presence (Rice et al. 2017; Riesch & Deecke 2011; Vongraven & Bisther 2014). Figure 3 and Figure 8 also show the use of the mouth of Eclipse Sound and Baffin Bay, where the Pond Inlet HARP is located, as a reasonable entrance and exit point, as we see no acoustic detections on the Pond Inlet HARP while the animals are in the Milne Inlet, Low Island region, with the exception of an ES1 and ES2 detected a day before. Likewise, we stop detecting killer whales on 9/17/17 in Milne Inlet, and then hear them on the Pond Inlet HARP as they are presumably exiting the area.

There is a higher diversity of call types on the Low Island hydrophone than detected on the Pond Inlet HARP (Figure 8). If the killer whales are actively hunting in this region, and only traveling past the Pond Inlet HARP, higher diversity of calls could be expected. A trade-off between biphonic call types is also seen, with ES1 dominating the beginning of the detections. ES5 dominates on 9/4/2017, the only date it is detected. Then, ES3 becomes the dominant biphonic call type until 9/17/2017, when calls on the Low Island hydrophone stopping being detected.

The biphonic structure of three of the call types is important to note, as biphonic sound production is only seen in a handful of mammals, primarily primates and the wild Asian dog (Dhol; *Cuon alpinus*), as well as birds such as king (*Aptenodytes patagonicus*) and emperor penguins (*Aptenodytes forsteri*) (Filatova et al. 2009). Similar to killer whales, these animals live in social groups, and group communication can become increasingly difficult in situations where signals can be impeded; either by dense vegetation or by loud conspecifics. Filatova (2009) noted that the call rate of biphonic calls of killer whales in Kamchatka, Russia increased when more than one pod was in the area, and that monophonic calls dominated when only a single pod was present. Biphonic calls were not observed to be associated with any specific behavior in Filatova's (2009) study. Biphonic calls in killer whale pods are proposed to be markers of individual group or matrilineal affiliation, and serve as a cohesion signal (Filatova et al., 2009, Papalc et al., 2015). Continuing with Filatova's hypothesis, the presence of three biphonic call types in the data may suggest that more than one pod is migrating to the Eastern Canadian Arctic. All three biphonic calls were detected in the known narwhal aggregation site, at the Low Island hydrophone.

Established ecotypes are only beginning to be identified in the North Atlantic due to the limited knowledge on distribution, migration, and prey selection of these killer whales. Two ecotypes have been proposed based on morphology and isotopic analysis: a Type 1 fish generalist and a Type 2 mammal specialist (Foote et al. 2009 ; Vongraven & Bisther 2014). Morphological differences in body length, tooth shape, and pigmentation have been used to describe the two. Type 2 killer whales are larger in size, and have sharper teeth; consistent with mammal-specialists in the Pacific Northwest and Antarctic. Type 1 killer whales have worn-down teeth which is consistent to suction feeding hunting habits for fish specialists (Foote et al. 2009). However, $\delta^{15}N$ levels from Foote's isotope study (2009) along with observational data from Iceland and Norway, report a generalist diet in the majority of pods. Additionally, predation on mammals is often easier to identify then predation on fish, as pursuit of mammalian prey is often at the surface and the overall size of the prey and predator are easier to spot (Higdon et al. 2011). While marine mammals were the only reported prey for killer whales in the Eastern Canadian Arctic, stomach contents of killer whales in Greenland and Norway have contained fish and cephalopod contents as well (Higdon et al. 2011; Higdon, Westdal & Ferguson 2014). It is highly possible that sympatric speciation is occurring in the North Atlantic, however it may be too soon to definitively assign pods to a Type 1 or Type 2 ecotypes based on prey preference alone.

Quantitative descriptions of acoustic repertoires are important for beginning to understand the distribution, behavior, seasonal migration, and habitat use of these killer whales invading the inlets and water ways in the Eastern Canadian Arctic. The Inuit communities that rely heavily on Arctic marine mammals for their subsistence hunting are now competing with highly adaptive, apex predators that are taking advantage of warming waters and ice-free conditions. Ice-free conditions may support the prolonged duration of these killer whales all over the Arctic, which in turn can have heavy impacts on the marine mammal communities in the area (Ferguson et al. 2010). Quantitative call analysis, like what is presented here, can provide the tools needed to further investigate the repertoire of the killer whales here, and develop automated detectors and continue monitoring population status and movement of these animals. Future work must include comparing this recorded repertoire to other acoustic recordings of killer whales from the Atlantic, to determine an origin for the killer whales migrating to the Eastern Canadian Arctic.

Conclusions

Killer whales were acoustically detected in late August through September of 2017, in Eclipse Sound in Nunavut, Canada. This thesis is to serve as the ground work for future research on this species to branch off of. By discriminating the 11 Eclipse Sound call types, we can continue to discover migration patterns, calling behavior, and ecological impact from these apex predators in this new environment. Through the presence of more than one biphonic call type, it is highly possible that more than one matrilineal pod is migrating here, potentially from different places of origin in the Atlantic. Continued sea ice loss and warming waters may support killer whale migration here earlier and for longer bouts of time, which in turn can have detrimental effects on endemic marine mammal species. This is of concern to the indigenous communities that place cultural importance and who rely on the presence of these species for food and socio-economic benefit. This work aims to contribute to the growing knowledge on the ecology of this species, and to contribute quantitative acoustic methods for analysis in the future.

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