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Killer Whale (*Orcinus orca*) Pulsed Calls in the Eastern Canadian Arctic

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ABSTRACT. Killer whales (*Orcinus orca*) produce a variety of acoustic signal types used for communication: clicks, whistles, and pulsed calls. Discrete pulsed calls are highly stereotyped, repetitive, and unique to individual pods found around the world. Discriminating amongst pod specific calls can help determine population structure in killer whales and is used to track pod movements around oceans. Killer whale presence in the Canadian Arctic has increased substantially, but we have limited understanding of their ecology, movements, and stock identity. Two autonomous passive acoustic monitoring (PAM) hydrophones were deployed in the waters of Eclipse Sound and Milne Inlet, in northern Baffin Island, Nunavut, Canada, in August and September 2017. Eleven killer whale pulsed call types, three multiphonic and eight monophonic, are proposed and described using manual whistle contour extraction and feature normalization. Automated detection of echolocation clicks between 20 and 48 kHz demonstrated little to no overlap between killer whale calls and echolocation presumed to be narwhal, which suggests that narwhal remain audibly inconspicuous when killer whales are present. Describing the acoustic repertoire of killer whales seasonally present in the Canadian Arctic will aid in understanding their acoustic behaviour, seasonal movements, and ecological impacts. The calls described here provide a basis for future acoustic comparisons across the North Atlantic and aid in characterizing killer whale demographics and ecology, particularly for pods making seasonal incursions into Arctic waters.

Key words: killer whale; *Orcinus orca*; bioacoustics; Canadian Arctic; passive acoustic monitoring

RÉSUMÉ. L’épaulard (*Orcinus orca*) produit divers types de vocalises acoustiques servant à communiquer : des clics, des sifflements et des signaux pulsés. Les signaux pulsés discrets sont grandement stéréotypés, répétitifs et uniques à chacun des bancs d’épaulards répartis de par le monde. La discrimination entre les vocalises propres à chaque banc peut aider à déterminer la structure de la population d’épaulards et permet de suivre les mouvements des bancs dans les océans. La présence d’épaulards dans l’Arctique canadien s’est accrue considérablement, mais nous avons une compréhension restreinte de leur écologie, de leurs mouvements et de l’identité du stock. Deux hydrophones autonomes de surveillance acoustique passive (SAP) ont été déployés dans les eaux du détroit d’Éclipse et de l’inlet Milne, dans le nord de l’île de Baffin, au Nunavut, Canada, en août et en septembre 2017. Onze types de signaux pulsés produits par des épaulards, dont trois étaient multiphoniques et huit, monophoniques, sont proposés et décrits à l’aide de l’extraction manuelle des contours de sifflements et de la normalisation des caractéristiques. La détection automatisée des clics d’écholocalisation se situant entre 20 et 48 kHz a permis de constater peu ou pas de chevauchements entre les vocalises d’épaulards et l’écholocalisation présumée des narvals, ce qui suggère que les narvals se font à peine audibles en présence d’épaulards. La description du répertoire acoustique des épaulards présents dans l’Arctique canadien de manière saisonnière favorisera la compréhension de leur comportement acoustique, de leurs mouvements saisonniers et des impacts écologiques. Les vocalises décrites dans cet article pourront servir de fondement aux futures comparaisons acoustiques dans l’Atlantique Nord et aideront à caractériser la démographie et l’écologie des épaulards, particulièrement en ce qui a trait aux bancs faisant des incursions saisonnières dans les eaux de l’Arctique.

Mots clés : épaulard; *Orcinus orca*; bioacoustique; Arctique canadien; surveillance acoustique passive

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INTRODUCTION

Killer whales (*Orcinus orca*) have a cosmopolitan distribution, with pods organized into ecologically distinct groupings, or ecotypes. Ecotypes are defined by specific morphological and molecular markers, specialized prey selection, and unique vocal repertoires (Ford and Fisher, 1983; Morin et al., 2010; Pitman et al., 2011; Higdon et al., 2012). Killer whales produce a variety of acoustic calls, including echolocation clicks, single-toned whistles, and discrete pulsed calls (Ford and Fisher, 1983; Simonis et al., 2012). Pulsed calls are the most common in killer whale vocal repertoires (Ford, 1984, 1989; Deecke et al., 2011; Selbmann et al., 2021). They have been described as acoustically complex, stereotyped, and include rapidly repeating broadband pulses with frequency modulated fundamental frequencies and strong harmonic structures (Wellard et al., 2015; Rice et al., 2017). The stereotyped nature of discrete pulsed calls has allowed them to be placed into "call types." Pod-specific repertoires have been hypothesized to be long-term and well-established vocal mechanisms for maintaining intragroup communication and group cohesion (Ford and Fisher, 1983; Filatova et al., 2009). These calls were either monophonic, composed of a single fundamental frequency, or biphonic, composed of two modulated fundamental frequencies produced simultaneously and independently by the same animal (Fitch et al., 2002; Filatova et al., 2009). Biphonic calls have been observed in the calls of cetaceans (Filatova et al., 2009; Jones et al., 2020), primates (Riede et al., 2004), canids (Volodina et al., 2006; Schneider and Anderson, 2011), and birds (Aubin et al., 2000) to date. These types of calls are believed to enhance pod or individual recognition, as a second fundamental frequency allows for more components when creating a unique and identifying call (Aubin et al., 2000; Filatova et al., 2009). For the purposes of this paper, we refer to calls with multiple and simultaneously produced fundamental frequencies as multiphonic, since some calls can be described as having multiple components to them.

Killer whales in the Northeast Pacific have been studied for decades, and vocal repertoires have been described for most resident and transient ecotypes (Ford, 1984; Sharpe et al., 2019; Madrigal et al., 2021; Selbmann et al., 2021). Vocal repertoires of Northeast Atlantic killer whales have only been described more recently (Deecke et al., 2011; Foote et al., 2014; Selbmann et al., 2021). For example, Norwegian killer whale pulsed calls exhibit strong harmonic banding, with fundamental frequencies that range between 0.04 and 4.8 kHz with durations between 0.11 and 2.2 s (Strager, 1995). Likewise, Icelandic killer whale pulsed calls have similar characteristics, with an average fundamental frequency between 0.16 and 3.28 kHz, and an average duration between 0.4 and 2.1 s (Moore et al., 1988). No detailed catalogue exists for vocalizations of killer whales occurring in the Northwest Atlantic, as these populations remain understudied compared to others.

This study focused on killer whale pulsed calls recorded in the eastern Canadian Arctic, specifically in the waters of Eclipse Sound and Milne Inlet in northern Baffin Island, Nunavut, Canada (72.7° N, 78.7° W). The use of passive acoustic monitoring (PAM) in this area can aid in the identification of repertoires from killer whales seasonally inhabiting the Canadian Arctic and in the study of their movements and distribution, as it has done for other Arctic marine mammal species (Marcoux et al., 2017). While whaling records from the 1800s showed that killer whales had been present in the area historically, a growing amount of evidence accumulated through Indigenous knowledge, photo-ID, and tagging efforts have confirmed that the number of individuals arriving in the area has been increasing since the 1950s (Reeves and Mitchell, 1988; Ferguson et al., 2010, 2012; Higdon et al., 2012, 2014). The Committee on the Status of Endangered Wildlife in Canada lists the North Atlantic killer whale populations as of special concern, as killer whales in the Northwest Atlantic and Canadian Arctic have been understudied compared to populations in the North Pacific and Antarctic (Laidre et al., 2006; COSEWIC, 2008; Higdon et al., 2012, 2014; Lefort et al., 2020). Field observations from the northern Baffin Island region report a peak in killer whale presence between the months of July and August, with individuals lingering in the area well into October (Laidre et al., 2006; Matthews et al., 2011; Lefort et al., 2020). Their prolonged stay and range expansion into higher latitudes were hypothesized to be connected to the overall decrease in Arctic summer sea ice, giving these ice-avoiding killer whales access to new waters that were previously inaccessible (Higdon and Ferguson, 2009; Matthews et al., 2011; Higdon et al., 2012; Lefort et al., 2020).

Understanding the ecology of North Atlantic and Canadian Arctic killer whales is crucial for monitoring population structure and predicting future impacts and ecological changes that killer whales may induce (Ferguson et al., 2012; Higdon et al., 2012). For example, killer whales in the Arctic have been observed predating on other Arctic marine mammals, including narwhal (*Monodon monoceros*), beluga whales (*Delphinapterus leucas*), and bowhead whales (*Balaena mysticetus*) (Laidre et al., 2006; Ferguson et al., 2010, 2012; Higdon et al., 2012; Breed et al., 2017). These predator-prey interactions were proposed to have negative effects on Arctic marine mammal stocks that had not been historically exposed to current predation levels (Breed et al., 2017; Matthews et al., 2020a).

Ferguson et al. (2010) and Lefort et al. (2020) summarized the known ecology of the killer whales in the Canadian Arctic thus far and noted the need for future bioacoustics analysis to aid in studies of their movements, distribution, and stock ID. This study starts to fill that knowledge gap by quantitatively describing 11 proposed killer whale pulsed call types, both monophonic and multiphonic, recorded through two PAM hydrophones deployed in Eclipse Sound and Milne Inlet, in northern Baffin Island.

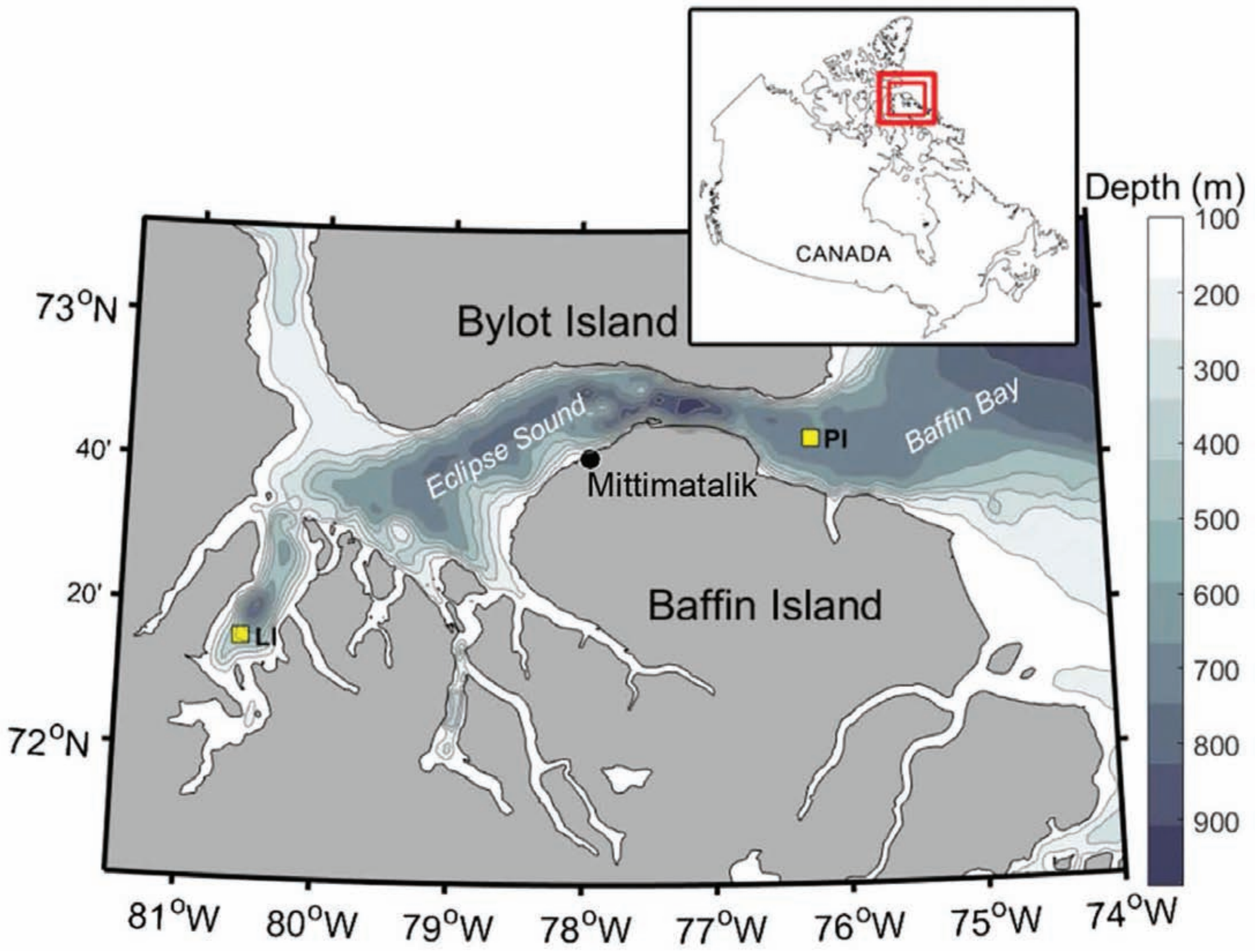

FIG. 1. Location of acoustic recording devices deployed in Eclipse Sound and Milne Inlet in Nunavut, Canada. "PI" refers to the High-frequency Acoustic Recording Package (HARP) and "LI" refers to the SM2M+ Deep Water mooring. Inset shows study location in regards to Nunavut.

TABLE 1. A comparison of recording efforts and specifications of the two autonomous passive acoustic recording instruments used in this study.

Recorder	Location Latitude/Longitude	Depth	Recording period	Sampling period	Sample rate
High-frequency Acoustic Recording Package (PI)	72.725 N, −76.230 W	670 m	8 August 2017 – 30 January 2018	Continuous	200 kHz
Wildlife Acoustics SM2M+ Deep Water mooring (LI)	72.257 N, −80.579 W	320 m	1 August 2017 – 24 September 2017	45 min beginning every hour	96 kHz

METHODS

Acoustic Recording

One High-frequency Acoustic Recording Package (HARP) (Wiggins and Hildebrand, 2007) and one Wildlife Acoustics SM2M+ Deep Water mooring (Wildlife Acoustics, 2013) were deployed in the waters of Eclipse Sound and Milne Inlet, respectively (Fig. 1; see Table 1 for comparison of specifications and recording effort for each instrument). The HARP had an effective recording bandwidth of 10 Hz to 100 kHz, with a hydrophone consisting of two stages, one for low frequency (< 25 kHz) and one for high frequency (> 25 kHz). The low-frequency stage was composed of six cylindrical transducers (Benthos AQ-1) wired in series (3) and parallel (2), providing a hydrophone sensitivity of −187 decibels (dB) re V/µPa and with an additional 55 dB of preamp gain. The high-frequency stage consisted of a spherical omni-directional transducer (ITC-1042; www.itctransducers.com) with an approximately flat frequency response of −200 dB root mean squared (RMS) re 1 V/µPa between 1Hz and 100 kHz with an additional 50 dB of preamplifier gain. The SM2M+ Deep Water mooring had an effective bandwidth of 50 Hz to 48 kHz, with a relatively flat hydrophone sensitivity of 166.5 (± 2) dB re 1 V/µPa between 50 Hz and 10 kHz.

The HARP was deployed approximately 60 km east of the community of Mittimatalik (Pond Inlet) (Fig. 1) in the narrow passage between Baffin and Bylot Islands, at the eastern entrance to Eclipse Sound from Baffin Bay. This passage is also referred to as Pond Inlet, and the instrument is identified hereafter as PI. This location is an entrance and exit point for commercial ships and also serves as the primary entry and exit point for narwhals migrating to and from the region, confirmed via satellite-telemetry data and Inuit knowledge (Matthews et al., 2011; Watt et al., 2012; White, 2012). The SM2M+ Deep Water mooring, hereafter identified as LI, was deployed near Low Island in Milne Inlet, approximately 100 km southwest of Mittimatalik. Milne Inlet is a summer aggregation site for the Eclipse Sound narwhal stock, with a regional abundance of about 12,000 animals as of 2016 (Marcoux et al., 2019). The two recording devices were approximately 173 km away from each other, measured via the waterway path through Eclipse Sound.

Pulsed Call Detection and Categorization

Long term spectral averages (LTSAs), computed as 5-second averages in 10 Hz bins, were reviewed in 2-hour segments within a maximum frequency of 10 kHz, using the custom-built acoustic analysis program Triton (Wiggins and Hildebrand, 2007) developed in MATLAB (MathWorks, Inc.). Recordings were manually scanned for killer whale acoustic activity (i.e., encounters) and presence or absence of killer whale calls was logged for each minute of acoustic data. Encounters were defined as periods of killer whale call activity separated by periods of 15 minutes or more in which no killer whale calls were detected (Rice et al., 2017). Encounters were reviewed using a 10 s spectrogram window (10 kHz max frequency, 5000-point Fast Fourier transform [FFT], Hanning windows, 70% overlap) and inspected for pulsed calls. We acknowledge the potential bias in using a single FFT value for analysis of calls recorded with different sample rates. While the majority of calls analyzed came from the LI hydrophone recordings, calls analyzed from the PI HARP were viewed using the same spectrogram parameters. A comparison of the frequency resolution between spectrograms is provided in the supplementary appendix (Fig. S1). Previous literature analysis of killer whale calls reported maximum call frequencies below 10 kHz, which indicated that a 10 kHz max frequency spectrogram window was a high enough bandwidth for this analysis (Ford, 1984, 1989; Moore et al., 1988; Stafford, 2019; Madrigal et al., 2021).

Calls with visually clear parameters in the spectrogram (clear contour shape, start and end time, minimum and maximum frequency) were manually logged and subjectively sorted into distinct call type categories based on visual and aural inspection. A call type was established when a call was repeated more than five times. A call was determined to be sufficient for contour tracing and analysis if the call was conspicuous against the spectrogram background, background noise was at a minimum or quiet, and the call was not overlapped by another call.

Call Contour Extraction

A process of call contour extraction and processing was performed to assist in visual validation of subjective call type categories. For calls that were determined to be of sufficient quality, the fundamental frequency and harmonics were manually traced on the computer using the custom software Silbido (Roch et al., 2011). Calls were plotted for visual inspection in 5 s time windows with a 10 dB signal-to-noise ratio (SNR) threshold. Silbido darkens regions of the spectrogram below the SNR threshold, computed separately for each time window, so only call components with received levels of 10 dB above the background were traced and extracted for further analyses. Traced components from a call (Fig. 2) were saved, and a feature file was written for each contour. All extracted contours for each call type were plotted without frequency normalization to compare duration (seconds) and frequency (kHz) of different call components. Call components were also frequency-normalized using a z-score transformation to compare subunits and the overall shape of a call's components, regardless of frequency. Normalizing the components allowed for comparison of the distinct contour shapes, which supported the qualitative identification of call types (Frasier et al., 2016).

Traced fundamental frequency components from the calls were then labelled tonal 1 to tonal 3 (t1 – t3), depending on the monophonic or multiphonic structure of the call (Fig. 2). A matrix of average fundamental frequency parameters was generated from the traced contours in MATLAB for each call type. Call type ES4 was the only call where the fundamental frequency was not always the most conspicuous, therefore the second harmonic was traced and labelled t1, as it was always the most visible on the spectrogram.

Differentiating between Killer Whale and Other Marine Mammal Calls

Acoustic data were analysed for the presence of sounds consistent with killer whale pulsed calls. Killer whale acoustic behaviour has not been described for the Canadian Arctic, so acoustic species identification was inferred from characteristics of killer whale sounds reported for other regions and through qualitative comparison with previously described repertoires of marine mammal species that inhabit this particular region. The species considered most likely for misidentification as killer whale in this study was narwhal because of the abundance of narwhal in the study area during the recording period. Narwhal whistles

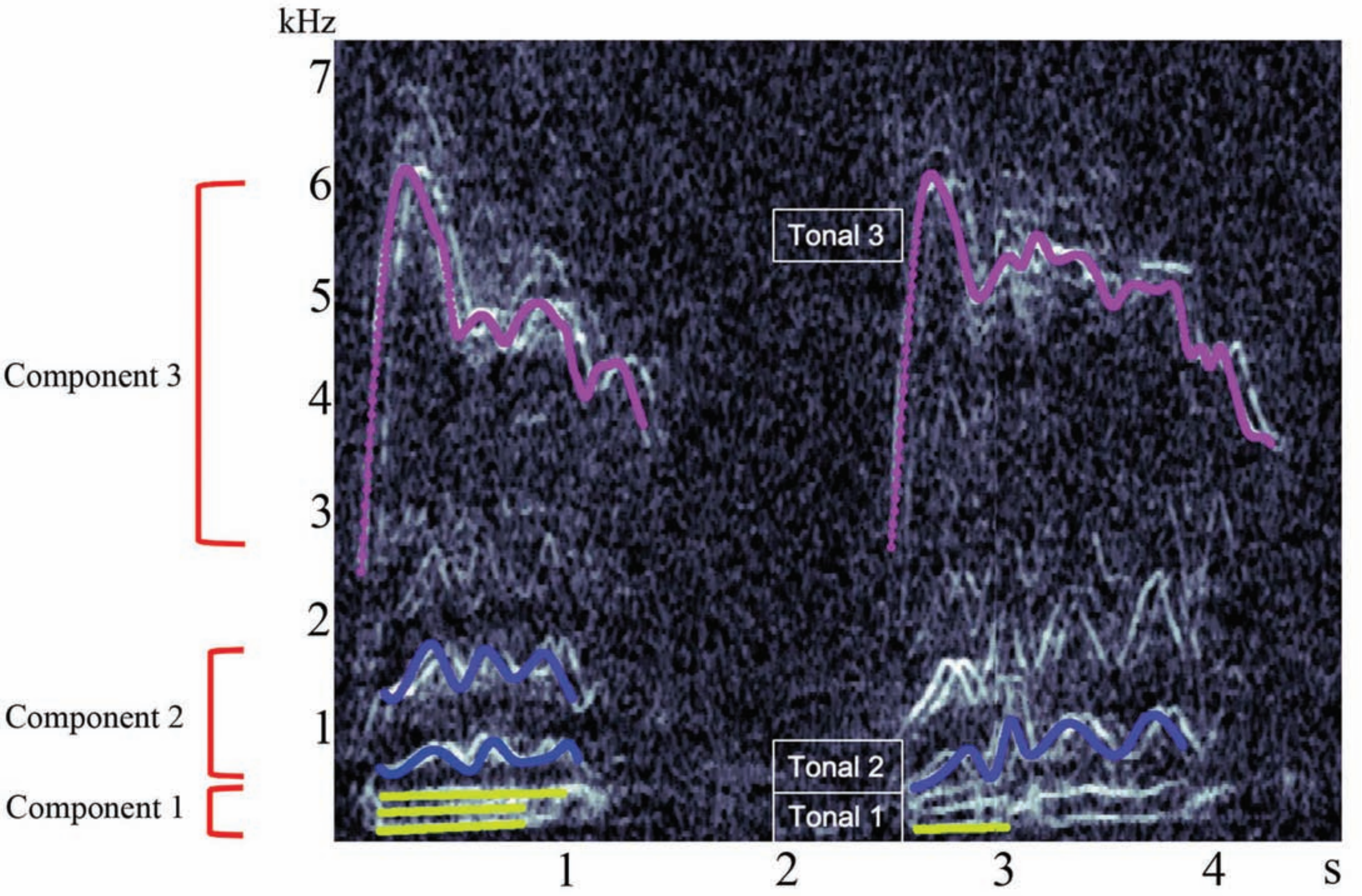

FIG. 2. ES1 call type shown in a cropped Silbido window (4-second duration window (x-axis), seven kHz maximum frequency (y-axis), 10 dB signal-to-noise threshold). Call components on the left, and the fundamental frequencies of each component (referred to as tonals [t]) on the right. Colours of the traces are randomized.

and pulsed calls have similar frequency parameters to Atlantic killer whale pulsed calls (Watkins et al., 1971; Ford and Fisher, 1978; Shapiro, 2006; Marcoux et al., 2012). In a qualitative comparison of pulsed calls for narwhal and North Atlantic killer whale, the killer whale pulsed calls appeared to be more stereotyped, had strong harmonic structure, and exhibited higher degrees of frequency modulation within calls. Additionally, both narwhal and killer whales produce echolocation clicks with peak energy between 20 and 50 kHz (Au et al., 2004; Simon et al., 2007; Frouin-Mouy et al., 2017; Zahn et al., 2021). One potential difference between the two species is that clicks can be reliably used to determine narwhal presence (Finley et al., 1990; Frouin-Mouy et al., 2017; Zahn et al., 2021), while mammal-eating killer whales have been found to produce few or no echolocation clicks (Guinet, 1992; Barrett-Lennard et al., 1996; Deecke et al., 2005). This difference in echolocation production has not been studied in Arctic waters but was investigated through the detection of presumed narwhal echolocation clicks in the recordings at LI and through qualitative comparison with the timing of killer whale pulsed call detections.

Belugas are another highly vocal odontocete species seasonally inhabiting the Canadian Arctic. Beluga acoustic presence is characterized by the occurrence of numerous whistle-type sounds, including pulsed and biphonic whistles (Panova et al., 2019), and characteristic echolocation clicks, with peak energy around 50 kHz (Frouin-Mouy et al., 2017; Zahn et al., 2021). Belugas are sighted occasionally in Eclipse Sound, but their migration routes and summering areas are elsewhere. The Lancaster Sound/Baffin Bay stock migrates west from their wintering grounds near the pack ice off the west coast of Greenland, through Lancaster Sound, to certain shallow river estuaries for the summer (Smith et al., 1985; Sjare and Smith, 1986; Finley et al., 1990). Cunningham Inlet is a primary summer aggregation area for this stock (Sjare and Smith, 1986) and lies more than 400 km west of the recording sites in Eclipse Sound and Milne Inlet. This species is not expected to be present in numbers in Eclipse Sound during August and September.

Bowhead whales make low-frequency calls (50–300 Hz) that range from short grunts (0.5 s) to longer moans (4.0–5.0 s) (Clark and Johnson, 1984; Pomerleau et al., 2011). Bowheads also produce songs that overlap in frequency with killer whale pulsed calls, but these songs typically contain multiple repetitions of discrete phrases organized into themes that are repeated (Tervo et al., 2011; Johnson et al., 2015). Whole songs may be several minutes in duration. This structure of song in bowhead whales is not present in killer whale vocalizations, a difference that helps to distinguish between the two species at times when bowhead song or killer whale calls may be present. Additionally, ice-breeding seals, including ringed, bearded, and harp seals, and Atlantic walruses are also present in Eclipse Sound during summer months. Ringed seals are the most abundant pinniped in the region (Yurkowski et al., 2019) and produce barks and yelps with typical durations of less than 0.5 s and low-frequency growls with fundamental frequency less than 100 Hz (Stirling et al., 1983; Jones et al., 2014). Bearded seals make characteristic trill sounds with complex frequency modulation, which are readily identifiable in acoustic data (Cleator et al., 1989; Risch et al., 2007). Harp seals produce a variety of vocalizations, most lacking clear harmonic structure (Terhune, 1994). Walrus produce a large number of underwater sounds, most commonly impulsive knocks and tonal bell sounds that are rhythmically repeated (Stirling et al., 1987; Nowicki et al., 1997).

Detection of Echolocation Clicks

Echolocation clicks were detected in the acoustic recordings from LI using automated signal detection and confirmed with visual validation. All signal processing was performed using custom software written in MATLAB. Acoustic data were band-pass filtered between 20 and 50 kHz to focus on frequencies where both killer whale and narwhal echolocation signals occur. Individual echolocation clicks were detected using a suite of energy detection criteria to identify impulsive signals (Frasier et al., 2017). A 200-sample window was analysed for each detected impulse, centred on the detected peak. Inter-click interval was estimated from successive window start times. An echolocation event was identified when 10 or more successive clicks occurred with inter-click intervals between 0.01 and 0.5 s. Frequency spectra were not included in this analysis, as the emphasis was on determining whether there was overlap in time of echolocation and pulsed signals presumed to be produced by killer whales. This analysis of echolocation clicks was intended to provide a preliminary result on potential co-occurrence of narwhals and killer whales and to assist with validation of identity of killer whale pulsed calls.

RESULTS

Pulsed Call Detection and Categorization

Killer whale pulsed calls were detected at PI on three days: 23 August, 21 September, and 30 September 2017. There were four encounters at PI with an average encounter duration of about two hours. Pulsed calls at LI were first detected on 22 August 2017 and then were acoustically present intermittently between 1 and 17 September 2017. A total of 48 encounters were detected on 12 days at LI, where the average encounter lasted about 20 minutes. There were no cases in which killer whales were acoustically detected at both recording sites on the same day (Fig. 3).

In total, 1265 individual calls were detected within 52 encounters. Eleven pulsed call types were created from those calls. About 22% of logged calls were not categorized within a recurrent call type, either because of lack of repeatability (under five repeated calls) or overlapping or "messy" calls where the structure of the call was unclear. Call type counts, as well as a breakdown of which calls were detected on which hydrophone are reported in Table 2. Representative examples of the 11 call types are shown in Figure 4. Traced components for each call type are aligned and plotted as non-normalized and normalized in Figures 5 and 6. Three call types can be described as multiphonic. ES1 appeared to have three independently produced components to the call: a low-frequency tonal with little to no frequency modulation (t1), a mid-frequency modulated tonal with 1–3 harmonics (t2), and a high-frequency modulated tonal (t3). The ES3 call type had a low-frequency component (t1) with 1–3 harmonics and a high-frequency component (t2) produced simultaneously. This call type appeared in two versions: ES3.1, which characteristically had an elongated and "flat" high-frequency component (t2), and ES3.2, which had a similar high-frequency component (t2) with a shorter duration and pointed high-frequency maximum. This variation in the ES3 call type can be seen in Figure 5, and the component parameters for ES3 as a whole, along with ES3.1 and ES3.2 separately, are presented in Table 3. The ES5 call type was also produced with three distinct components: a short, low-frequency upsweep with 1–3 harmonics (t1), a high-frequency tonal (t2) that overlapped a low-frequency click train (5 clicks on average), followed by a low-frequency tonal with 1–3 harmonics (t3).

Detection of Echolocation Clicks

A total of 1.6 million clicks with peak energy between 20 and 48 kHz were detected in the acoustic recordings from LI. Echolocation clicks were often accompanied by burst-pulsed sounds at frequencies of 10–20 kHz with a few whistle-like sounds present (Fig. 7A), consistent with narwhal acoustic behaviour (Frouin-Mouy et al., 2017). There were few occasions during which clicks and killer whale pulsed calls were detected in the same time span. Most notably, this occurred during the first occurrence of killer whale pulsed sounds at LI on 22 August 2017 (Fig. 7B). During this detection event, click detections had occurred consistently from 12:10 to approximately 15:30 GMT. The first detection of killer whale pulsed calls occurred at 15:25 GMT. These first killer whale calls were relatively faint and not included in repertoire analysis because their SNR was below 10 dB. Within 5 minutes, the echolocation had mostly ceased, and burst-pulsed sounds above 10 kHz continued sporadically, while killer whale pulsed calls continued and increased in relative received

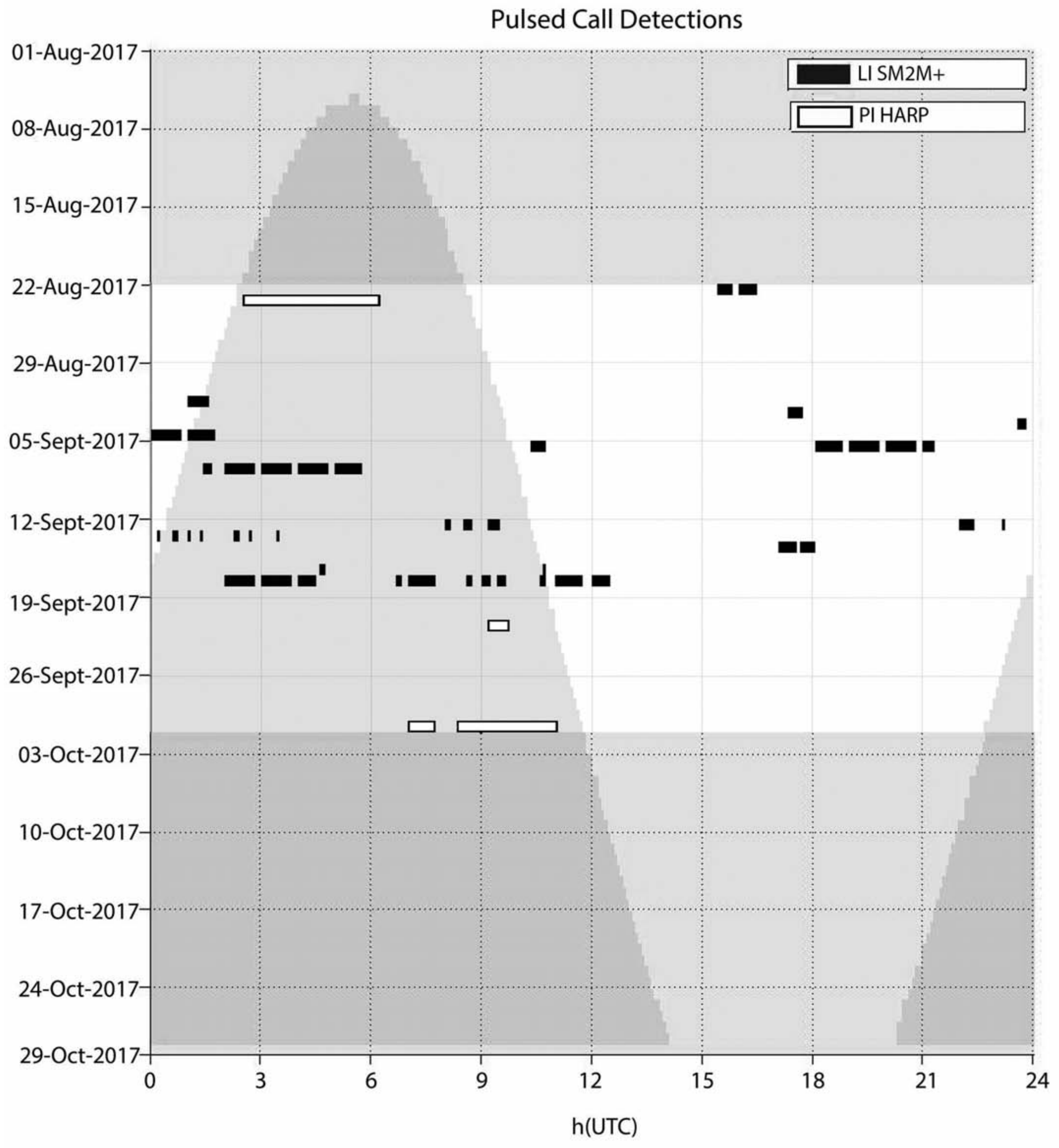

FIG. 3. Diel plot showing killer whale acoustic encounters at PI (white box with black outline) and LI (solid black box). Night is represented as the concave shadowing. Date on the y-axis refers to recording effort of both hydrophones combined. Time on the x-axis is in the 24-hour system. Shading above and below detections connote combined efforts when hydrophones were recording but no detections were made.

level (Fig. 7C). By 15:36 GMT, echolocation clicks were no longer detected, and killer whale pulsed calls over 10 dB SNR continued until 15:43 GMT (Fig. 7D). At 15:44, killer whale calls over 10 dB SNR stopped, but relatively faint calls were still detectable.

Echolocation detections were present on 33 of 54 days (61%) from the beginning to the end of the recording effort at LI, with no clicks detected during four periods: 12 to 14 August (three days), 30 August to 2 September (four days), 4 to 14 September (11 days), and 16 to 18 September (three days) (Fig. 8). Killer whale pulsed calls were detected during

TABLE 2. Call counts per recording location, including calls that were unable to be placed in a call type. Call proportion from total number of calls logged (0.0 – 1.0).

Call type	Calls from Pond Inlet	Calls from Low Island	Call count	Proportion of total
ES1	0	103	103	0.0814
ES2	0	35	35	0.0277
ES3	87	85	172	0.1360
ES4	322	145	467	0.3692
ES5	0	21	21	0.0166
ES6	0	9	9	0.0071
ES7	5	50	55	0.0435
ES8	0	12	12	0.0095
ES9	0	8	8	0.0063
ES10	21	41	62	0.0490
ES11	0	43	43	0.0340
Unclassified			278	0.2198
Total:	435	552	1265	

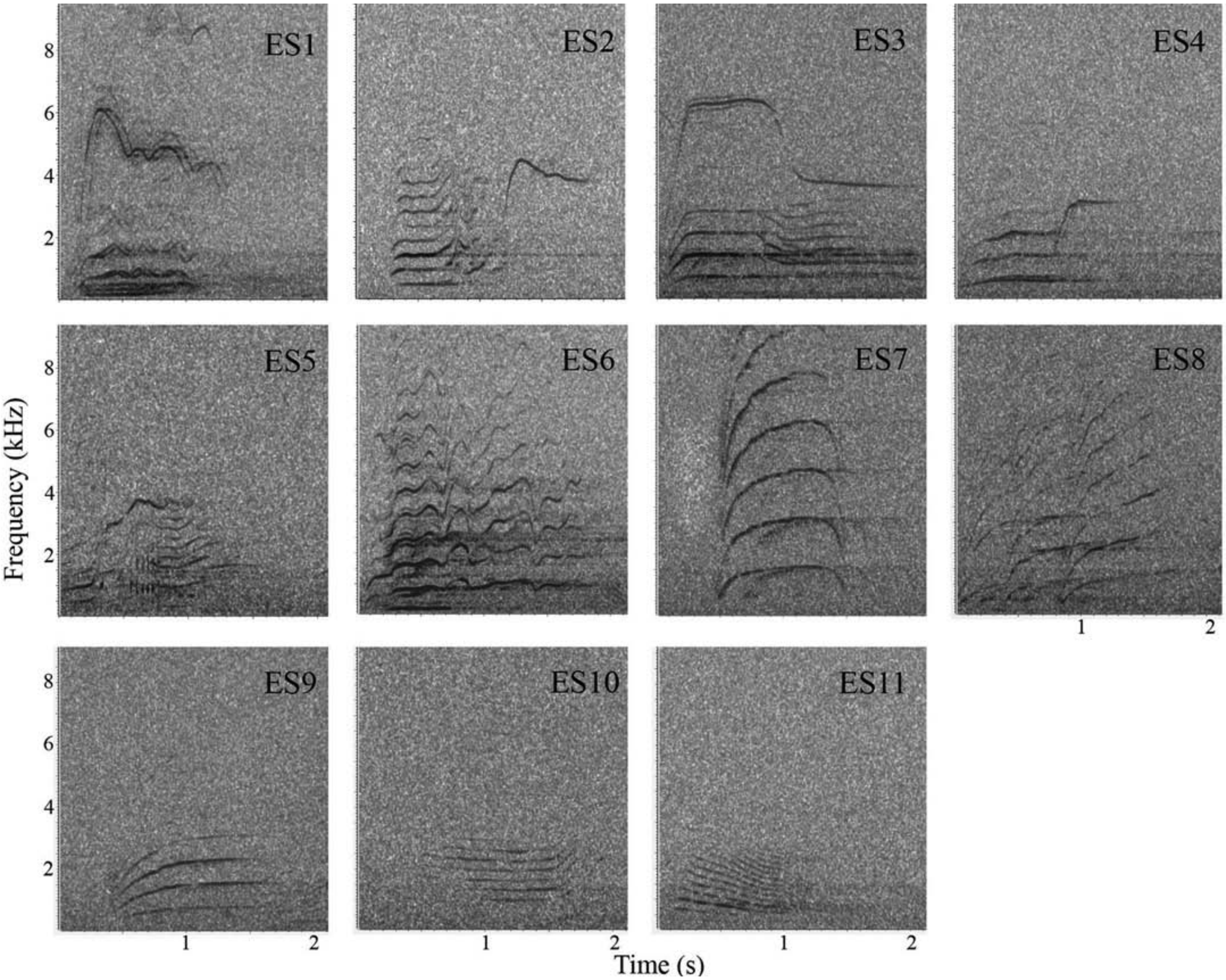

FIG. 4. Spectrogram examples of the 11 ES call types, with a maximum frequency of 9 kHz (y-axis), and 2-second time window (x-axis). All spectrograms were made using Raven 1.6 and have a FFT of 2048, Hop size of 600, 50% overlap, Hann window, 0 – 10 kHz frequency range, and a 10 second time window.

three of four periods with no echolocation detection. With the exception of 22 August, echolocation clicks between 20 and 48 kHz were not detected on days with killer whale pulsed calls. On days with click detection, clicks were present in the recordings for 2 – 20 hours per day. During the period from 23 August to 29 August, echolocation was present again for 2 – 20 hours per day, and killer whales were not detected at LI but were detected at PI (Fig. 3).

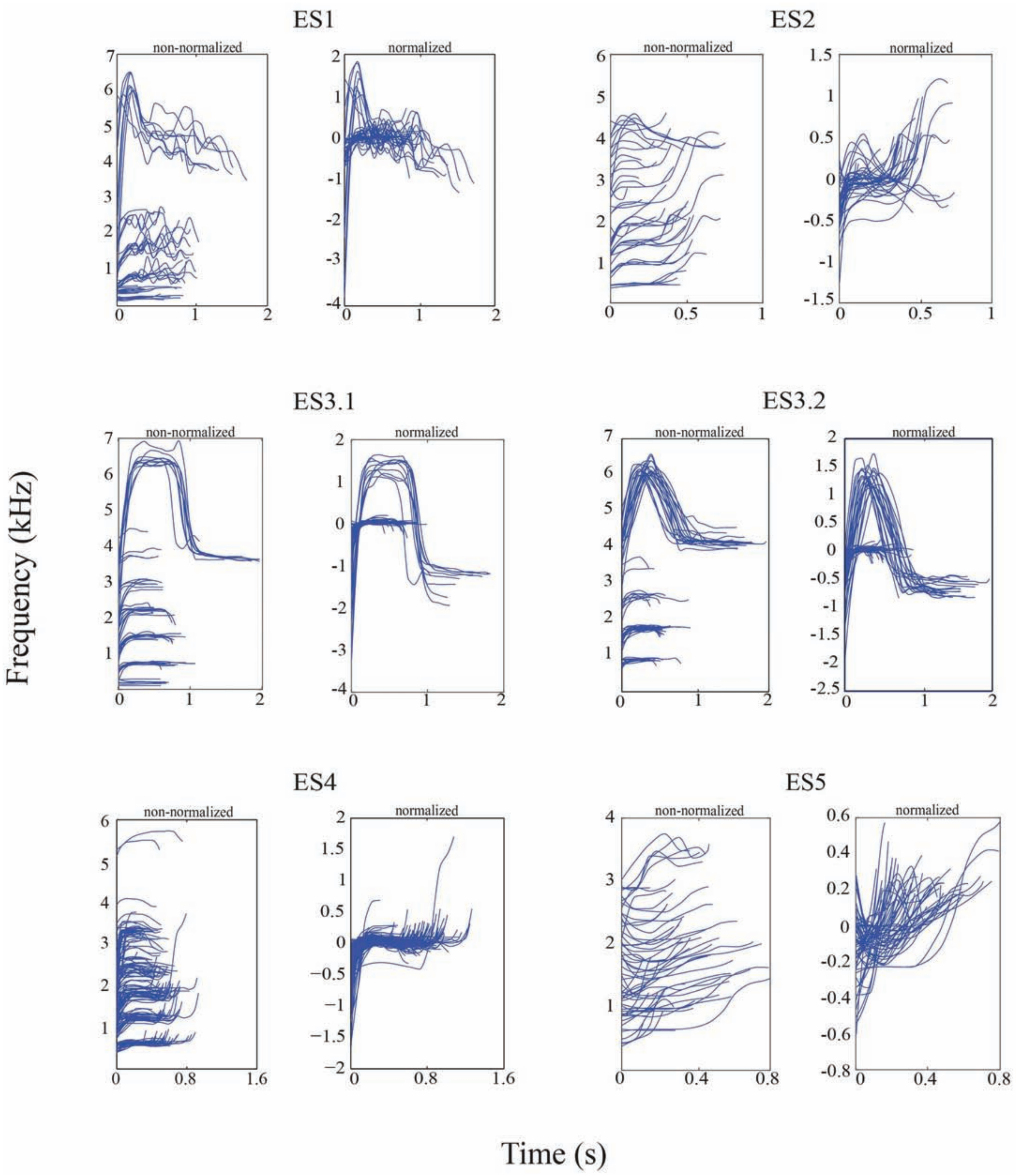

FIG. 5. Traced contours for call types ES 1 – 5. Non-normalized (left) and z-score normalized (right) contours are plotted for each call type, including fundamental frequency and harmonics. Further parameters of each call are presented in Table 3.

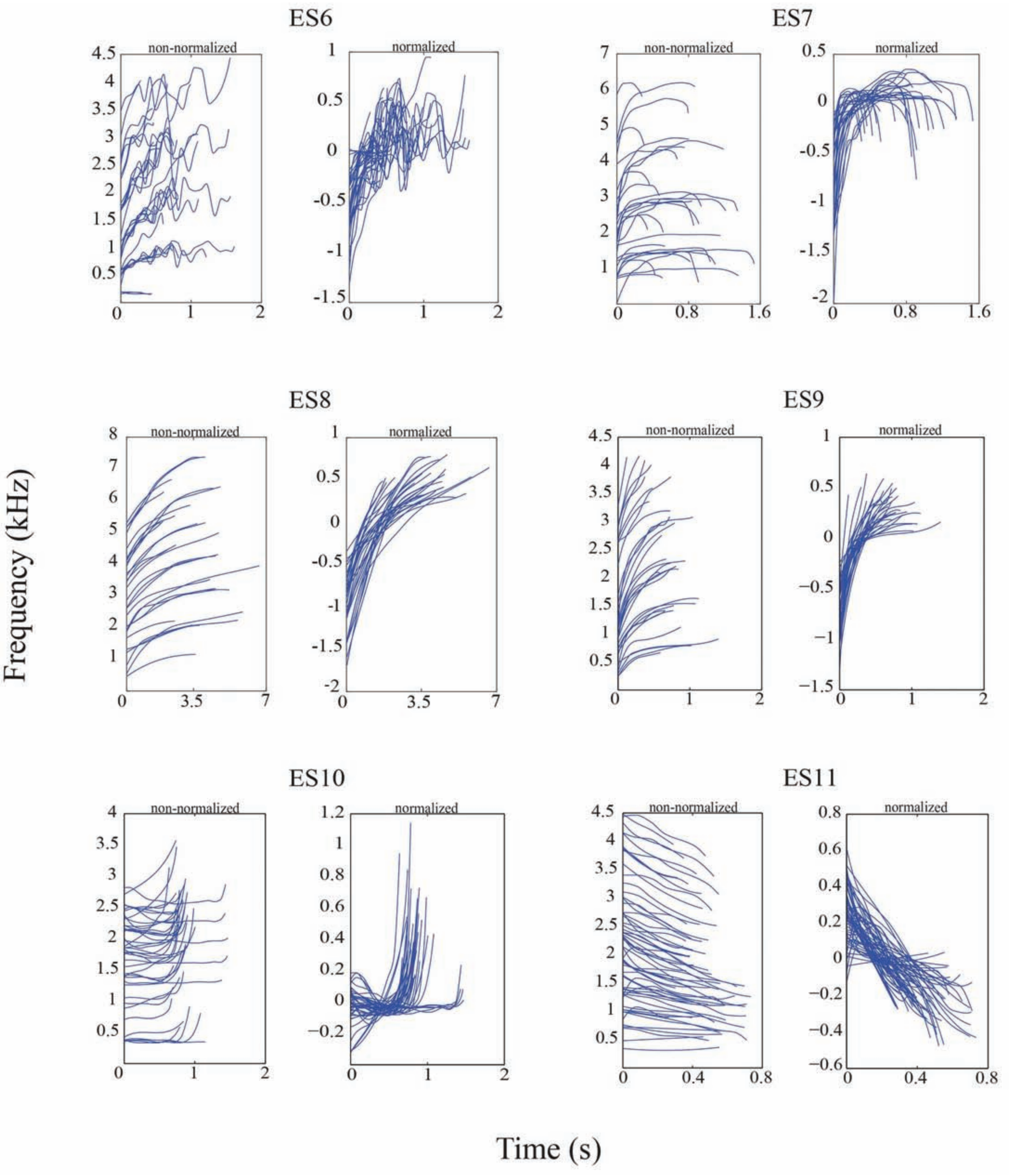

FIG. 6. Traced contours for call types ES 6–11. Non-normalized (left) and z-score normalized (right) contours are plotted for each call type, including fundamental frequency and harmonics. Further parameters of each call are presented in Table 3.

TABLE 3. Descriptive statistics for individual fundamental frequency averages from each component of the call. Mean measurements ± 1 SD are presented. Fundamental frequencies are labeled t1 – t3 depending on call structure. Qualitative description describes the overall contour shape. ES3 is presented as one call and then further broken down to show variation within the call type.

Call type	N	Qualitative description	Max. frequency (kHz)	Min. frequency (kHz)	Mean frequency (kHz)	Start frequency (kHz)	End frequency (kHz)	Duration (s)
ES1:								
t1	16	Flat	0.19 ± 0.04	0.15 ± 0.02	0.17 ± 0.02	0.15 ± 0.02	0.18 ± 0.04	0.65 ± 0.21
t2	20	Modulated	1.08 ± 0.14	0.46 ± 0.08	0.80 ± 0.07	0.50 ± 0.08	0.97 ± 0.18	1.06 ± 0.33
t3	20	Modulated	5.84 ± 0.31	2.10 ± 1.07	4.51 ± 0.21	2.21 ± 1.29	3.92 ± 0.23	1.39 ± 0.23
ES2:								
t1	9	Flat upsweep	1.43 ± 0.55	0.57 ± 0.17	1.05 ± 0.40	0.57 ± 0.17	1.41 ± 0.54	0.73 ± 0.31
t2	9	Modulated upsweep	4.58 ± 0.16	3.33 ± 0.39	4.07 ± 0.16	3.40 ± 0.49	3.84 ± 0.23	0.76 ± 0.14
ES3:								
t1	42	Flat	0.77 ± 0.18	0.60 ± 0.18	0.73 ± 0.17	0.61 ± 0.18	0.72 ± 0.18	0.67 ± 0.18
t2	42	Modulated	6.4 ± 0.24	3.5 ± 0.53	5.1 ± 0.31	3.9 ± 0.86	3.9 ± 0.40	1.5 ± 0.27
ES3.1:								
t1	26	Flat	0.68 ± 0.18	0.51 ± 0.15	0.65 ± 0.17	0.51 ± 0.14	0.64 ± 0.17	0.77 ± 0.12
t2	26	Modulated	6.53 ± 0.18	3.30 ± 0.46	5.19 ± 0.30	3.73 ± 0.99	3.70 ± 0.37	1.46 ± 0.26
ES3.2:								
t1	16	Flat	0.90 ± 0.05	0.74 ± 0.12	0.87 ± 0.05	0.76 ± 0.13	0.85 ± 0.08	0.50 ± 0.12
t2	16	Modulated	6.19 ± 0.16	3.95 ± 0.37	4.89 ± 0.23	4.15 ± 0.53	4.19 ± 0.19	1.51 ± 0.29
ES4:								
t1	33	Flat	1.94 ± 0.20	1.37 ± 0.18	1.74 ± 0.13	1.38 ± 0.20	1.94 ± 0.19	0.78 ± 0.16
t2	33	Flat upsweep	3.31 ± 0.16	2.35 ± 0.42	3.15 ± 0.14	2.35 ± 0.42	3.29 ± 0.16	0.38 ± 0.14
ES5:								
t1	13	Flat upsweep	0.89 ± 0.12	0.44 ± 0.02	0.55 ± 0.04	0.44 ± 0.02	0.89 ± 0.12	0.20 ± 0.06
t2	15	Flat modulated	3.53 ± 0.27	2.68 ± 0.30	3.22 ± 0.21	2.69 ± 0.30	3.45 ± 0.27	0.38 ± 0.10
t3	15	Flat upsweep	1.00 ± 0.31	0.74 ± 0.17	0.83 ± 0.19	0.80 ± 0.18	0.98 ± 0.33	0.47 ± 0.20
ES6:								
t1	7	Modulated upsweep	1.20 ± 0.38	0.47 ± 0.10	0.92 ± 0.24	0.47 ± 0.10	1.07 ± 0.42	1.07 ± 0.34
ES7:								
t1	17	Flat concave	1.17 ± 0.34	0.67 ± 0.19	1.08 ± 0.29	0.70 ± 0.21	0.83 ± 0.23	0.92 ± 0.28
ES8:								
t1	9	Flat upsweep	1.70 ± 0.73	1.01 ± 0.67	1.45 ± 0.67	1.01 ± 0.67	1.69 ± 0.73	0.37 ± 0.14
ES9:								
t1	11	Flat upsweep	1.43 ± 0.70	0.66 ± 0.40	1.19 ± 0.61	0.66 ± 0.40	1.42 ± 0.70	0.81 ± 0.26
ES10:								
t1	16	Flat upsweep	1.08 ± 0.75	0.69 ± 0.45	0.75 ± 0.48	0.71 ± 0.45	1.08 ± 0.76	0.82 ± 0.15
ES11:								
t1	12	Flat downsweep	1.24 ± 0.25	0.91 ± 0.26	1.07 ± 0.24	1.20 ± 0.22	0.92 ± 0.27	0.59 ± 0.09

DISCUSSION

Repertoire and Calling Behaviour

Killer whale calls were detected at PI and LI between 22 August 2017 and 30 September 2017, with a total of 52 encounters between both sites (Fig. 3). Eleven call types were categorized from these PAM recordings. About 22% of killer whale calls selected for repertoire analysis were not classified. Similar to Ford (1989), calls that lacked a clear shape or were not obviously repeated were not placed into a call type. Killer whale call repertoires have been reported to range from 8 to 43 unique call types for pods (Ford, 1987, 1989; Wellard et al., 2020), so the potential for more call types to be identified and described is highly likely as long-term PAM in the area continues. While pulsed calls can be discrete and stereotyped with readily identifiable structure, Figures 5 and 6 show the variability within call types. This variation could be the result of younger whales with maturing vocal apparatuses learning the call, individual differences in calling behaviour, or the presence of call types that were not resolved in this study.

The presence of three multiphonic call types will aid in recognition of this distinctive repertoire in future years and potentially in other locations. ES1 was often made up of three separate components produced simultaneously. While the t1 tonal was not always present, the ability to produce three components simultaneously is quite unique. Cetaceans produce phonations through pairs of phonic lips in the nasal cavity (Ridgway et al., 1980; Madsen et al., 2011). It has been experimentally proven for bottlenose dolphins (*Tursiops truncatus*) that the right pair of phonic lips was mainly responsible for click production, and the left pair was responsible for whistle production (Madsen et al., 2013). Similar to the syrinx in birds and the "two-voiced" phenomena, pairs of phonic lips allow for a variety of complex call structures and simultaneous call components, including two (or more) simultaneous fundamental frequencies, or overlapping whistles and clicks (e.g., the ES5 call type) (Lilly and Miller, 1961; Zollinger et al., 2008; Jones et al., 2020). Multiphonic calls in killer whale pods have been proposed to be markers of matrilineal pod affiliation and may serve as a cohesion signal (Filatova et al., 2009; Papale et al., 2015). Their occurrence could

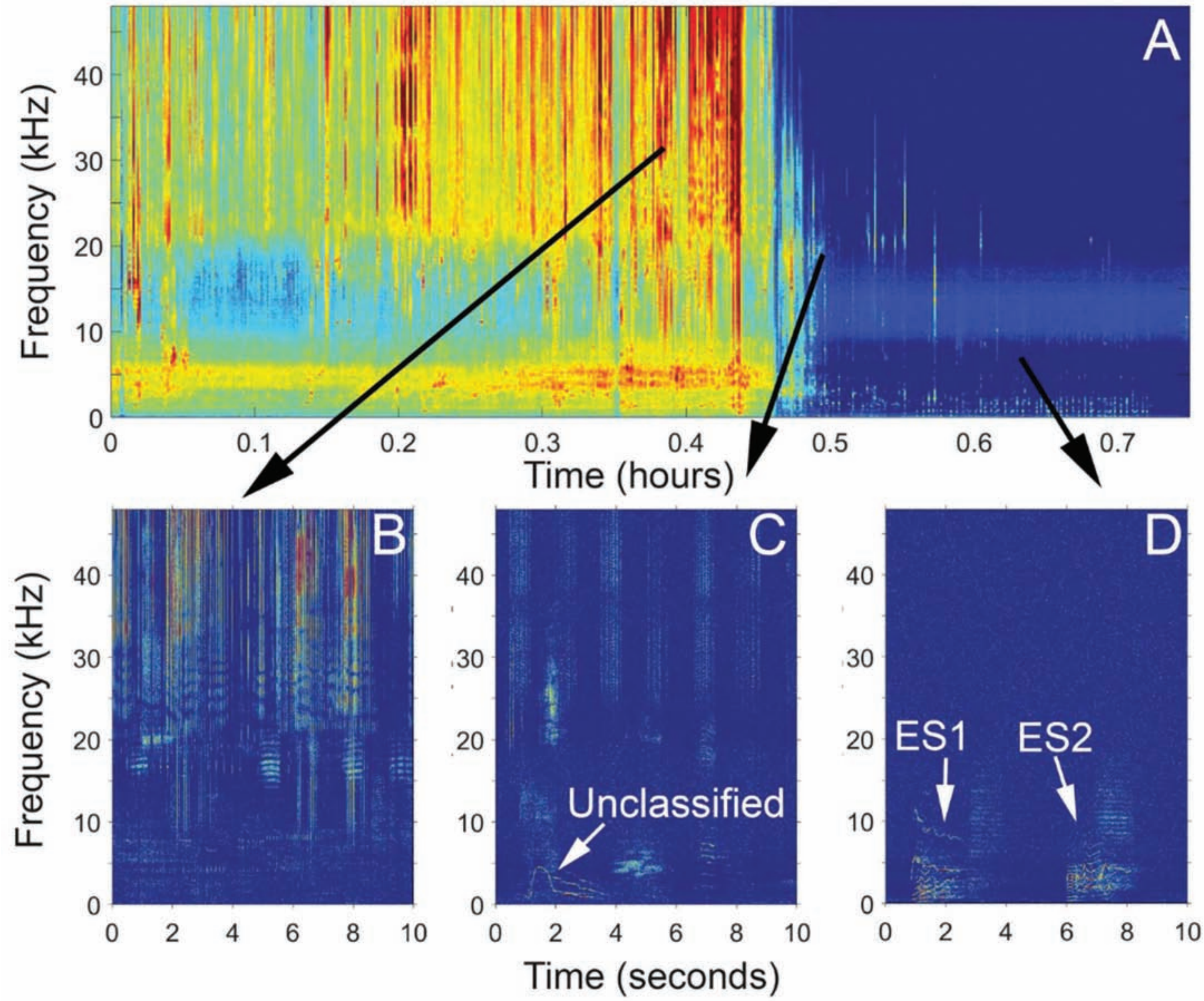

FIG. 7. A 45-minute long-term spectral average (5 s time bin, 50 Hz frequency bin) of narwhal acoustic presence and first detection of killer whale pulsed calls at LI on 22 August 2017 at 15:00 GMT (A). Narwhal echolocation clicks and burst-pulsed sounds present prior to first killer whale detection (B). Clicks rapidly decrease during first acoustic presence of killer whale calls (C; call type Unclassified), then cease altogether while killer whale calls persist (D; call types ES1 and ES2). Spectrogram FFT length: 3000, overlap: 70%, window: Hanning, 0–50 kHz frequency range, 0–10 second time window.

suggest that more than one matriline was present in Eclipse Sound and Milne Inlet during the summer of 2017. Filatova et al. (2009) identified that the proportion of multiphonic calls recorded in Kamchatka, Russia, positively correlated with the number of different pods in the immediate area and did not differ based on behavioural activity. The use of multiphonic calls is also hypothesized to communicate the arousal and valence of an animal. Schneider and Anderson (2011), in their study on red wolf (*Canis rufus*) calls, reported that biphonations were common when wolves were at play or socially interacting with pen mates and suggested a connection between high arousal (i.e., excitement) and biphonation production. The high arousal of a successful kill or of killer whales socializing may elicit these multiphonic calls.

A higher diversity of call types was identified at LI compared to the calls identified at PI (Table 2). ES3, ES4, ES7, and ES10 were the only call types to be identified at both locations, while all other call types were only identified at the LI hydrophone (Table 2). If multiple pods of killer whales were calling and gathering at this location, a higher diversity of calls would be expected. Additionally, not all killer whale pods may have used Eclipse Sound as an entry point into the area, as there is an alternative entry point into Milne Inlet from the north (i.e., through Navy Board Inlet via Lancaster Sound), and therefore avoided passing the PI HARP. It is also possible that some call types serve different communicative functions, such as celebrating a successful hunt (Deecke et al., 2005) or facilitating group cohesion during traveling. Ford (1989) reported that the

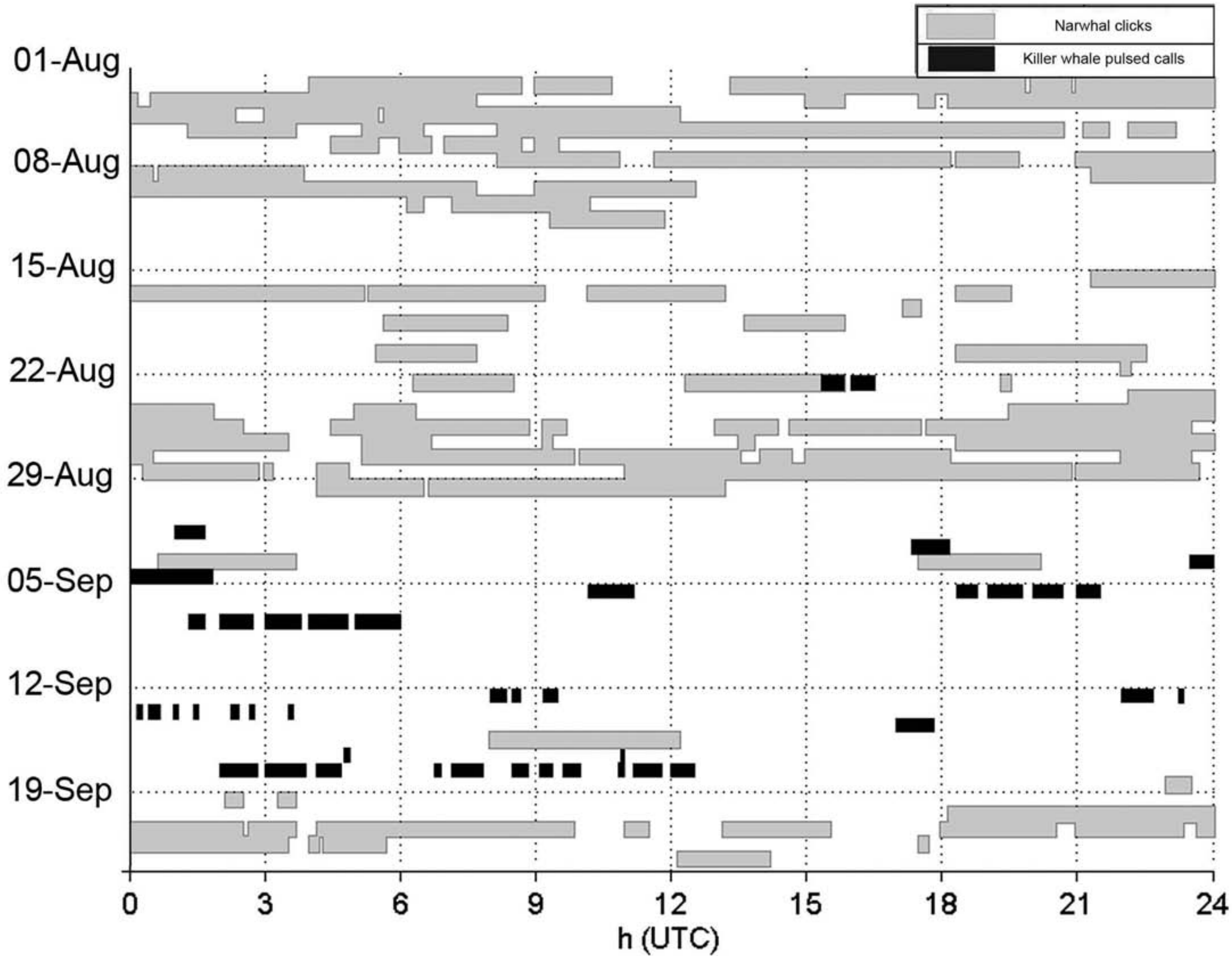

FIG. 8. Acoustic detections at LI of echolocation clicks, presumed to be narwhal, with energy between 20 and 48 kHz (grey bars) and detections of killer whale pulsed calls (black bars) with more than 10 dB signal-to-noise ratio, between 1 August and 24 September 2017.

traveling behaviour, while the least observed in his study, produced a high rate of repeated discrete pulsed calls. That behaviour is seen here with the ES4 call type, as it was the most repeated call at PI ($n = 322$). If killer whales are using this pathway to enter the area, perhaps the ES4 call type is a traveling or group cohesion call.

Acoustic Presence of Killer Whales

From the time series of acoustic detections at PI and LI (Fig. 3), killer whales appeared to enter Eclipse Sound from Baffin Bay and spend a substantial amount of time in Milne Inlet before returning to Baffin Bay via the same route. There were no dates when killer whale calls were detected on both recording devices. However, the absence of call detections, especially between encounter times, cannot prove the absence of killer whales in the area (Riesch and Deecke, 2011; Vongraven and Bisther, 2014; Rice et al., 2017). Killer whales could have been resting, been outside of the hydrophone detection range, or were simply not vocalizing. It has been observed that ecotypes that predate on marine mammals (e.g., transient/Bigg’s killer whales in the North Pacific and marine mammal specialists in Iceland) produced lower rates of clicks, whistles, and pulsed calls compared to the vocalization rates of fish-specializing ecotypes (Ford, 1984; Deecke et al., 2005). Unlike fish, cetaceans and pinnipeds have hearing ranges that overlap with the typical frequency range of killer whale pulsed calls, therefore high vocalization rates may be energetically costly if eavesdropping by prey is a factor (Deecke et al., 2005; Vongraven and Bisther, 2014; Wellard et al., 2015). The LI hydrophone was located in Milne Inlet, which is a historic summering ground for narwhals (White, 2012; Marcoux et al., 2019). The 48 encounters recorded for this site had an average duration of 00:20:09, which was much shorter than the average duration for the four encounters recorded at PI (01:56:59). Shorter bouts of vocal activity would be expected if killer whales were actively hunting narwhal in the area and attempting to avoid detection, compared to traveling and maintaining group cohesion.

Killer whale call detection in Eclipse Sound corresponds closely to the ice-free period of 2017. A review of Canadian Ice Service daily ice charts (https://iceweb1.cis.ec.gc.ca/Archive) showed no sea ice in Eclipse Sound or Milne Inlet during all the days of killer whale acoustic presence. The last day of ice cover in the region was 22 August 2017, when one-tenth sea ice cover remained near the northern entrance to Milne Inlet from Eclipse Sound. Sea ice formation began again on 25 September, when there was two-tenths ice cover in Milne Inlet. Sea ice cover generally increased after that date until the region was fully ice covered. Telemetry studies in the eastern Canadian Arctic have documented that killer whales avoid areas with dense sea ice cover and make rapid, long-distance movements out of the area during ice formation (Matthews et al., 2011; Lefort et al., 2020). As sea ice extent and duration continues to decrease in these high latitudes, the ability for killer whales to infiltrate the Arctic will increase (Higdon and Ferguson, 2009).

Co-occurrence of Killer Whales and Narwhals

Through interviews with Inuit community members, Ferguson et al. (2012) reported that killer whales in the eastern Canadian Arctic have been observed preying on narwhals, beluga, seals, and bowhead whales. More specifically, in northern Baffin Island, narwhals were noted to be the main prey item by approximately 90% of those interviewed in the region (Ferguson et al., 2012). Additionally, Laidre et al. (2006) described an eye-witness account of a narwhal predation event in Admiralty Inlet, just northwest of Eclipse Sound, in which a pod of 12–15 killer whales of mixed sex and age successfully hunted several narwhals within two predation events, hours apart from each other. Understanding how the presence of an apex predator will affect this endemic population is a topic for further investigation. Killer whale presence in the vicinity of narwhals is apparent in this study, as are behavioural responses of narwhal to killer whale presence. Developing a spatial context for the acoustic presence of both species requires an understanding of the area being monitored with the single hydrophone at LI. Effective detection radius around the hydrophone may differ substantially for signals such as echolocation clicks and pulsed calls due to frequency-dependent sound propagation losses. A study modelling the effects of sound absorption on click amplitude for Blainville's beaked whale (*Mesoplodon densirostris*) clicks (bandwidth from 24 to 48 kHz) and sperm whale clicks (bandwidth from 2 to 20 kHz) found detection probability dropped to zero at distances of about 1 to 2 and 7 to 20 km from the source, respectively (Von Benda-Beckmann et al., 2018). Assuming that absorption is the primary factor affecting propagation losses in the frequencies investigated for echolocation clicks in this study (i.e., 20–48 kHz), a reasonable guess is that detected clicks were produced by animals within 1–2 km of the recorder. Pulsed calls may have been detectable over longer distances.

The first appearance of killer whale calls at LI coincides with rapid disappearance of presumed narwhal echolocation clicks (Fig. 7A), which was most likely due to cessation of click production by narwhals. Assuming narwhal were within 1 km of the recorder when detected clicks reached maximum received levels for detected clicks, narwhal would need to swim directly away from the recorder at a speed of about 20 km/h for increasing distance to explain the reduction in detected clicks that occurred over a period of three minutes between 0.45 h and 0.5 h in Figure 7A. Swimming speeds of tagged narwhal have varied between 2.9 and 8.2 km/h (Dietz and Heide-Jørgensen, 1995). More likely, the rapid reduction in click detections occurred because narwhal ceased production of echolocation clicks at the time killer whale calls were first apparent in the acoustic recordings. There was only one instance in this study of presumed narwhal echolocation overlapping with killer whale pulsed calls, so causation cannot be established for the abrupt stop in narwhal echolocation observed.

Narwhals have been observed to become visually and audibly inconspicuous when exposed to man-made underwater noise (Finley et al., 1990) by ceasing production of echolocation clicks (Tervo et al., 2021). This apparent behavioural sensitivity suggests that additional influences, such as predator response, could be the cause of the absence of clicks. Studies of narwhal behaviour in the presence of Arctic killer whales observed that narwhals moved closer to shore when exposed to killer whales (Laidre et al., 2006; Breed et al., 2017). A similar response to killer whales in Milne Inlet could result in narwhals moving away from the LI recording site during periods when killer whales were present in Milne Inlet.

CONCLUSION

Quantitative descriptions of acoustic repertoires are important for initial comparisons of the distribution, behaviour, seasonal movements, and habitat use of killer whales moving around the North Atlantic and eastern Canadian Arctic. As in prior studies, subjective interpretation of call types made by a trained analyst was the starting point for identifying call type categories. The added step of contour tracing provided supportive metrics to verify call type classification and distinction by comparing contours through z-score transformation (Frasier et al., 2016). Possible errors in call analysis could be attributed to the variability of calls either selected or not selected for the process of manual tracing. Using a consistent SNR threshold of 10 dB during the call contour tracing step should minimize errors resulting from manual contour tracing, making sure only clearly visible call components are included in analyses. Quantitative call analysis using the contour tracing and comparison of tonal components can provide the efficient tools needed to further investigate the repertoire of the killer whales in this region, with future steps including the development of automated detectors and trained classifiers to further improve analysis. Future work should also include comparing this recorded repertoire to other acoustic recordings of killer whales from the North Atlantic to determine an origin for the killer whales traveling to the eastern Canadian Arctic in the summer. Satellite tracking studies to date have not been able to determine wintering grounds, however a 2019 discovery of epizoic barnacles attached to the killer whales in Milne Inlet suggested a migration through more tropical low-latitude waters (Matthews et al., 2020b).

PAM data have the potential for long-term monitoring of marine mammal presence in these fast-changing Arctic regions. These acoustic studies can provide details on species identification, distribution, use of environment, and changes to those aspects brought on by increased human activity and climate change. Industry-sponsored surveys have reported that the narwhal stock in Eclipse Sounds had declined in 2021 compared to past aerial survey population estimates done in 2013, 2016, and 2019 (Golder Associates, 2022). Additionally, Watt et al. (2021) reported a correlation between shipping activity and stress levels in narwhal, reporting a significant increase in cortisol levels between samples taken before shipping activity (2000 – 06) and during the increase of shipping activity (2013 – 19) for the region. Increased shipping, resource development, sea ice loss, and novel predator-prey interactions all have the potential to disrupt marine mammal communication, health, and distribution. Continuing to monitor killer whale activity as another confounding factor in the impacts of narwhal will provide a better understanding to further inform monitoring and mitigation (Breed et al., 2017; Matthews et al., 2020a). Effective passive acoustic monitoring programs can fill knowledge gaps and provide needed data-driven insights to guide conservation and policy.

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