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ABSTRACT

The minke whale (*Balaenoptera acutorostrata*) is a small species of baleen whale with a cosmopolitan distribution. Despite extensive study on the vocalizations of other balaenopterids, the acoustic repertoire of minke whales is not well known. Individuals of the North Pacific subspecies (*B. acutorostrata scammoni*) produce unique vocalizations ('boings') during their putative breeding season from fall to spring. However, no vocalizations have been previously reported for this subspecies in any eastern North Pacific feeding ground. We present two call types recorded in the presence of six minke whales, two of which were confirmed as female, in Cormorant Channel, British Columbia, Canada, during the summer of 2012. The calls consist of downsweeps and pulse chains. These call types share some characteristics with calls described elsewhere, although they are not identical to similar call types observed for other populations. Calling rates for minke whales in this study region are very low compared to those reported for this subspecies on its putative breeding grounds, as well as for other subspecies on their feeding grounds. We propose predation risk, sexual segregation and acoustic masking as potential causes of the low calling rates observed for minke whales in Cormorant Channel.

Introduction

The common minke whale is a small baleen whale found in all oceans of the world. In the northern hemisphere, two subspecies are recognized. *Balaenoptera acutorostrata acutorostrata* is found in the North Atlantic Ocean and *B. acutorostrata scammoni* is found in the North Pacific Ocean (Stewart and Leatherwood 1985). In the southern hemisphere, a dwarf form of common minke whale exists as an unnamed subspecies (Jefferson et al. 2015). Several types of vocalizations have been attributed to the three subspecies of common minke whales.

In the southern hemisphere, the vocalizations of the dwarf minke whale are best known from the waters around the Great Barrier Reef in Australia (Arnold 1997). In this region, minke whales are known to make a complex, multi-component, amplitude and frequency modulated call spanning 50 Hz–9.4 kHz that lasts up to 2.5 s (Gedamke et al. 2001). This

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Supplemental detail for this article can be accessed here.

call is commonly referred to as the star wars vocalization and has characteristics consistent with songs produced by other baleen whales advertising reproductive potential. Another less common minke whale call recorded during at least 59% of encounters in this region was a 0.2–0.3 s downsweep ranging in frequency from 250 to 50 Hz (Gedamke et al. 2001).

A similar downsweep vocalization has also been attributed to minke whales from the St. Lawrence River estuary in the North Atlantic Ocean. In this region, 0.4 s downsweep vocalizations typically ranging from 100 to 200 Hz to <90 Hz were detected during 51% of minke whale encounters (Edds-Walton 2000). These calls are also similar in duration and structure to some vocalizations of Antarctic minke whales (*Balaenoptera bonaerensis*) (Schevill and Watkins 1972). Both species were found to make these calls in summer feeding grounds. Other types of vocalizations made by minke whales in the North Atlantic primarily include trains of low frequency pulses in the 50–400 Hz range lasting from 10 to 60 s. These pulse trains have been recorded speeding up, slowing down and with consistent inter-pulse intervals in the Caribbean in winter (Winn and Perkins 1976; Mellinger et al. 2000) and off of Massachusetts in spring and fall (Risch et al. 2013). It is also hypothesized that North Atlantic minke whales emit high frequency clicks (Beamish and Mitchell 1973) and pings (Winn and Perkins 1976).

In the North Pacific, only one type of vocalization has so far been attributed to minke whales. This call commonly referred to as a boing has only been recorded from fall to spring, usually in low latitude oceanic regions off the coasts of Mexico, Hawaii and the Mariana Islands (Rankin and Barlow 2005; Norris et al. 2012). However, boings with characteristics similar to those recorded in Hawaii have also been detected in the Bering Sea (Delarue et al. 2012). These central Pacific boings have a mean pulse repetition rate of 115 s^{-1} and duration of approximately 2.6 s. In the eastern tropical North Pacific, minke whale boings have been recorded with a lower pulse repetition rate (92 s^{-1}) and longer duration (3.6 s) (Rankin and Barlow 2005). Like the star wars vocalizations, these boings are detected mainly in regions where, and at times when minke whales are thought to breed (Thompson and Friedl 1982; Oswald et al. 2011).

From spring to fall, small numbers of North Pacific minke whales can be found distributed in temperate waters of western Canada (Towers et al. 2013). In this region, they are usually only documented over or near shallow banks where they can sometimes be observed feeding (Towers et al. In review). One such area off north-eastern Vancouver Island is Cormorant Channel (Towers et al. In review). In order to determine frequency of use patterns, behaviour and the acoustic signals of minke whales in this area, we made concurrent shore-based observations and acoustic recordings during the summer of 2012. This report presents the acoustic results of this study including details on two types of vocalizations previously undocumented for this subspecies.

Materials and methods

Data collection

A Wildlife Acoustics SM2M outfitted with an HTI-96-min transducer (sensitivity: −165 dB re. 1 V/μPa with manufacturer reporting flat frequency response above 100 Hz) was set to make continuous recordings at a sampling rate of 16 kHz (Bit rate: 16). It was anchored to the seafloor at 50° 36.2 N, 126° 56.7 W in Cormorant Channel at 20 m depth on June 10th,

2012. This location was 208 m at a magnetic compass bearing of 40° northeast from an observation point at the high tide line on the shore of Cormorant Island. Visual observations of minke whales were conducted from the observation point from June 11th to August 15th (Figure 1). Observers used naked eyes and 15 × 80 Steiner binoculars with built-in magnetic compass and reticle bar mounted on a levelled Velbon C-600 fluid-panning tripod to conduct visual surveys for up to 13 h a day when Beaufort sea state levels were ≤2. Data including Beaufort sea state, tide height and notes on visibility were recorded every 30 min of survey effort. The time, compass bearing, and reticle distance from the Malcolm Island shoreline were recorded each time a minke whale surfaced and also when other marine mammals were observed (Towers et al. In review). The behaviour of cetaceans was noted when apparent and effort was taken to visually identify individual minke whales based on their unique natural markings portrayed in Towers (2011). Effort to biopsy these known whales using the technique outlined in Barrett-Lennard et al. (1996) was also undertaken in Cormorant Channel in the summers of 2013 and 2014.
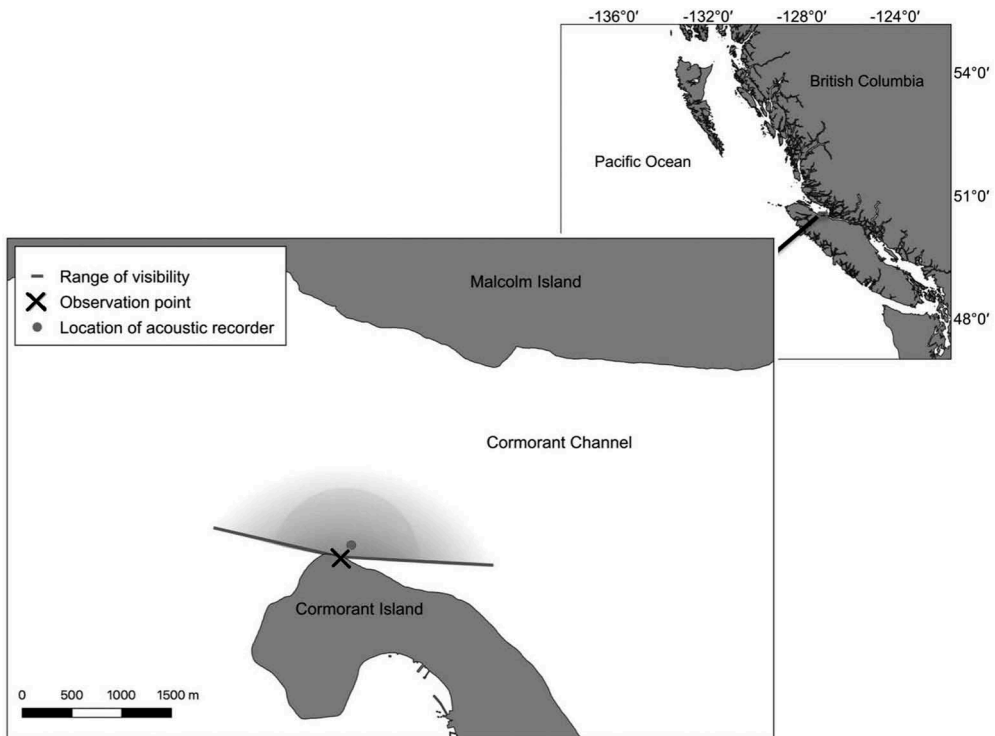
Figure 1. Map of study area in Cormorant Channel, British Columbia. The X denotes the shore-based visual observation site from which minke whale presence was confirmed. The light grey dot denotes the location of the SM2M omnidirectional hydrophone and acoustic recorder. The grey lines portray the arc of the area surveyed by observers and the shading between the lines includes all surveyed waters 3 or more reticles from the Malcolm Island shore. The lighter tone of grey shading denotes the area in which the 3 reticle limit fluctuated due to the semi-diurnal tidal activity. All acoustic data recorded from 5 min before to 5 min after minke whales were observed within the shaded area were analyzed. Map created by Christie McMillan, Marine Education and Research Society, Port McNeill, BC, Canada; used with permission.

Data analysis

Prior to manual analysis, a detection algorithm was designed and applied to the entire acoustic dataset to check for the presence of minke whale boing vocalizations (Rankin and Barlow 2005). The detector used was a programmable Band-Limited Energy detector in Raven Pro 64 v.1.5 (Cornell Lab of Ornithology). Detector parameters were as follows: Bandwidth 1000–1600 Hz; duration 1.4–5.0 s; minimum separation 6.0 s; minimum occupancy 50%; SNR threshold 10.0 dB re: 1 μPa; block size 15 s; percentile 20%.

Detailed acoustic analysis was conducted for the time periods when minke whales were observed within 998 m of the moored hydrophone. These time periods were defined as the interval of time including 5 min before a minke whale was first seen surfacing within 3 or more reticles (≤1176 m) of the observation point, to 5 min after the whale was seen within that radius (Figure 1). Sightings were considered part of the same time interval if sightings of minke whales within the defined radius were no more than 10 min apart, to account for possible missed surfacings in between. This method of subsampling the acoustic data was chosen to maximize the probability of observing calls heard by minke whales with high signal-to-noise ratio (SNR), and minimize the possibility of attributing the calls of other animals to minke whales due to lack of visual confirmation.

Odontocetes were sometimes present at these time intervals; however, the only cetacean regularly observed in the area that may produce similar calls to a minke whale was the humpback whale (*Megaptera novaeangliae*). Calls closely resembling known humpback whale vocalizations were discarded from further analysis. In addition, candidate minke whale calls that were recorded within two hours of a humpback whale sighting in the study area were discarded, as humpback whale calls from outside visual range may have been heard. In the event that multiple call types were heard within one analysis period, the SNR of calls was to be compared to determine which call type was more likely to come from close range; however, this overlap did not occur in our analysis. Other vocalization sources in the study area include harbour seals (*Phoca vitulina*) and several species of soniferous fish. Harbour seal vocal repertoires from this region have been documented (Nikolich et al. 2016; Matthews et al. 2017) and were observed in several analysis periods. Any candidate minke whale calls that resembled portions of harbour seal roars were removed from further analysis. Candidate call types were compared to known vocalizations of fish in the area, and any calls matching fish vocal characteristics were discarded.

Recordings were analysed manually using Raven Pro 64 v.1.5 (Cornell Lab of Ornithology) to identify biological sounds both visually using spectrograms (Hann window, 2560-point fast Fourier transform [resolution = 160 ms × 6.25 Hz], 50% overlap) and aurally by listening to the recordings. Signals that matched previous descriptions of minke whale calls from other locations were manually selected from the spectrograms. Signals that appeared mammalian in origin, but could not be classified to another marine mammal, were also selected. All selected calls were then placed into categories based on similar spectral contour and acoustic properties. Measurements of duration (seconds), upper and lower frequency (Hz), and peak frequency (Hz) were taken for all calls categorized in this way. Mean and standard deviation was calculated for each measurement, for each call type.

For pulse chain call types, spectrograms were examined using a 400-point fast Fourier transform (resolution = 25 ms × 40 Hz; all other spectrogram parameters remained the same as above). This increased resolution in the time domain, which allowed more accurate measurement of inter-pulse intervals. Pulse chains which had a sufficient SNR to be measured (i.e. their beginning, end, high and low frequencies were clearly visible in spectrographic analysis) were divided roughly into thirds of their durations, and inter-pulse interval within the chain was measured once per third to determine whether pulse chains showed increasing, decreasing, or constant pulse rates. Duration, peak frequency, high frequency, and low frequency were compared among pulse chain types using analysis of variance (ANOVA) when parametric assumptions were met, or Kruskal-Wallis rank-sum tests when parametric assumptions were not met.

Each time interval that was analysed was qualitatively assessed for anthropogenic noise level. Anthropogenic noise was considered to be noise attributable to boat motors, fishing gear, or aircraft. Each time interval was given an average noise rating between 0 (no anthropogenic noise for most of the interval) to 4 (very loud anthropogenic noise for most of the interval). All intervals were found to have some anthropogenic noise; thus, noise level ratings ranged from 1 to 4. To determine whether noise masking had an effect on manual selection of potential calls, a Kruskal-Wallis rank sum test was used to detect statistical differences between the number of calls selected at each noise level, and whether there were statistical differences in average noise level during intervals in which calls were selected versus intervals in which no calls were selected.

DNA was extracted from each biopsy sample using standard phenol:chloroform procedures (Sambrook and Russell 2001; Wang et al. 2009). Samples were then sexed using the method described in Gilson et al. (1998).

Results

Minke whales were observed at three or more reticles from the Malcolm Island shore for a total of 721 min during 77 surfacing bouts in June; 896 min during 104 surfacing bouts in July; and 210 min during 24 surfacing bouts in August. The total number of surfacings recorded was 890, 157 of which occurred within 5 min of when one or more minke whales were observed surfacing within the 3 reticle arc (Figure 1; Table 1). Surface feeding behaviour was observed within 3 or more reticles of the observation point on 6 occasions (Table 1). Observer experience, weather, and surfacing behaviour allowed for the identities of 6 unique minke whales (M001, M002, M003, M004, M006, M022; see Towers 2011) to be recognized

Table 1. Summary of minke whale sightings (by number of surfacings observed) that occurred close to the hydrophone (i.e. 3 or more reticles from the Malcolm Island shore), and sightings that occurred within this range within 5 min of the vocal activity described in this study. '≥2 Animals' column refers to sightings that occurred within 5 min of when two or more different minke whales were observed or suspected >3 reticles.

	Total	Alone	≥2 Animals	Feeding	ID confirmed
≥3 Reticles	890	733	157	6	132
Vocal activity	54	54	0	1	9

on 132 occasions (Table 1). DNA extracted from biopsy samples of two of these individuals (M001 and M006) confirmed that they are both female.

The detection algorithm for boings yielded no positive results. By manual analysis, 1,491 min of acoustic data were analysed from June, 1,936 min were analysed from July, and 450 min were analysed from August. Initial manual examination of the data yielded only 4 downsweep calls which were similar to documented minke whale vocalizations in other regions. We then expanded our search to include biological signals that may not closely match known minke whale calls, but could also not be classified to other species. In this way we annotated a total of 115 calls heard over 8 of the 43 days (19% of days) that minke whales were visually observed within 3 or more reticles of the observation point (calling rate was therefore 1.79 calls*hour^{-1} or 0.030 calls*min^{-1}). These calls were placed into two categories based on spectral characteristics: Pulse Chain (PC; N = 111) and Downsweep (DS; N = 4). Two other interesting vocalization types were recorded, each on only one occasion: the Broadband Pulse (N = 2) and the Tonal Waver (N = 22) (Supplemental Materials 1). Due to the fact that these calls were only observed once each in the presence of minke whales, we do not include them as candidate call types here. Examples of acoustic recordings of each call type, including the two calls heard only on one occasion each, have been provided as supplemental materials (Supplemental Materials 2–5).

Pulse chains were observed on June 17th, June 21st, June 29th, July 1st and July 28th, at times when minke whales were the only marine mammal seen in the area (Figure 2). Those recorded on June 21st were made when female minke whale M006 was observed
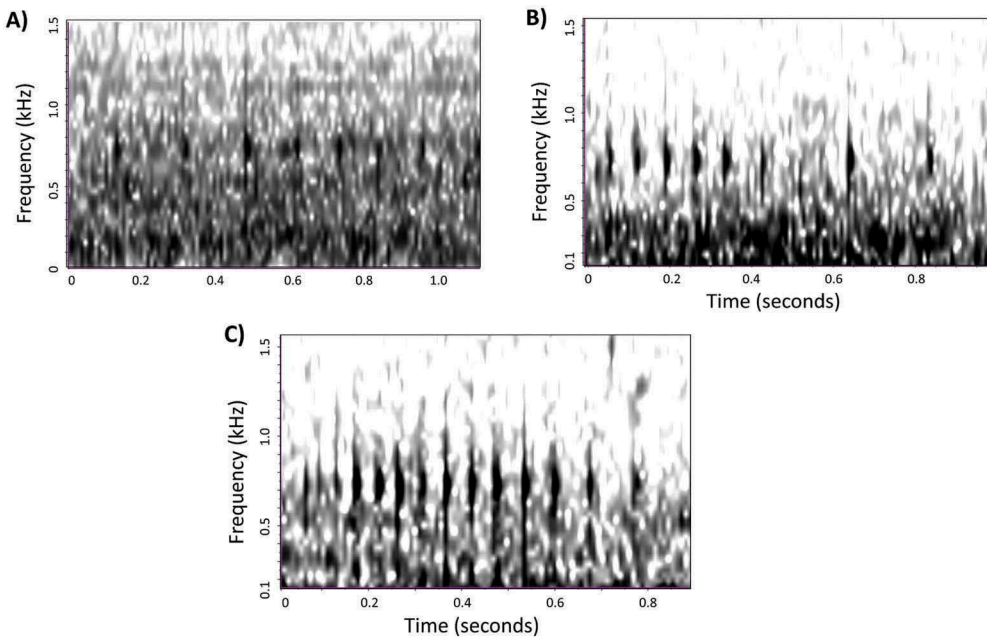
Figure 2. Spectrogram showing the pulse chain candidate call type (300-point fast Fourier transform, Hann window with 50% overlap) including three call subtypes: pulse chains which (a) increase in pulse rate, (b) decrease in pulse rate and (c) remain constant in pulse rate over their duration. Calls were recorded in Cormorant Channel, British Columbia, Canada, during times when minke whales were the only baleen whale visually observed.

near the hydrophone during nine consecutive surfacings (Table 1). Most pulse chains (95/111) were observed on the morning of July 28th, between 8:00 and 11:00 local time. Of the total number of pulse chains observed, 70 (63%) were deemed suitable for further analysis. Of these 70 pulse chains, inter-pulse interval increased over the duration of 39 calls (decreased in pulse rate), and decreased over the duration of 7 calls (increased in pulse rate). The remaining 24 pulse chains were constant in pulse rate, meaning the inter-pulse interval did not increase or decrease more than 10 ms over the duration of the call. There were no significant differences in low frequency (overall mean = 327 ± 173 Hz), high frequency (overall mean = 1205 ± 459 Hz), or peak frequency (overall mean = 676 ± 246 Hz) among the different pulse chain types (ANOVA and Kruskal-Wallis tests, all $p > 0.05$). However, pulse chains that decreased in pulse rate were significantly longer in duration than pulse chains which had constant pulse rates (ANOVA, $F_{2,67} = 3.26$, $p = 0.045$; Tukey post-hoc pairwise tests). Pulse chains which increased in pulse rate did not have a significantly different duration from either of the other pulse chain types (Table 2).

Downsweeps (Figure 3) were heard on June 29th and July 5th. A downsweep recorded on June 29th occurred 4 min 23 sec before a minke was observed lunge feeding at the surface (Table 1). Downsweeps had an average high (starting) frequency of 142 ± 69 Hz and a low (ending) frequency of 38 ± 11 Hz. The average duration of the downsweeps was 648 ± 152 ms (Table 2).

Vocalizations could not be significantly correlated with any specific behaviours recorded by observers, due to the low number of calls recorded and infrequency with which specific activities other than surfacing to breathe were observed. Anthropogenic noise levels were not statistically different between time intervals with calls found and time intervals with no calls found (Wilcoxon rank sum test, $W = 5180$, $p = 0.649$). Similarly, the number of calls selected was not statistically different among noise levels (Kruskal-Wallis rank sum test, $X^2 = 0.639$, $p = 0.887$).

Discussion

We present two call types that were recorded in the presence of North Pacific minke whales in Cormorant Channel, neither of which have been previously documented for this subspecies. However, because calls could not be localized in space, the source of the calls could not be positively concluded. Neither of the two calls described here resembled the boing, which is the only call type previously described for North Pacific minke whales (Rankin and Barlow 2005). However, both call types are similar

Table 2. Summary of acoustic parameters describing the two call types attributed to minke whales in Cormorant Channel, British Columbia, including call subtypes for pulse chains. All statistics are reported as mean ± standard deviation. Subscripts denote significant difference between call subtypes for the indicated parameter.

Call type	Call subtype	Sample size	Low frequency (Hz)	High frequency (Hz)	Duration (ms)	Peak frequency (Hz)
Pulse chain	Decreasing pulse rate	39	323 ± 146	1142 ± 233	885 ± 275[a]	673 ± 127
	Constant pulse rate	24	334 ± 214	1249 ± 610	704 ± 281[b]	915 ± 508
	Increasing pulse rate	7	331 ± 180	1401 ± 760	831 ± 224[ab]	1070 ± 691
Downsweep	–	4	38 ± 11	142 ± 69	648 ± 152	105 ± 36
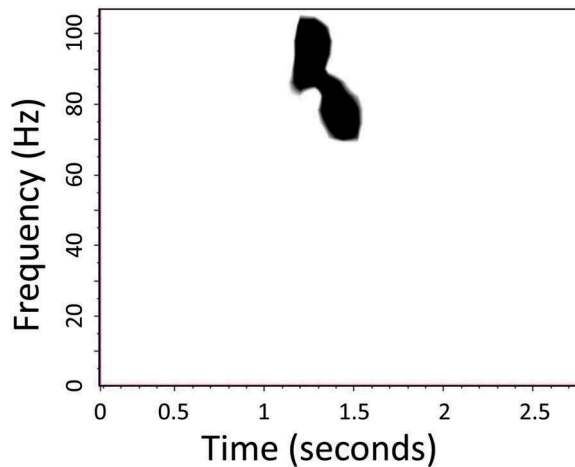
Figure 3. Spectrogram showing the downsweep candidate call type (2500-point fast Fourier transform, Hann window with 50% overlap). Calls were recorded in Cormorant Channel, British Columbia, Canada, during four occasions when minke whales were visually observed.

to those found in other subspecies (Winn and Perkins 1976; Edds-Walton 2000; Mellinger et al. 2000; Gedamke et al. 2001; Risch et al. 2013). An additional two call types, heard on only one occasion each, are undescribed for minke whales elsewhere. Because of the small sample size of these two call types and our inability to localize sound sources, we can only infer that these signals were produced by minke whales until further investigations can confirm that this species is the true source of these signals (Supplemental Materials 1).

The downsweep vocalizations observed in Cormorant Channel are similar in frequency range and frequency transition to those described for common minke whales in the St. Lawrence estuary, Canada and the Great Barrier Reef, Australia by Edds-Walton (2000) and Gedamke et al. (2001), respectively. However, while St. Lawrence estuary and Great Barrier Reef minke whales produced downsweeps that were 0.2–0.4 s in duration, the mean duration of the downsweeps observed in this study was 0.7 s (Table 2). One downsweep was heard within 5 min of a surface feeding event (Table 1). Edds-Walton (2000) reported few observations of feeding behaviour, but proposed that downsweeps may be used to maintain contact between individuals while feeding on patchy prey. However, Gedamke et al. (2001) only recorded downsweeps during the suspected calving and breeding season, when minke whales were not observed or expected to be feeding.

The pulse chains observed in Cormorant Channel were broadband extending from ~300 to 1400 Hz whereas the pulse trains described in the Atlantic by Mellinger et al. (2000) and Risch et al. (2013) were lower in frequency and narrowband, only extending from ~100 to 400 Hz. However, pulse chains have similar pulse durations and inter-pulse intervals to the 'zip-like' calls described by Winn and Perkins (1976) in the Atlantic, which are short pulse bursts extending up to 14,000 Hz with clicks approximately 50 ms apart. In this study, we further classify pulse chains into three categories based on the way that pulse trains have been described elsewhere (Mellinger et al. 2000; Risch et al. 2013, 2014). In the North Atlantic, these pulse trains were produced in

a stereotyped series of call types resembling song and were associated more with travelling or socializing than feeding (Mellinger et al. 2000; Risch et al. 2014). This call type may be correlated with the age or sex of the caller (Risch et al. 2014) and has been proposed to serve a reproductive function (Risch et al. 2013) or to maintain group spacing (Risch et al. 2014). The pulse chains that we observed were produced by single animals and none were recorded when more than one minke whale was observed within 3 reticles of shore, suggesting that they may have been made to communicate with other whales throughout or beyond the study area. One of the individuals documented emitting a pulse chain is a known female. However, considering that summer is thought to be a time when these whales are focused primarily on feeding (Towers et al. 2013; In review), pulse chains were not likely made in relation to reproductive behaviour.

Very few calls were identified using manual analysis even though minke whales were observed during 224 of 565 h of effort during the study period (presence per unit effort: 44% – see Towers et al. In review). The calling rate in Cormorant Channel (2.79 calls*hour^{-1} or 0.030 calls*min^{-1}) was much lower than that observed for individual minke whales in a migration corridor in the North Atlantic (average 48.6 calls*hour^{-1}; Risch et al. 2014), and 2 orders of magnitude less than peak rates reported in another summer feeding ground in the St. Lawrence estuary in eastern Canada (up to 3.6 calls*min^{-1}; Edds-Walton 2000). Minke whales in Cormorant Channel are also much less vocal in this summer feeding ground than they are in their putative breeding grounds in the tropics (Oswald et al. 2011; Martin et al. 2013). The relative vocal silence in this area may be explained by several factors discussed below.

Mammal-eating Bigg's killer whales are relatively common and widespread in coastal waters of BC (Ford et al. 2013), but during the course of this study the presence per unit effort of Bigg's killer whales was only 2% (Towers et al. In review). However, even in areas where killer whale density is low, this species is known to inhibit the vocal activity of their prey (Rankin et al. 2012). We therefore suggest that minke whales may remain relatively quiet in Cormorant Channel due to predation risk, especially considering killer whales have been observed chasing minke whales in Cormorant Channel and attacking and killing them in other nearby waterways (Ford et al. 2005).

The relatively low calling rates for minke whales in Cormorant Channel may also be in part due to sexual segregation. Male and female minke whales are known to have little overlap in some feeding grounds (Laidre et al. 2009) and to date, all eight minke whales stranded in coastal waters of BC and Washington for which sex was recorded were female, whereas the only two minke whales killed in offshore waters of BC for which sex were recorded were male (Ford 2014). Additionally, two of the most commonly observed individuals during this study were confirmed to be female through analysis of DNA acquired in biopsy samples and no boings were recorded. Only male minke whales are suspected to produce boings (Martin et al. 2013), similar to the vocal behaviour of males of other baleen whale species (e.g. humpback, fin, blue) advertising reproductive potential (Tyack 1981; Croll et al. 2002; Oleson et al. 2007). If so, it is speculative but possible that the relative quietude of female minke whales may help enable them to exploit prey in near-shore habitat despite the increased risk of predation by killer whales, whereas males may forage further offshore.

Cormorant Channel experiences high levels of vessel traffic during the summer from small recreational and commercial vessels all of which produce underwater noise in the frequency band occupied by previously described minke whale calls (Edds-Walton 2000; Mellinger et al. 2000; Risch et al. 2014). Therefore, it is likely that acoustic masking is taking place. Other sources of masking noise include surface disturbance, flow noise and bottom movement produced by strong current, and the low-frequency vocalizations of other marine animals such as harbour seals, fish, and invertebrates (Hanggi and Schusterman 1994; Širović and Demer 2009; Richardson et al. 2013; Staaterman et al. 2013). While we did not see a quantifiable effect of ambient noise on the number of calls observed at any given time, there were no recordings analysed during which the ambient soundscape was completely free of vessel noise. While it is unlikely that acoustic masking prevented the detection of all or most minke whale vocalizations, it is possible that a small percentage of calls were not identifiable as such because the source level of the calls was low, leading to attenuation at short distances, or because transmission of the calls was hindered by masking noise. Other environmental factors such as temperature or mineral content can also affect propagation; however, these conditions were unlikely to fluctuate appreciably throughout the recording period. Although source levels for minke whale pulse trains in the Atlantic (Risch et al. 2014) were higher than those reported for humpback whale pulse trains in Alaska (Fournet et al. 2018), it is also possible that minke whales lower the source level or rate of calling in areas with a high density of predators.

This report provides the first evidence that minke whales produce vocalizations while on feeding grounds in the eastern North Pacific, albeit at a lower rate than has been documented for other subspecies in other regions. We also introduce novel call types, which have not been described for this species, suggesting that some vocalizations of minke whales in the North Pacific may be distinct from calls produced by other subspecies on feeding grounds. The vocal behaviour presented in this paper will provide acousticians with reference material when analysing new and existing acoustic datasets from the North Pacific. This is especially important because minke whales can often be difficult to track visually (Norris et al. 2017), and therefore typically go undetected during environmental impact assessments used to inform development projects. We hope that our findings will provoke further study leading to a better understanding of the acoustic ecology of minke whales in this region.

Disclosure statement

Funding

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