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Call repertoire and inferred ecotype presence of killer whales (*Orcinus orca*) recorded in the southeastern Chukchi Sea

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ABSTRACT:
Killer whales occur in the Arctic but few data exist regarding the ecotypes present. The calling behavior differs among ecotypes, which can be distinguished based on pulsed call type, call rate, and bandwidth. In this study, a passive acoustic recorder was deployed 75 km off Point Hope, Alaska, in the southeastern Chukchi Sea to identify which ecotypes were present. A total of 1323 killer whale pulsed calls were detected on 38 of 276 days during the summers (June–August) of 2013–2015. The majority of calls ($n = 804$, 61%) were recorded in 2013 with the most calls recorded in July (76% of total calls). The calls were manually grouped into six categories: multipart, downsweep, upsweep, modulated, single modulation, and flat. Most detections were flat ($n = 485$, 37%) or multipart calls ($n = 479$, 36%), which contained both high and low frequency components. Call comparisons with those reported in the published literature showed similarities with other transient populations in fundamental frequency contour point distribution and median frequency. This study provides the first comprehensive catalog of transient killer whale calls in this region as well as reports on previously undescribed calls.
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I. INTRODUCTION

The southern Chukchi Sea is highly productive and driven by advection and a supply of nutrient-rich water, originating in the Bering Sea (Springer *et al.*, 1996; Grebmeier *et al.*, 2006). This drives seasonal influxes of plankton in the spring and summer and makes the Chukchi Sea a feeding ground for many seasonally migrant baleen whales such as the gray whale (*Eschrichtius robustus*), fin whale (*Balaenoptera physalus*), and humpback whale (*Megaptera novaeangliae*), as well as odontocete species, including killer whales (*Orcinus orca*).

Globally, killer whales are delineated into ecotypes, which are genetically distinct groups that differ in home range, morphology, social structure, calling behavior, and diet (Ford, 1989, 1991; Deecke *et al.*, 2005). As apex predators, killer whales can have large impacts on ecosystems through top-down predation (Estes *et al.*, 1998; Williams *et al.*, 2004). To assess potential impacts on the ecosystem, it is important to identify the ecotypes present in an area. Three killer whale ecotypes are believed to occur in the North Pacific and Alaska waters: resident, transient, and offshore. Resident killer whales are fish specialists, travel in stable, matrilineal groups, and typically display high site fidelity with home ranges of less than 200 km (Baird *et al.*, 1992; Deecke *et al.*, 2005; Saulitis *et al.*, 2005; Fearnbach *et al.*, 2014). Transient (or Bigg's) killer whales feed on marine mammals and travel in less stable associations as they usually transition away from matrilineal associations once they are sexually mature (Morton, 1990; Baird *et al.*, 1992; Ford and Ellis, 1999). Transients have large home ranges; photo identification has documented Alaska transient ranges spanning from the Aleutian Islands to Barrow, Alaska, in the northeastern Chukchi Sea, a distance of approximately 2000 km (Clarke *et al.*, 2013). Little is known regarding the offshore killer whale ecotypes; however, it is thought that they prey primarily on shark and teleost fish, spend most of their time in the outer continental shelf maintaining a distance of >15 km from the shore, and can travel one-way distances of over 4000 km (Ford *et al.*, 1994; Morin *et al.*, 2006; Dalheim *et al.*, 2008; Ford *et al.*, 2014).

In addition to behavioral differences, ecotypes differ in terms of their sound production. Killer whales use acoustic communication for a variety of functions, including maintaining contact or group cohesion, mediating social interactions, and foraging (Ford and Fisher, 1983; Ford, 1984). Killer whales produce three sound types, which serve different functions: clicks, whistles, and pulsed calls (Ford and Fisher, 1983). Short-duration broadband clicks are used in echolocation, which functions in feeding and navigation (Barrett-Lennard, 1996; Au *et al.*, 2004). Whistles are narrowband signals that function in close-range communication (Thomsen *et al.*, 2001; Riesch *et al.*, 2008). Pulsed calls are

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the most common signal type used for communication and are composed of a series of pulses produced in such rapid succession as to sound tonal (Watkins, 1967). Pulsed calls are usually stereotyped, and repertoires of pulsed calls are often used to distinguish among ecotypes. General frequency characteristics of pulsed calls have been found to differ among ecotypes (Foote and Nystuen, 2008; Filatova *et al.*, 2015). Residents produce calls in higher frequency ranges with significantly higher minimum, peak, and median call frequencies (Foote and Nystuen, 2008; Filatova *et al.*, 2015), Fundamental frequencies of transient calls are typically lower in peak frequency and fall within a smaller range than resident calls (Foote and Nystuen, 2008; Filatova *et al.*, 2015). A variety of hypotheses have been proposed to explain the call frequency disparities between the ecotypes. Foote and Nystuen (2008) hypothesized frequency differences to be a strategy used to avoid detection by salmonid prey that have their hearing sensitivity in a lower frequency range (Deecke *et al.*, 2005). More recently, Filatova *et al.* (2015) suggested that killer whales may take advantage of the characteristics of sound propagation in the ocean as a strategy to enhance communication. Low frequency sounds can propagate farther distances and attenuate more slowly, which could enhance detectability and facilitate long-distance communication, essential for transients that travel in smaller and more fluid groups. The offshore ecotype produces calls with a higher minimum frequency than other ecotypes. Although very little is known about this ecotype, Foote and Nystuen (2008) suggest that the higher frequencies may be a technique used to avoid masking by low frequency, chronic wind noise that increases in amplitude as frequency decreases, and which is characteristic of offshore waters.

In addition to fundamental frequency differences, call rate and repertoire diversity can also be used to discriminate ecotypes. Residents call frequently, have diverse repertoires consisting of 6–17 call types, and have pod-specific dialects (Ford, 1991; Saulitis *et al.*, 2005; Deecke *et al.*, 2010). Residents produce pulsed calls as the primary mode of communication when spatially distant and often when foraging (Ford and Fisher, 1983). In contrast to residents, transients produce fewer calls to avoid detection by prey that have a similar auditory frequency range. Transients have repertoires of only approximately six call types and primarily call when milling after a kill so as not to disclose their presence and location to prey during the hunt (Deecke *et al.*, 2000; Deecke, *et al.*, 2005). Few descriptions or comparisons of offshore pulsed calls exist (Foote and Nystuen, 2008; Gassmann *et al.*, 2013) with more work done on occurrences of high frequency whistles (see Filatova *et al.*, 2012; Simonis *et al.*, 2012).

In the North Pacific, both residents and transients are known to occur in the Gulf of Alaska and Bering Sea (Muto *et al.*, 2019); sightings of offshores are rare (Dalheim *et al.*, 2008) and limited to south of the Aleutians. However, less is known about the killer whale populations in the Chukchi Sea (Muto *et al.*, 2019). Killer whale presence has been documented in the Chukchi Sea from aerial and boat-based surveys since the 1980s (Ljungblad and Moore, 1983; Lowry *et al.*, 1987; George and Suydam, 1998; Aerts *et al.*, 2013; Clarke *et al.*, 2013; Vate Brattström *et al.*, 2019), and many of these sightings have included observations of predation events on marine mammals, indicating the presence of transient killer whales (Ljungblad and Moore, 1983; Clarke *et al.*, 2013; Huntington and Quakenbush, 2013; Vate Brattström *et al.*, 2019). Although acoustic detections of killer whales have been reported in the Chukchi Sea, some of which have been reported as transient (Clarke *et al.*, 2013; Hannay *et al.*, 2013; Stafford, 2019), none of these studies have provided information on call characteristics or a description of call types. Overall, there is little published research identifying the presence of residents in the Chukchi Sea.

The lack of detailed acoustic analysis of killer whale ecotypes in this region is, in part, a result of a lack of dedicated effort until recent years due to the difficulties of accessing the Chukchi Sea. Long-term passive acoustic monitoring is a powerful tool that can determine ecotype presence year-round without the need for a full-scale survey. In this study, we sought to identify killer whale ecotype presence at a site in the southern Chukchi Sea by characterizing pulsed calls recorded during three consecutive summers. We predicted that transients would be the primary ecotype detected at this site, based on prey availability, previous observations, and home range. Identifying the ecotype presence at this site will increase our knowledge of the spatiotemporal distribution of killer whales in the Arctic and have implications for ecosystem management in this area. This study also provides the first call catalog of transient killer whale calls recorded in the Chukchi Sea, which can be used as a baseline for future acoustic studies in the Alaska region.

II. METHODS

A. Study site and data collection

Data used in the current study were collected as part of the Arctic Whale Ecology Study (ARCWEST; Vate Brattström *et al.*, 2019). Passive acoustic data were collected using Autonomous Underwater Recorders for Acoustic Listening (AURAL; Multi-Électronique, Inc., Rimouski, QC, Canada[1]) devices, deployed on subsurface moorings in the southeastern Chukchi Sea. Data used in the current study were recorded from a mooring location approximately 75 km southwest of Point Hope (Fig. 1).

The recorders, located approximately 6 m above the seafloor, were sampled at 16 kHz on a duty cycle of approximately 30% (Table I). Spectrograms with 8 kHz bandwidth or less have been used in previous studies to depict killer whale pulsed calls (Ford, 1989, 1991; Stafford, 2019), indicating that a 16 kHz sampling rate will capture the fundamental frequency contour of pulsed killer whale calls (Deecke *et al.*, 2005; Saulitis *et al.*, 2005). Moorings were deployed annually from mid-August 2012 to mid-September

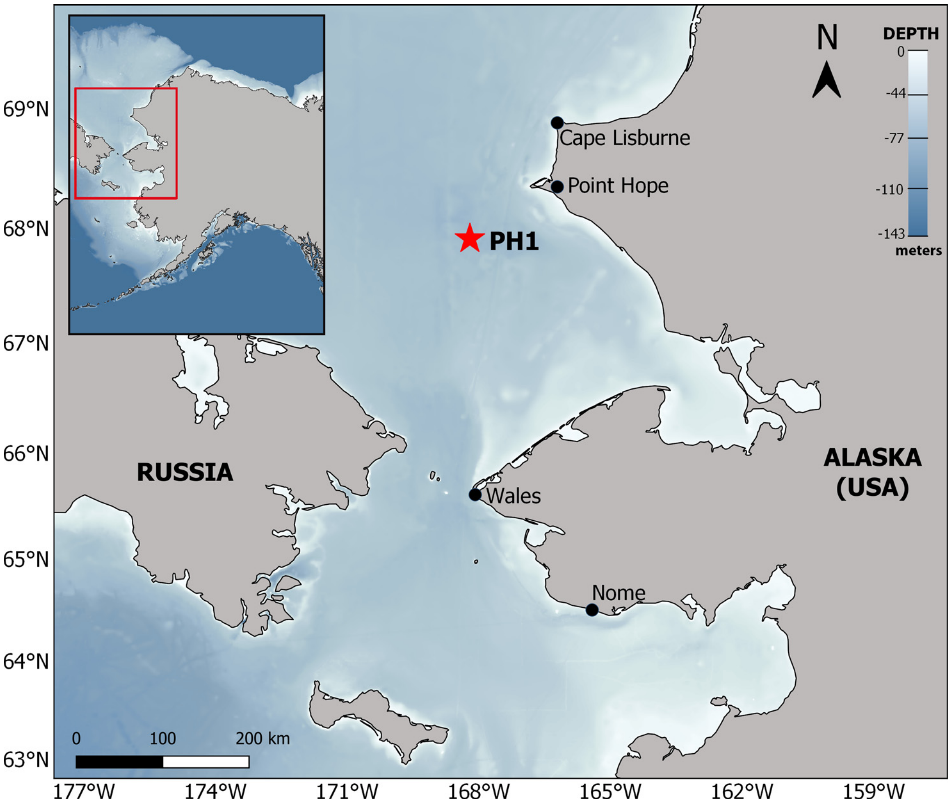


FIG. 1. (Color online) The map of the southern Chukchi Sea and study site, PH1 (red star), 75 km southwest of Point Hope, AK.

2015 (Table I). The manual analysis conducted by the National Oceanic and Atmospheric Administration (NOAA) Alaska Fisheries Science Center (AFSC) Marine Mammal Laboratory indicated a distinct peak in detections from June to August every summer (Vate Brattström *et al.*, 2019). Detailed analyses for this study were, therefore, limited to the months of June–August in 2013–2015.

B. Acoustic analysis

Acoustic recordings were first manually inspected in Adobe Audition (version CC2018, San Jose, CA) to determine the presence of killer whale pulsed calls (Madrigal, 2019). Files containing pulsed calls were then run through an energy detector in MATLAB (version R2016b; MathWorks, 2019; based on the signal envelope exceeding 35% of the maximum amplitude of each file) to extract potential calls for further processing. All extracted calls were manually verified. False positives, overlapping calls, and calls lacking a clear start and end time were considered poor-quality calls and excluded from the analysis. The semiautomated detector identified an estimated 21% of total calls (based on a validation exercise comparing detector results from those of a manual analyst, using ten files from one date that represented approximately 2.4% of the dataset), which yielded a subset of data from which to identify ecotypes and capture call type diversity.

From the extracted calls, the fundamental frequency contour was traced from spectrograms [512 fast Fourier transform (FFT), 16 kHz, Hann 50% overlap, 31 ms time analysis resolution] using the manual contour extraction method in ROCCA (real-time odontocete call classification algorithm) for the PAMGUARD 1.15.14 software module (Oswald and Oswald, 2013). The following nine parameters were extracted from the contour trace and used to compare the call categories: start frequency (Hz), end frequency (Hz), minimum frequency (Hz), maximum frequency (Hz), median frequency (Hz), duration (s), bandwidth (Hz), peak frequency (Hz), and frequency slope mean (Hz/s; Table II; Fig. 2). Noise sensitivity in ROCCA was adjusted for each individual call to extract the best contour match (Oswald and Oswald, 2013). Contour points were adjusted manually for each call to best match the contour trace.

1. Call catalog of pulsed calls

Alphanumerical naming systems have been developed to catalog killer whale calls (Ford, 1984, 1987; Deecke *et al.*, 2005; Saulitis *et al.*, 2005; Rehn *et al.*, 2011).

TABLE I. The mooring information from 2012 to 2015, including location, depth, recording time periods, number of days with recordings, and duty cycle.

Year	Latitude (°N)	Longitude (°W)	Depth (m)	Recorder start date	Recorder end date	Days with recordings	Duty cycle (min)
2012–2013	67.90895	168.19462	58	8/22/2012	8/23/2013	366	85/300
2013–2014	67.90745	168.20265	55	8/24/2013	9/15/2014	387	80/300
2014–2015	67.90793	168.20217	58	9/17/2014	9/20/2015	368	80/300

TABLE II. The variables measured by ROCCA and used to characterize and compare calls in this study.

Variable name	Units	Explanation (Oswald, 2013)
Start frequency	Hz	Frequency at the start point of the call
Ending frequency	Hz	Frequency at the end point of the call
Minimum frequency	Hz	Lowest frequency of the call
Maximum frequency	Hz	Highest frequency of the call
Median frequency	Hz	Middle frequency of the call
Duration	s	Duration of the call
Bandwidth	Hz	Maximum frequency - minimum frequency
Peak frequency	Hz	Determined by the contour point file and based on the peak frequency that corresponded with the highest energy value of the call.
Frequency slope mean	Hz/s	Overall mean change in frequency over time

However, naming schemes differ among locations and are often study specific. Here, we developed an alphanumerical naming system that is based on the call acoustic structure, which differs from previously published killer whale catalogs from other regions (Ford, 1987; Yurk *et al.*, 2002; Filatova *et al.*, 2007) but can serve as a baseline catalog for future research in this area. This system incorporated a three-part naming system to delineate call types, including geographic location, call type, and call type subcategory. The letter abbreviation "CH" indicated the recording location (Chukchi Sea). The general contour shape was expressed using an abbreviation for both the call type category (Fig. 3) and subcategory.

Calls were first manually categorized by a single observer (BM) into call types based on the contour shape and compiled into a call catalog. Six call contour categories were used: multipart calls (*p*), flat (*f*), downsweep (*d*), upsweep (*u*), modulated (*m*), and single modulation (*s*; Fig. 3). The "multipart" (CHp) call type was defined as being composed of a combination of 1–4 low frequency components (LFCs) and one high frequency component (HFC). LFCs and HFCs have been used previously to describe two major acoustic components of killer whale pulsed calls (Ford 1989, 1991; Filatova *et al.*, 2015). HFCs are overlapping and can be produced simulatenously with LFCs (Filatova *et al.*, 2015). "Flat" calls (CHf) were linear calls with a bandwidth of <225 Hz. The "downsweep" (CHd) calls had a higher start frequency than end frequency. "Upsweep" (CHu) calls had a start frequency that was lower than the end frequency. "Modulated" (CHm) calls had two or more modulations in the frequency, which were counted manually to determine the modulation rate (mod/s). Whereas other studies have referred to these as "excitement calls" because the behavioral state was unknown and a state of excitement cannot be confirmed, for this study, these are referred to only as modulated (Rehn *et al.*, 2011). "Single modulation" calls (CHs) were calls containing only one modulation (Fig. 3).

Within these call contour categories, automated subcategorization of call types was conducted in *R* (version 3.6.1, *R* Development Core Team, University of Auckland, New Zealand). A hierarchical cluster analysis in the *R* package *pvclust* [distance measure (method.dist) = Euclidean, agglomerative method (method.hclust) = average] was used to divide the single part call types (e.g., downsweep) into subcategories based on the minimum frequency, maximum frequency, start frequency, end frequency, peak frequency, duration, and frequency slope mean (Fig. S1). For the flat category (described below), only four parameters were used (start frequency, end frequency, duration, and frequency slope mean) due to the high correlation among variables. An unbiased, multi-scale bootstrapping (number of bootstrap

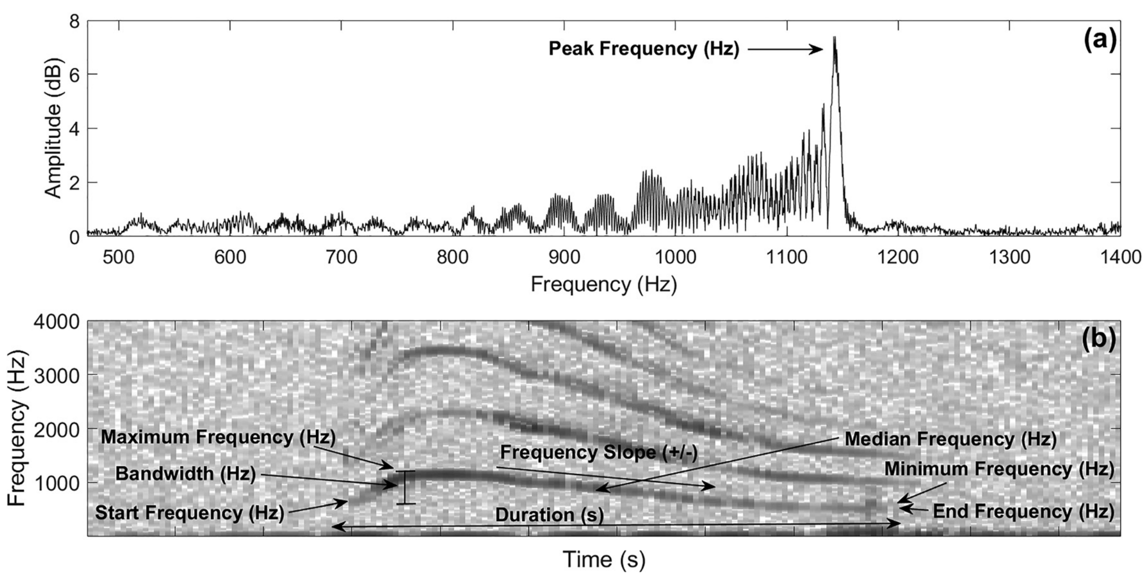


FIG. 2. The parameters extracted in ROCCA from connected contour points. (a) Amplitude spectrum, including the peak frequency (Hz), (b) spectrogram (FFT size 1024, 16 kHz, Hamming 50% overlap) of a killer whale pulsed call, including start frequency (Hz), end frequency (Hz), duration (s), minimum frequency (Hz), maximum frequency (Hz), median frequency (Hz), bandwidth (Hz), and slope mean (Hz/s).

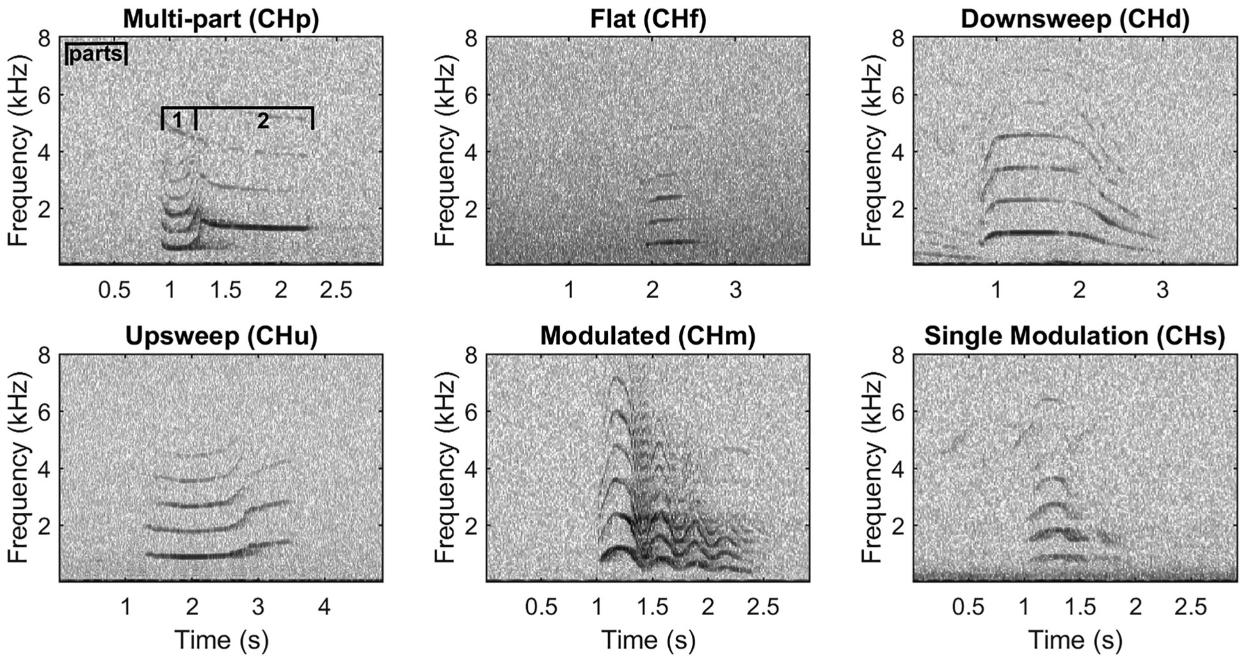


FIG. 3. The representative examples of each call category. All spectrograms have FFT size 512, 16 kHz, Hamming 50% overlap are shown.

replications: nboot = 1000) resampling calculated the *p*-value associated with each cluster of the dendrogram output as well as the approximately unbiased *p*-value (AU is labeled in red) and bootstrap probability (BP is labeled in green; see the CHd example in the supplementary material, Fig. S1[2]). Clusters with an AU greater than 95% (red rectangles on dendrograms) were strongly supported by the call parameters (Fig. S1). For multipart calls, the cluster analysis was not used, and subcategories were determined manually based on discrete stereotyped calls (e.g., Ford, 1991; Yurk *et al.*, 2002; Saulitis *et al.*, 2005). Subcategorical variation within each call category was denoted numerically in the call name based on the order that the call grouping appeared in the branching of the dendrogram.

C. Statistics

The descriptive statistics (i.e., mean and standard deviation) of all of the parameters were calculated to compare call types in this study. A principal components analysis (PCA) was conducted in the *R* package *pvclust* to assess the similarity between the call categories based on five factors: minimum frequency, maximum frequency, peak frequency, start frequency, and end frequency. These parameters were chosen because they produced optimal clustering in *R*. A one-way analysis of variance (ANOVA) and Tukey *post hoc* test was conducted in the Statistical Package for Social Sciences (SPSS) to test for differences between the call categories using seven parameters: start frequency (Hz), end frequency (Hz), minimum frequency (Hz), maximum frequency (Hz), peak frequency (Hz), duration (s), and frequency slope mean (Hz/s). Fifty calls randomly selected from each type category were used to standardize the sample size across call types. One call type (CHs) only contained 31 calls; this category was not subsampled and the entire dataset was used.

D. Ecotype comparison with literature

Call contour fundamental frequency points extracted (including LFC and HFC) in ROCCA were plotted as histogram distributions to compare to the calls (containing LFC and HFC) of the populations described in Filatova *et al.* (2015), which served as an indicator of the ecotype. To determine which ecotypes were detected in the Chukchi Sea, we compared calls from our study to published data for resident and transient populations described in Filatova *et al.* (2015). Filatova *et al.* (2015) compared HFC and LFC fundamental frequency contour point distributions of calls across eight populations: North Atlantic (Iceland and Norway), resident (Kamchatka, Alaska, Southern resident, Northern resident), and transient (West Coast and False Pass) populations. We also compared boxplots of median fundamental frequencies in our study with those of the eastern North Atlantic, North Pacific resident, and transient populations described in Filatova *et al.* (2015). Historic sighting data in the southeastern Chukchi Sea were used to confirm the ecotype presence (Ljungblad and Moore, 1983; Clarke *et al.*, 2013; Huntington and Quakenbush, 2013; Vate Brattström *et al.*, 2019), and gray whale passive acoustic monitoring data were used to confirm the presence of transient primary prey species at (study site) PH1 in July and August in 2013–2015 (Vate Brattström, *et al.*, 2019).

III. RESULTS

Of the 276 days analyzed and a total 1648 h of recordings from the three summers (June–Aug. of 2013–2015), 66 h (38 days) contained killer whale calls and were

TABLE III. The summary of the distribution of the number of hours/day of recordings and hours/day containing pulsed calls.

Summer (June–August)	Number of days of recordings	Number of hours of recordings (hh:mm:ss)	Number of days with calls	Number of hours with calls (hh:mm:ss)	Number of calls extracted
2013	92	619:54:00	16	30:24:36	804
2014	92	589:08:57	15	24:29:33	460
2015	92	588:48:58	7	11:49:47	59
Total	276	1647:51:55	38	66:43:54	1323

included in the analyses (2013, 30 h; 2014, 24 h; 2015, 12 h; Table III; Fig. 4). Given the low sampling rate and low number of detections, whistles were not included in this study. A total of 1323 pulsed calls were extracted and met the criteria for the analysis. The majority of calls ($n = 804$, 61%) were recorded in 2013 with the most calls recorded in July (June, 134 calls; July, 570 calls; August, 100 calls). Of the three months, July contained the most detections (76%) within all three years (2013, 10 days; 2014, 8 days; 2015, 3 days; Fig. 4). The mean minimum, maximum, and peak fundamental frequency of all pulsed calls (primary LFC only) combined was 611 Hz (±159 Hz), 857 Hz (±244 Hz), and 724 Hz (±204 Hz), respectively. The mean duration of all pulsed calls was 0.75 s (±0.40 s).

A. Call categories

Results from the PCA supported the manual call type categorization (explained variance ratio, 0.84). Most of the variance in the data is explained by PC1, which is driven by the maximum and minimum frequencies. The separation of call categories along the PC2 axis is driven by the start, peak, and end frequencies (Hz). The dendrogram outputs resulting from the hierarchical cluster analysis showed discrete subcategories within each call type (see the CHd example in the supplementary material, Fig. S1[2]).

The two most common call types, CHp and CHf, shown in Figs. 3 and 5, together comprised 73% of all calls detected (Table IV). CHf was one of the most common call types ($n = 485$ calls, 37% of all calls), produced on the most days overall ($n = 34$ out of 38 days). CHp was another common call type and comprised approximately one-third of the total calls ($n = 479$, 36%; $n = 23$ days). The primary LFC (Fig. 5) had a maximum frequency <2 kHz (mean maximum frequency = 783 kHz), and the HFC had a mean maximum frequency of 3.93 kHz (Table V). The downsweep call type, CHd ($n = 176$, 13%; $n = 21$ days), was the only call type with an overall negative average frequency slope mean of −279 Hz/s (±266 Hz/s). The upsweep calls, CHu ($n = 92$, 7% of calls; 20 days), had the highest positive and overall average frequency slope mean (709 Hz/s ± 858 Hz/s) of all call types. The modulated calls, CHm ($n = 60$, 5% of calls, 9 days), comprised 5% of all calls with an average modulation rate of 3.6 mod/s. Single modulation calls, CHs, were the least common call type, comprising only 2% of the total calls ($n = 31$, 2%; $n = 11$ days).

CHp calls contained a HFC; these HFCs were significantly higher in minimum, peak, maximum, start, and end frequencies than all other call type categories (one-way ANOVA, $p < 0.0001$; Tukey *post hoc* comparison of means, $p < 0.0001$; Fig. 5). CHu calls had a significantly higher end frequency than all other call types (ANOVA, $p < 0.0001$; Tukey, CHp_LFC, $p = 0.006$; CHd, $p < 0.0001$; CHm, $p = 0.001$; CHf, $p = 0.004$; CHs, $p = 0.039$). CHu had a significantly higher maximum frequency than CHp_LFC, CHf, and CHm (ANOVA, $p < 0.0001$; Tukey, CHp_LFC, $p = 0.009$; CHf, $p = 0.024$; CHm, $p = 0.008$). The call duration was also a discriminatory factor among call types (Fig. 6). The CHp LFC was significantly shorter in duration than all other call types except for CHs and CHf (ANOVA, $p < 0.0001$; Tukey, CHd, Chu, CHf, $p < 0.0001$; CHm, $p = 0.001$; Fig. 6). CHs was significantly shorter in duration than all categories, excluding CHp (ANOVA, $p < 0.0001$; Tukey, CHd, CHf, CHu, $p < 0.0001$; and CHm, $p = 0.001$; Fig. 6). As expected, the bandwidths of the CHf calls were significantly lower than most call types, including CHp_HFC but excluding CHp_LFC and CHm (ANOVA, $p < 0.0001$; Tukey, CHp_HFC, CHd, CHu, $p < 0.0001$; CHs: $p = 0.001$). Alternatively, CHm calls had a significantly higher bandwidth than CHd, CHu (ANOVA, $p < 0.0001$; Tukey, $p < 0.0001$), and CHs (ANOVA, $p < 0.0001$; Tukey, $p = 0.001$).

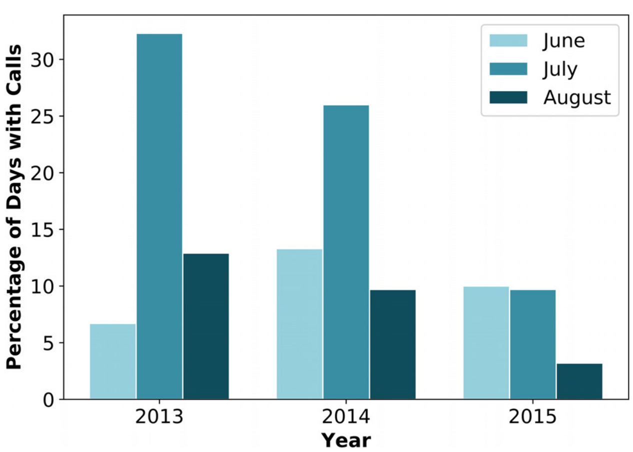
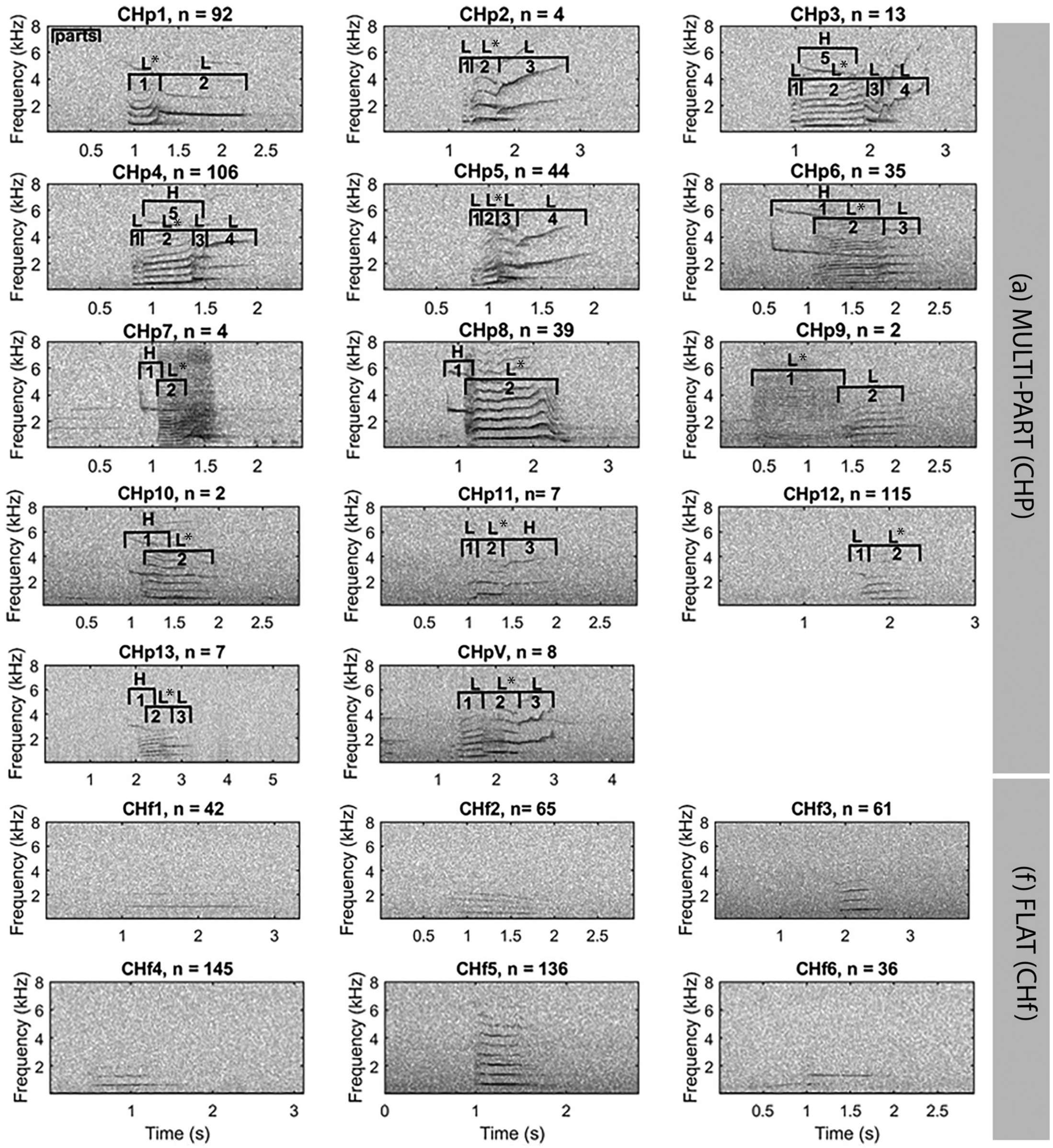


FIG. 4. (Color online) The percentage of days per month (June–August) with calls detected for 2013–2015.

B. Subcategories

Dendrograms for all of the categories except for CHp showed branching, indicating 2–7 subcategory classifications. CHs had the fewest number of call categories ($n = 2$) and CHp had the most call subcategories ($n = 14$; Table IV;



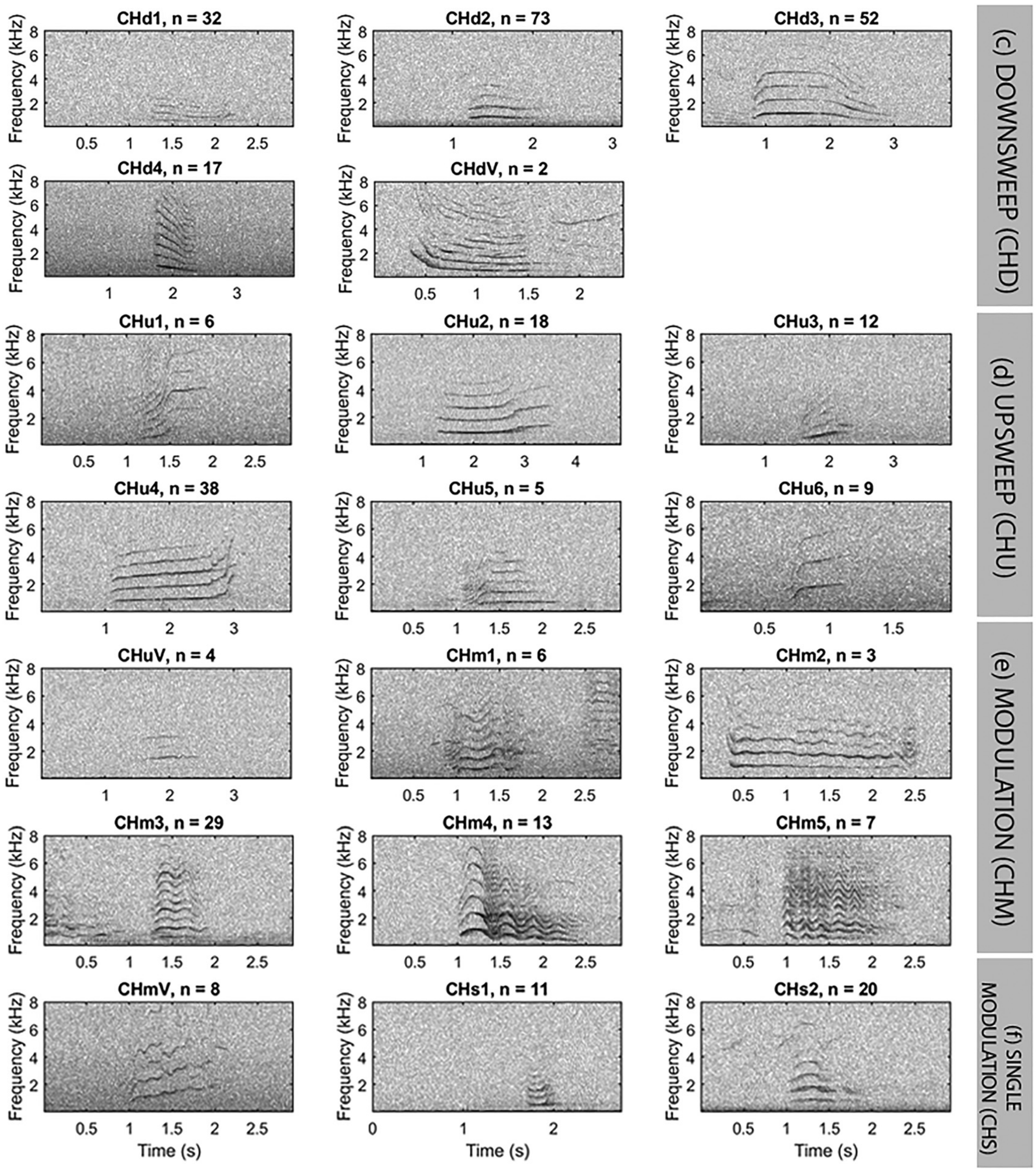
(b)

FIG. 5. Representative examples of the subcategories within each call. (a) Multipart (CHp), (b) flat (CHf), (c) downsweep (CHd), (d) upsweep (CHu), (e) modulation (CHm), and (f) single modulation (CHs). All CHp call exemplars contain brackets indicating the different parts of the call, including LFCs (*L*) and HFCs (*H*). All spectrograms have FFT size 512, 16 kHz, Hamming, 50% overlap.

Fig. 5).[2] CHf5 was the most common subcategory ($n = 136$) followed by the CHp12 ($n = 115$) and CHp4 subcategories ($n = 106$; Fig. 5). The majority (81%) of the CHp4 calls were detected on one day (10 July 2013; Fig. 5).

C. Ecotype comparisons with previous literature

Histograms of the fundamental frequency contour points of resident calls from Filatova *et al.* (2015) show a bimodal distribution with a second peak at 5–9 kHz, corresponding to the HFC (Fig. 7). The transient histograms from Filatova *et al.* (2015) are unimodal with no distinct second peak despite inclusion of the HFC. Resident histograms had a peak in frequencies from 500 Hz to 1.5 kHz, whereas transients had a peak $\leq$500 Hz (Filatova *et al.*, 2015). Our call histograms from the Chukchi Sea are most similar to the transient call histograms described in Filatova *et al.* (2015) with a unimodal distribution (Fig. 7). The lack of a second peak is not an artifact of the sampling rate as the HFC contours were visible up to 8 kHz (e.g., Fig. 5). The distribution of frequency values in this study (Chukchi Sea, CH) was most similar to the West Coast transient and False Pass (Gulf of Alaska/Aleutian Islands/Bering Sea, GAB) transient histograms with a single distinct peak from 0.6 to 0.8 kHz and a short tail (Filatova *et al.*, 2015, Fig. 4; this study, Fig. 7). The CH distribution is narrower with the majority of frequencies <1 kHz compared to the more widespread resident distribution with the majority of values



(b)

FIG. 5. (*Continued*)

extending to 2 kHz. Whereas the CH data peak in frequencies are within the range of values Filatova *et al.* (2015) reported for resident calls, these data lie at the lower limits of the range. Furthermore, comparison of the median fundamental frequency LFC between the Chukchi Sea calls and resident and transient calls from Filatova *et al.* (2015) shows a distinct overlap with the transient calls (Fig. 8).

IV. DISCUSSION

A. Killer whale presence in the Chukchi Sea

The aim of this study was to describe the killer whale presence and call repertoire in the Chukchi Sea and ultimately infer which ecotype(s) of killer whales were present in the Chukchi Sea in the summer. During three summers of recording from a single moored autonomous recorder, 1323 killer whale calls were extracted and included in the analysis. Calls were detected in every summer month (June–Aug.) in every year on a total of 38 days with most calls detected in July ($n = 1002$). This indicates that killer whales appear in this area in the summer. This is consistent with new data, suggesting that the killer whale presence is increasing in the southern Chukchi Sea as sea ice decreases (Stafford, 2019). Although these data support the seasonal occurrence of killer whales in this area, factors, including ecotype calling behavior, the nature of duty-cycled recorders, and the high missed call rate of the detector, suggest that these data likely underrepresent the killer whale presence during the summer months near Point Hope. The lack of detections at other times of the year was likely due to the

TABLE IV. The general call contour categories, including the number of calls and call subcategories. The abbreviations are included along with a description of each call category.[a]

Category	Abbreviation	n	Subcategories	Description
Multipart	p	479	13[a]	Calls comprised of 2–4 parts, including high frequency components (HFCs) and low frequency components (LFCs)
Downsweep	d	176	4[a]	Descending call contour, higher start frequency than end frequency
Upsweep	u	92	6[a]	Ascending call contour with lower start frequency than end frequency
Modulated	m	60	5[a]	Call with greater than two modulations.
Single modulation	s	31	2	Calls with one inflection.
Flat	f	485	6	Linear calls with a bandwidth <225 Hz

[a]Contains variable call category (e.g., CHpV).

sea ice cover during the majority of fall and winter; this seasonal pattern followed previously published research (Frost *et al.*, 1992; Clarke *et al.*, 2013; Huntington and Quakenbush, 2013).

1. Ecotype determination

The frequencies of calls recorded at PH1 suggest they are produced by transients. It is important to acknowledge that although there are published call examples from all North Pacific resident and transient populations, there are only a limited number of published calls from the GAB transient population. Saulitis *et al.* (2005) only tentatively classified a small sample ($n = 8$ calls) as Gulf of Alaska calls, and a more recent extensive classification described 36 GAB call types (Sharpe *et al.*, 2017). However, there is no published literature describing calls recorded north of the Pribilof Islands in the Bering Sea. Call spectrograms of the Chukchi Sea dataset were compared to published calls from a variety of call catalogs representing all ecotypes, but none were an exact match. One of the most distinguishing features in the Chukchi Sea dataset was the presence of multiple call components in the pulsed calls. CHp1–CHp5 call types (characterized by 2–5 distinct call parts) were not found in any other published dataset and, yet comprised 54% of the CHp call types (Fig. 5). One of the most common call subcategories, CHp4, was produced primarily on one day (10 July 2013), potentially indicating a unique group or possibly a different population passing through the area. Although humpback whales are common in the southern Chukchi Sea in the summer and fall (Clarke *et al.*, 2013) and have been acoustically detected from June to September (Vate Brattström *et al.*, 2019), calls were identified as killer whales by using contextual clues and reviewed by three independent analysts. However, there is a possibility that some calls may have been produced by humpbacks because we did not have associated visual surveys or behavioral data for a portion of the time.

Although the spectrogram comparisons yielded no exact matches, the call contour frequency feature comparisons with previous research (Figs. 7 and 8) suggest that the calls detected off Point Hope, Alaska, were produced by transients. Other non-call sounds were also detected, whicht lend support to the hypothesis that the calls were produced by transient whales. On 12 July 2013, more than 40 pulsive fluke cavitation sounds were detected and associated with a peak in calls produced on this day, suggesting a marine mammal predation event was under way (Ford and Pilkington, 2019).[3] Fluke cavitation in transients is caused by the rapid acceleration in the speed of the flukes when hunting (Nachtigall and Moore, 2012). Transient killer whales would also benefit from the abundance of potential prey in this region. Gray whales are a prey source for transient killer whales and are present in high densities in the southern and eastern Chukchi Sea in summer and fall (Barrett-Lennard *et al.*, 2011). In particular, the area off

TABLE V. Summary of variables measured by ROCCA (mean ± standard deviation).

Call type	Duration (s)	Start frequency (Hz)	End frequency (Hz)	Minimum frequency (Hz)	Maximum frequency (Hz)	Peak frequency (Hz)	Median frequency (Hz)	Frequency slope mean (Hz/s)	Bandwidth (Hz)
CHf, $n = 485$	0.82 ± 0.36	728 ± 157	733 ± 169	666 ± 156	785 ± 166	724 ± 165	724 ± 164	13.2 ± 146	118 ± 55
CHp_LFC,[a] $n = 479$	0.57 ± 0.34	627 ± 170	756 ± 200	547 ± 127	783 ± 195	626 ± 161	59 ± 143	422 ± 691	236 ± 155
CHpLFC,[b] $n = 1023$	0.46 ± 0.32	1066 ± 708	1158 ± 725	966 ± 662	1231 ± 767	1047 ± 693	1064 ± 726	211 ± 1105	265 ± 250
CHp HFC, $n = 142$	0.47 ± 0.24	3890 ± 1146	3435 ± 980	3413 ± 985	3924 ± 1123	3559 ± 1001	3575 ± 1024	−1019 ± 860	511 ± 479
CHd, $n = 175$	0.95 ± 0.40	859 ± 252	619 ± 170	588 ± 150	1006 ± 244	844 ± 225	799 ± 167	−279 ± 266	418 ± 253
CHu, $n = 92$	0.90 ± 0.52	738 ± 201	1133 ± 337	713 ± 196	1178 ± 326	909 ± 259	958 ± 264	709 ± 858	465 ± 238
CHm, $n = 60$	0.88 ± 0.34	738 ± 158	699 ± 298	574 ± 131	1067 ± 271	849 ± 188	787 ± 178	7 ± 442	493 ± 296
CHs, $n = 31$	0.45 ± 0.21	737 ± 178	789 ± 235	623 ± 168	953 ± 226	754 ± 205	758 ± 201	186 ± 599	329 ± 215

[a]Primary LFC only.
[b]The N value is inflated due to the inclusion of all LFC parts.

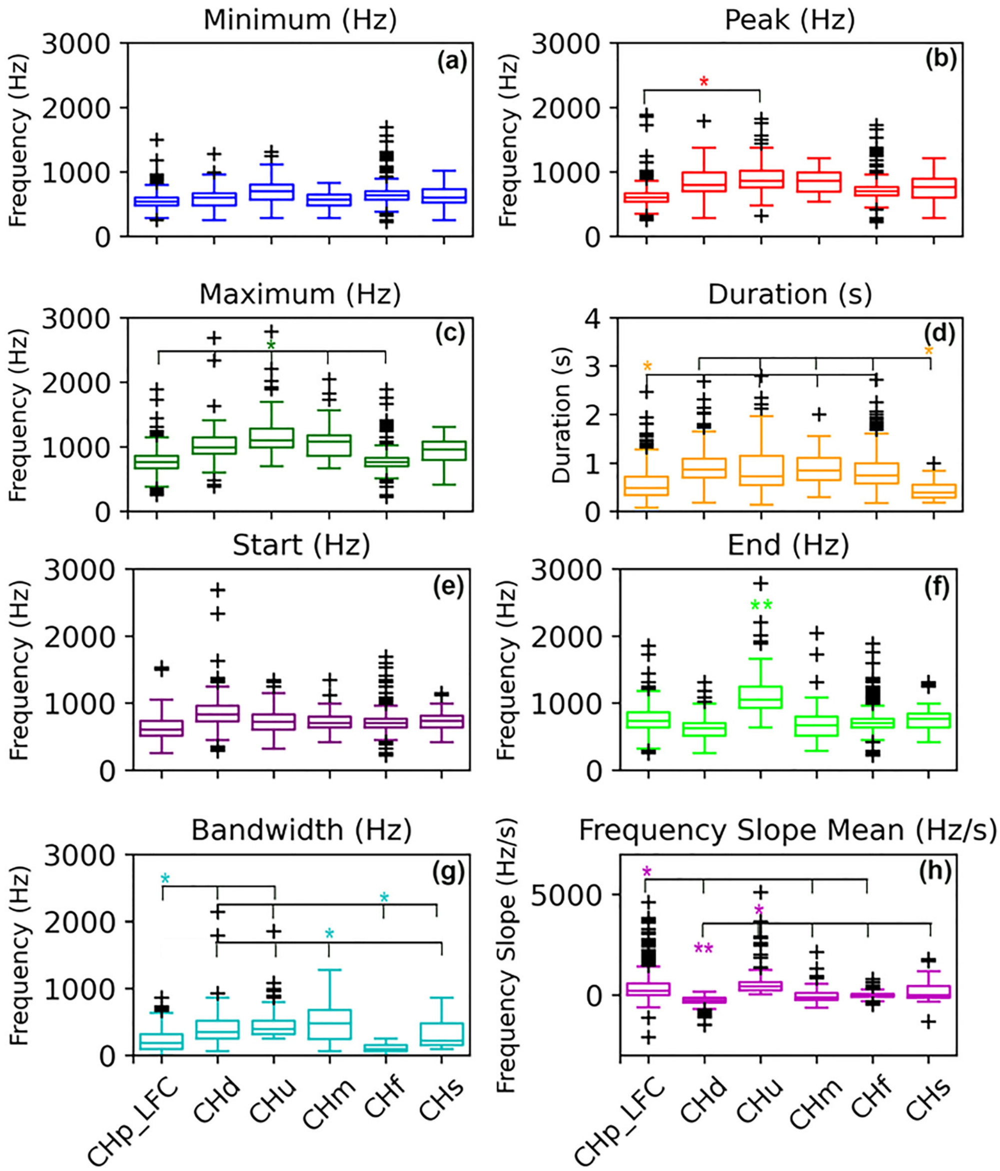


FIG. 6. (Color online) The comparison of the means of the call frequency parameters. (a) Minimum frequency (Hz), (b) peak frequency (Hz), (c) maximum frequency (Hz), (d) duration (s), (e) start frequency (Hz), (f) end frequency (Hz), (g) bandwidth (Hz), and (h) frequency slope mean (Hz/s) across all six call categories. Multipart, CHp (LFC only); downsweep, CHd; upsweep, CHu; modulated, CHm; single modulation, CHs; and flat, CHf. Asterisks indicate significance at the 0.05 level with the corresponding call types (indicated with brackets). The double asterisks (**) indicate the significance between that call category and all other categories.

Point Hope, Alaska, is a hotspot for feeding gray whales (Clarke and Moore, 2002; Moore, 2003; Bluhm *et al.*, 2007; Clarke *et al.*, 2015; Grebmeier *et al.*, 2015; Vate Brattström *et al.*, 2019). The recordings used in this study were also used for a passive acoustic study on gray whales, and a peak in gray whale calling was noted in July and August during 2013–2015 at our study site (Vate Brattström *et al.*, 2019), which overlaps with our July peak in killer whale detections. This is strong evidence of high prey availability for transients at our recording location, and sightings historically have included observations of killer whale predation events on gray whales near Point Hope (Ljungblad and Moore, 1983; George and Suydam, 1998; Huntington and Quakenbush, 2013). Presently, whale abundance at PH1 cannot be estimated using a single recorder; however, these data provide insight into the seasonal occurrence of transient killer whales at that location. The current stock assessments recognize only the GAB transient population in Alaska waters. Based on the location and acoustic results presented here, it is likely that these Chukchi Sea transients are from this population, although we cannot discount the possibility of other whale populations. In addition, the recorder is technically in "offshore" waters with respect to the ecotype designation (75 km offshore); as such, we cannot rule out the possibility that these are offshore whales, although the lower fundamental frequencies make this unlikely. More acoustic data are needed to further distinguish between offshore and transient whales.

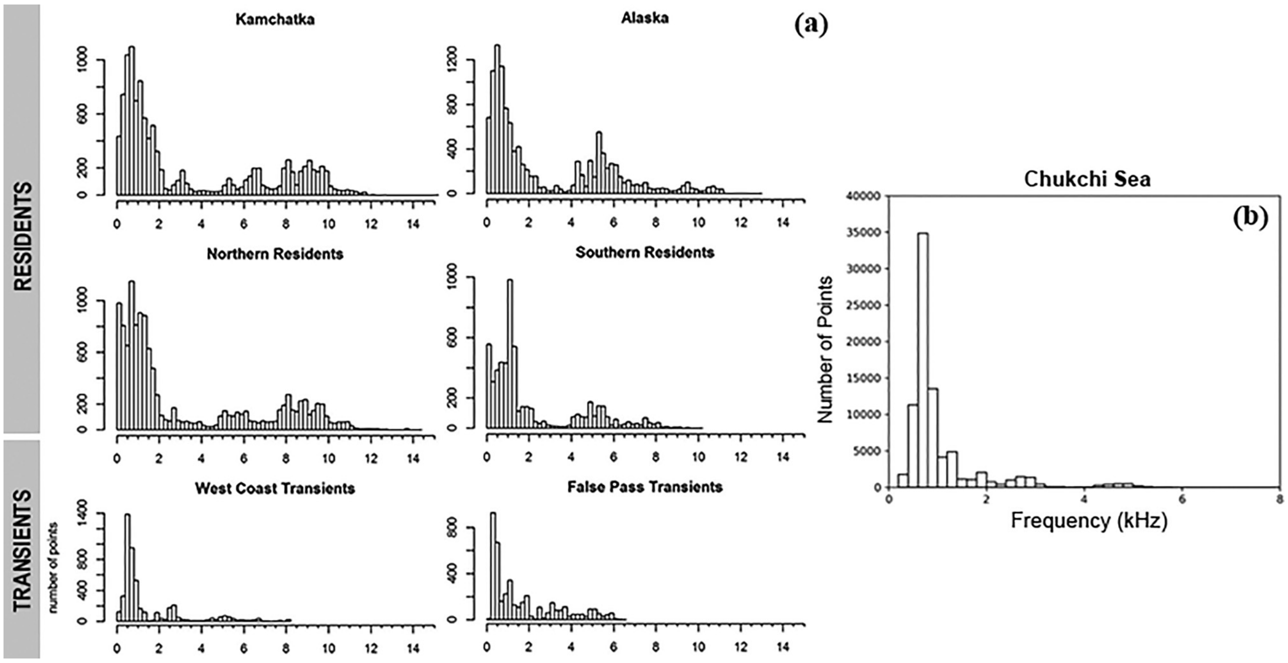


FIG. 7. (a) The histogram of the fundamental frequency points extracted from the spectrogram contours of the calls (LFC and HFC) from four resident killer whale populations (Kamchatka, Alaska, Northern residents and Southern residents) and two transient killer whale populations (West Coast transients and False Pass transients) in the North Pacific. Reprinted with permission from Filatova, O. A., Miller, P. J., Yurk, H., Samarra, F. I., Hoyt, E., Ford, J. K., Matkin, C. O., and Barrett-Lennard, L. G. (**2015**). "Killer whale call frequency is similar across the oceans, but varies across sympatric ecotypes," J. Acoust. Soc. Am. **138**, 251–257. Copyright 2015 AIP Publishing LLC. (Filatova *et al.*, 2015). (b) The histogram of the fundamental frequency contour points of all calls (LFC and HFC) extracted in this study.

B. Implications

Understanding the impact of killer whales on prey populations of an area is difficult without knowing the true extent of their distribution. Visual observations of transient killer whales in the Chukchi Sea have been made for decades (Ljungblad and Moore, 1983; Lowry *et al.*, 1987; George and Suydam, 1998; Aerts *et al.*, 2013; Clarke *et al.*, 2013; Vate Brattström *et al.*, 2019), and more recently, acoustic detections have begun to provide more insight on the killer whale presence (Clarke *et al.*, 2013; Hannay *et al.*, 2013; Stafford, 2019; Vate Brattström *et al.*, 2019; this study); however, it remains unknown if residents also occur in the Chukchi Sea. The concentration of calls on specific days in this study indicates periods when specific groups of transients might be passing through the area. This area of the southeastern Chukchi Sea is likely a key feeding ground for transients in the summer and fall as baleen whales use this habitat as a feeding ground and migration route (Clarke *et al.*, 2015).

Changing climatic conditions are also resulting in extended open water periods that may leave baleen whale species, like bowhead whales, more susceptible to killer whale predation (Higdon and Ferguson, 2009, 2010; Reinhart *et al.*, 2013; Willoughby *et al.*, 2020). Killer whales are the only natural predator of bowhead whales; recently, Willoughby *et al.* (2020) found evidence that killer whale predation on bowhead whales is increasing in the

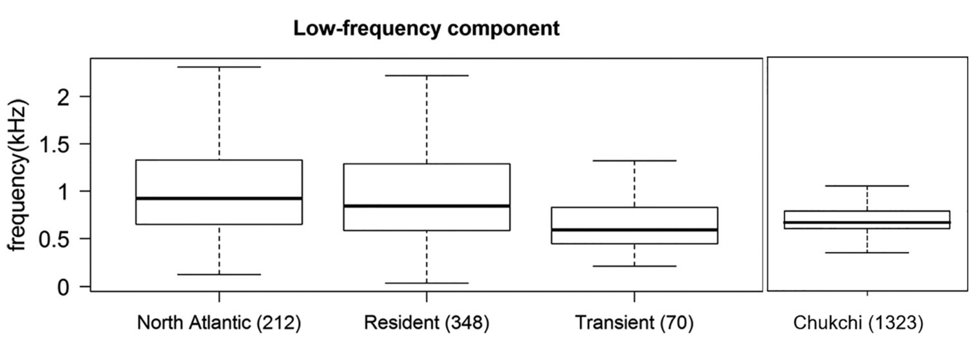


FIG. 8. The median frequency of the LFC fundamental frequency of killer whale calls from the Chukchi Sea compared to the eastern North Atlantic, North Pacific resident, and transient populations. Reprinted with permission from Filatova, O. A., Miller, P. J., Yurk, H., Samarra, F. I., Hoyt, E., Ford, J. K., Matkin, C. O., and Barrett-Lennard, L. G. (**2015**). "Killer whale call frequency is similar across the oceans, but varies across sympatric ecotypes," J. Acoust. Soc. Am. **138**, 251–257. Copyright 2015 AIP Publishing LLC. (Filatova *et al.*, 2015). The sample size is shown in parentheses.

eastern Chukchi Sea. Mortality was attributed to killer whales in years coinciding with this study (2013 and 2015) with the most deaths attributed to killer whales in 2015 (Willoughby *et al.*, 2020). A killer whale sighting off Point Hope and a corresponding bowhead stranding with injuries indicative of killer whale predation off Cape Lisburne suggest that this area may be a key area for killer whale and bowhead interactions. This net increase in apex predators will ultimately exert more top-down pressure on the ecosystem.

Baleen whales in the Arctic not only serve as a vital resource for killer whales but also as an important resource for humans. Arctic Native communities rely heavily on marine mammals for subsistence, including gray whales in Russia (Reeves, 2002) and bowhead whales in Alaska (Marquette and Braham, 1982). Point Hope is one of the whaling villages in Alaska with a long history of subsistence hunting and catches, consisting of almost exclusively bowhead whales (Marquette and Braham, 1982; Huntington, 1989). Although gray whales are the primary targets for killer whales, the presence of transient killer whales during the harvest season could disrupt the behavior of the bowhead whales, potentially impacting Native subsistence hunting.

V. CONCLUSION

This study investigated the killer whale presence in a logistically difficult-to-study region of the southeastern Chukchi Sea using passive acoustic data. These data suggest that transient killer whales were detected in every year of the study and every summer month off Point Hope, Alaska, indicating a seasonal occurrence in this area. An important outcome of this study was the development of a call catalog. Killer whales have complex acoustic repertoires, and catalogs for these repertoires are important for call organization, delineating dialects, and describing and comparing geographic variation in repertoires. This study provides the first detailed catalog and comprehensive description of calls produced by killer whales in the Chukchi Sea. Many unique and previously unidentified calls were described, which suggests the presence of different populations that likely coexist in the Chukchi Sea, such as Russian whale populations. We predict that the calls recorded in this study are likely from whales within the Aleutian/Bering Sea population but do not want to exclude the possibility of the presence of other populations because that could explain the differences between the calls described in this study and previously described calls. Future studies are encouraged to provide acoustic details of reported calls to facilitate call comparisons among populations. Although this catalog serves as a foundation for future studies, collection of concurrent visual sighting and behavioral data will be instrumental in understanding the call divergence and relatedness of similar calls to improve the catalog classification. These data provide new insight into transient acoustic behavior and call diversity in the Chukchi Sea and can serve as a baseline for future acoustic work on killer whales in the Arctic.

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[1]Reference to trade names does not imply endorsement by the National Marine Fisheries Service or NOAA.

[2]See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0005405 for an example of the CHd dendrogram output resulting from the hierarchical cluster analysis, as well as a .wav file containing each call subcategory from each call type (in the same order as they appear in Fig. 5).

[3]John Ford, University of British Columbia, and James Pilkington, Fisheries and Oceans Canada Pacific Biological Station. Email communication. 28 April 2019 and 1 May 2019.

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