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ORIGINAL PAPER

Fish sounds near Sachs Harbour and Ulukhaktok in Canada's Western Arctic

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Abstract

The sounds of Arctic marine fishes recorded in situ have been largely ignored in the literature, despite the successful application of passive acoustic monitoring (PAM) for mapping the presence of fishes at lower latitudes. Polar cod, *Boreogadus saida*, is a known soniferous species that holds keystone status in the Arctic and for which PAM could be a useful tool for understanding their distributions-particularly during their spawning seasons during the Arctic winter. PAM recordings from Sachs Harbour and Ulukhaktok (covering 1.5 years between them) were analysed for fish sounds. A total of 44 grunts and 3 knocks were recorded, the majority of which were recorded at Ulukhaktok during January. A difference in the number of fish calls was also seen between months with the highest number occurring during January. No diurnal patterns in the number of fish calls were observed. K-means cluster analyses based on the 90% bandwidth, duration, peak and centre frequencies showed three clusters. Type 1 occurred during October through April, Type 2 from October through February and Type 3 during October. Type 2 calls were only noted near Ulukhaktok and Type 1 calls resembled those from polar cod. These results either suggest different species or the vocal repertoire of a single species. Based on the spectral and temporal characteristics, all fish sounds resembled those from gadids. The detection of fish calls and the apparent spatio-temporal variation following the expected spawning season of polar cod illustrate the potential usefulness of PAM for Arctic fishes—particularly at a time when climate change is forcing Arctic nations to better prepare for ecological shifts and changing predator/prey relationships.

Keywords Arctic · Polar cod · *Boreogadus saida* · Fish sounds · Arctic cod · Passive acoustic monitoring · Vocalisation

Introduction

Passive acoustic monitoring (PAM) has become a popular method for long- and short-term monitoring of vocal/noisy marine fauna. Having evolved the largest diversity of sound-generating mechanisms among vertebrates (Kaatz 2002), many fish species produce sounds under a variety of conditions—such as when engaging in reproductive activities, defending territories, foraging, responding to threats, synchronising mating or as a by-product of any physical activity/movement (Amorim 2006). Accordingly, a wealth of information can be obtained by deploying hydrophones long term in ecologically vital, but very remote, regions of the world such as the Arctic. Polar cod (*Boreogadus saida*) is a keystone species in the Canadian Arctic, as no other prey fish compare with its abundance and energetic transfer values (Finley et al. 1990; Tynan and DeMaster 1997). They are key prey for higher-level predators, such as bearded seals (*Erignathus barbatus*), ringed seals (*Pusa hispida*) and beluga whales (*Delphinapterus leucas*) (Quakenbush et al. 2011; Chambellant et al. 2013; Crawford et al. 2015), representing as much as 75% of the energy transfer from the zooplankton to marine mammal predators (Kessel et al. 2015). Polar cod are also soniferous, producing grunts that compare with other gadid species, such as Atlantic cod (*Gadus morhua*) (Riera et al. 2018a). Large schools can occur in areas of marginal ice (Tynan and DeMaster 1997). Little is understood concerning their mating behaviours, although it is known that they spawn under the ice during winter (Craig et al. 1982; Bradstreet et al. 1986)—making it difficult to study such behaviours in the field (Graham and Hop 1995). In Franklin Bay (in the Amundsen Gulf in NWT, Canada), polar cod biomass builds from January and peaks during

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April, particularly below 140 m (Benoit et al. 2008). Polar cod were also detected nearer the surface at Franklin Bay during the winter months (Benoit et al. 2008). Since light is extremely limited during the Arctic winter the use of visual cues during spawning would be unlikely and therefore acoustic and olfactory cues may take precedence (Cott et al. 2014). Therefore it is likely that acoustic communication may be a key component to the spawning behaviour of polar cod. This may also be the case for other Arctic or sub-Arctic gadids, such as walleye pollock (*Gadus chalcogrammus*), Pacific tomcod (*Microgadus proximus*), Arctic cod (*Arctogadus glacialis*), saffron cod (*Eleginus gracilis*), and Greenland cod (*Gadus ogac*).

Given the likelihood that Arctic gadids have a high dependence on acoustic signals and cues during their winter spawning, the spatio-temporal variations in Arctic gadids within Canada's Arctic can potentially be investigated using PAM and correlated with marine mammal distributions/activities (to better understand potential local predator–prey relationships and identify potential spawning grounds that may warrant more legislative protection for particular areas). This is increasingly important to do as Canada's Arctic is undergoing increasingly rapid changes, including receding summer sea-ice cover and an associated increase in human access to the region (Moore et al. 2012). Since polar cod, among other species, are often associated with sea-ice (Gradinger and Bluhm 2004), changes in the thickness and extent of sea-ice is a potential impact with poorly understood consequences (Bouchard et al. 2017, 2018). There is also the increased human access to the region due to climate change, which will lead to substantially increased levels of underwater noise primarily from increased vessel activity and other possible pollution—potentially impacting non-spawning fish at all depths and across whole regions. As an example, non-spawning polar cod have been shown to change their movement behaviour in response to ships and presumably ship noise (Ivanova et al. 2020). Such noise increases are particularly important in areas that typically have low ambient sound levels, such as the western Canadian Arctic where median ambient sound levels between 50 and 1000 Hz drop below 75 dB re 1 µPa over the winter months—several orders of magnitude lower than temperate regions (Insley et al. 2017).

The Northwest Passage is anticipated to be ice-free during the summer months by 2050 (Overland and Wang 2013; Hauser et al. 2018), leading to increasing concern among Arctic nations on how to conserve Arctic ecosystems from increasing anthropogenic impact. The collection of baseline data on the present ecology of Canada's Arctic has therefore become imperative as conservation strategies and marine spatial planning for the Northwest Passage are being formulated. While the introduction of in situ PAM systems for marine mammal monitoring have been successful in the western Canadian Arctic (see Halliday et al. 2018, 2019), no studies have investigated the sounds of Arctic marine fish. Notwithstanding, PAM techniques have been used successfully under ice to detect the sounds made by the freshwater gadoid species, burbot (*Lota lota*) (Cott et al. 2014). This study aims to (1) investigate the utility of PAM for monitoring gadids in the Arctic in areas where polar cod are expected to be present; (2) potentially identify the breeding season of cod, including any relationships with sea-ice concentration; and (3) provide the first insight into the potential temporal distribution of marine fish sounds recorded from two sites within the Inuvialuit Settlement Region (ISR) of Canada's western Arctic.

Materials and methods

Study area

Year-round underwater noise recordings were obtained using SM3M song meters (Wildlife Acoustics, Maynard, MD, USA), positioned approximately 8 km west of Sachs Harbour and 2.5 km southwest of Ulukhaktok (Fig. 1). These two locations were selected for their expected fish aggregations based on indigenous knowledge from the communities of Ulukhaktok and Sachs Harbour, as well as the differing seal populations between the two sites [since predation on polar cod by ringed seals far out-weighs predation by bearded seals (Crawford et al. 2015)]. Polar cod have also been detected nearer the surface within Franklin Bay in the Amundsen Gulf, which is also within the same geographic area (the Inuvialuit Settlement Region in Canada's NWT) (Benoit et al. 2008). The distance between the two sites was approximately 300 km. Both recorders were set at a 48 kHz sampling rate. The Sachs Harbour recorder had a duty cycle of 5 min recorded every 35 min (14% duty cycle) with gain set to + 18 dB, and the Ulukhaktok recorder had a duty cycle of 5 min recorded every 30 min (17% duty cycle) with gain set to + 12 dB. The gain setting for the Ulukhaktok recorder was lowered after the Sachs Harbour recorder showed no benefit to having a higher gain setting. Monitoring took place between 20 August 2015 and 8 July 2016 at Sachs Harbour, and between 12 October 2016 and 14 April 2017 at the Ulukhaktok site (due to power issues at the Ulukhaktok site). The water depths were 28.5 m and 30.5 m at the Sachs Harbour and Ulukhaktok sites, respectively, with the hydrophone deployed 3 m above the seafloor. These depths were selected to reduce the risk of the winter sea-ice coming in contact with the recorder and to improve the detection range of low-frequency fish sounds (since the wavelength of 100 Hz signal in water (− 1 °C) is approximately 14.43 m).

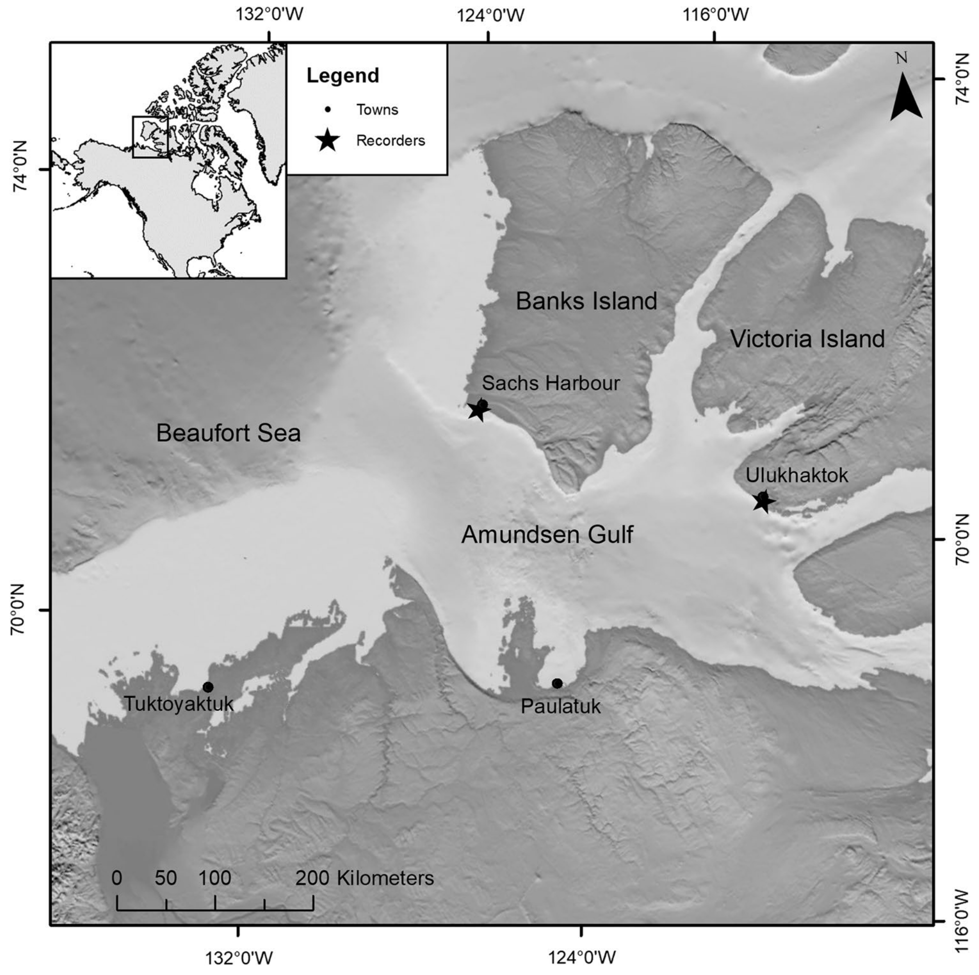


Fig. 1 Map of the study area showing the location of the two monitoring sites near Sachs Harbour and Ulukhaktok

Data analysis

Daily spectrograms were first generated using purpose-written scripts in MATLAB (MathWorks) to identify any potentially problematic interference from the SM3M recorders. After visually inspecting the spectrograms and ruling out contamination issues, the data were run though a custom written time–frequency energy-based detector in MATLAB to identify potential fish sounds. The detection algorithm calculated the 20th percentile background sound level within 50 Hz bandwidths (set between 50 and 2000 Hz), for every 2 s (with 50% overlap between time windows). It then flagged the time a signal exceeded 6 dB over that background sound level (i.e. a signal-to-noise (SNR) of 6 dB) within 1 or more bands for a duration between 0.08 and 0.35 s that holds 40% occupancy (i.e. 40% of data points inside a detection that exceeds that 6 dB SNR), producing a list of.WAV files containing a detection, as well as the start time with the.WAV file the detection occurred. While the use of detectors can substantially accelerate the data processing, the performance of the detector in this case was poor as it was confounded by the presence of ringed seal barks and bearded seal calls of overlapping spectral content. Machine learning or deep learning detectors were unable to be developed for this project as no training datasets were available due to a lack of Arctic fish sounds. As a result 100% of the data were manually analysed, and all detections were manually checked (by visually inspecting the spectrogram and audio playback) and verified, including all data containing no detections.

Once all individual fish detections were confirmed, they were manually annotated. The centre and peak frequencies (Hz), 90% bandwidth (Hz), duration (s) and burst rate per call were then measured using the measurement table function in Raven Pro for each individual vocalisation. The date and time of each vocalisation was also recorded, as well as the total number of detections per month from each site. To determine the presence of different vocalisation types, a cluster analysis was performed using k-means clustering in MATLAB. The k-means clustering partitions the spectral and temporal characteristics of each individual fish sound into k distinct clusters based on the distance to the centroid of each cluster, exposing natural patterns in the detections.

The variables used for the k-means clustering were centre and peak frequencies, 90% bandwidth and duration. Due to the low amplitude of some calls in relation to the background waveform, burst rate was unable to be accurately measured for 32% of fish sounds and was therefore not a parameter included in the cluster analysis.

Results

A total of 47 fish sounds were recorded from both sites over the monitoring period: seven of which were from the Sachs Harbour site and the remaining 40 from the Ulukhaktok site. Of those 47, only three were knocks (determined aurally as a distinctive *knocking* sound, with one being from Sachs Harbour and two from the Ulukhaktok site) while the rest were grunts (determined aurally as a distinctive *grunt* sound (six from Sachs Harbour and 38 from the Ulukhaktok site). The substantially higher number of fish sounds recorded at the Ulukhaktok site suggests a potential spatial difference in fish vocal activity within the ISR, although it is important to note the two sites were sampled over two different years.

Analyses revealed a seasonal shift in the detection of fish sounds. At the Sachs Harbour site, where data were analysed from August 2016 through July 2017, fish sounds were only detected during December [a total number of three (i.e. $n=3$)] and February ($n=4$) (Table 1). At the Ulukhaktok site, however, fish sounds were recorded from October through April (Fig. 2). The highest number of fish sounds at the Ulukhaktok site was recorded during January ($n=18$), when sea-ice concentration was highest (Fig. 2), while few differences in the total number of fish sounds were recorded between October ($n=4$), November ($n=3$), December ($n=4$), February ($n=4$), March ($n=2$) and April ($n=5$). No diurnal patterns in any of the sound types were seen (Fig. 3).

The cluster analysis revealed three clusters, based on the temporal and spectral characteristics of each fish sound (Fig. 4). A total of 31 sounds were labelled as Type 1 (represented as the blue cluster in Fig. 4), 11 sounds belonged to Type 2 (represented by the red cluster in Fig. 4) and 5 sounds were Type 3 (represented by the purple cluster in Fig. 4). The 90% bandwidth, peak frequency and centre frequency centroid points of each call type were 180, 168 and 142 Hz (Type 1); 218, 300 and 302 Hz (Type 2); and 448, 330 and 259 Hz (Type 3). Representative examples of spectrograms and power spectra for each call type are provided in Fig. 5, while the differences in spectral aspects are provided in Table 1. Type 1 calls were below 400 Hz, with 5 harmonics at 80, 120, 180, 220 and 310 Hz. Type 2 calls were above 200 Hz, with 5 harmonics between 250 and 500 Hz, while Type 3 calls were comprised of multiple harmonics spanning the widest bandwidth of approximately 420–520 Hz (Fig. 5). Type 1 and 3 were recorded at both sites, while Type 2 was only recorded at the Ulukhaktok site. The type 1 sound was recorded during October through April, while Type 2 was recorded from October through February and Type 3 was

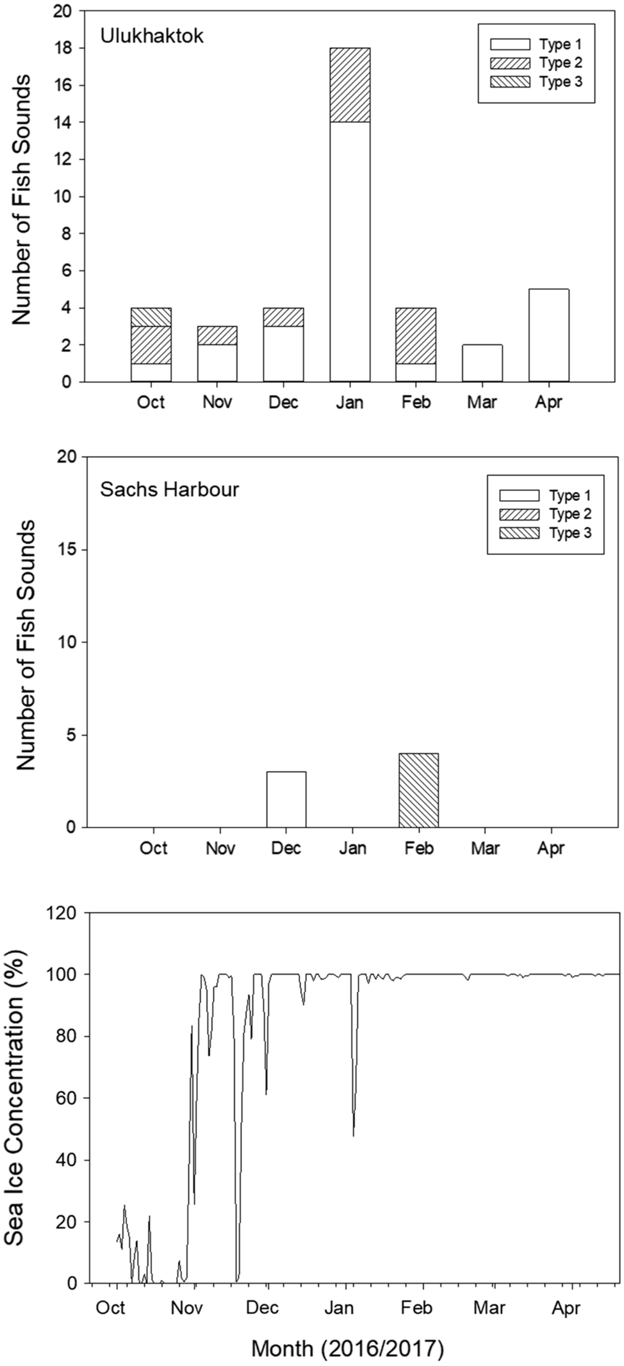


Fig. 2 Total number of fish calls recorded within each month at both sites (top and middle) and corresponding ice concentration (bottom) near Ulukhaktok. The ice concentration data were sourced from the Advanced Microwave Scanning Radiometer 2 (AMSR2) satellite sensor, obtained through the Physical Analysis of Remote Sensing and Images group at the University of Bremen, Bremen, Germany (Spreen et al. 2008)

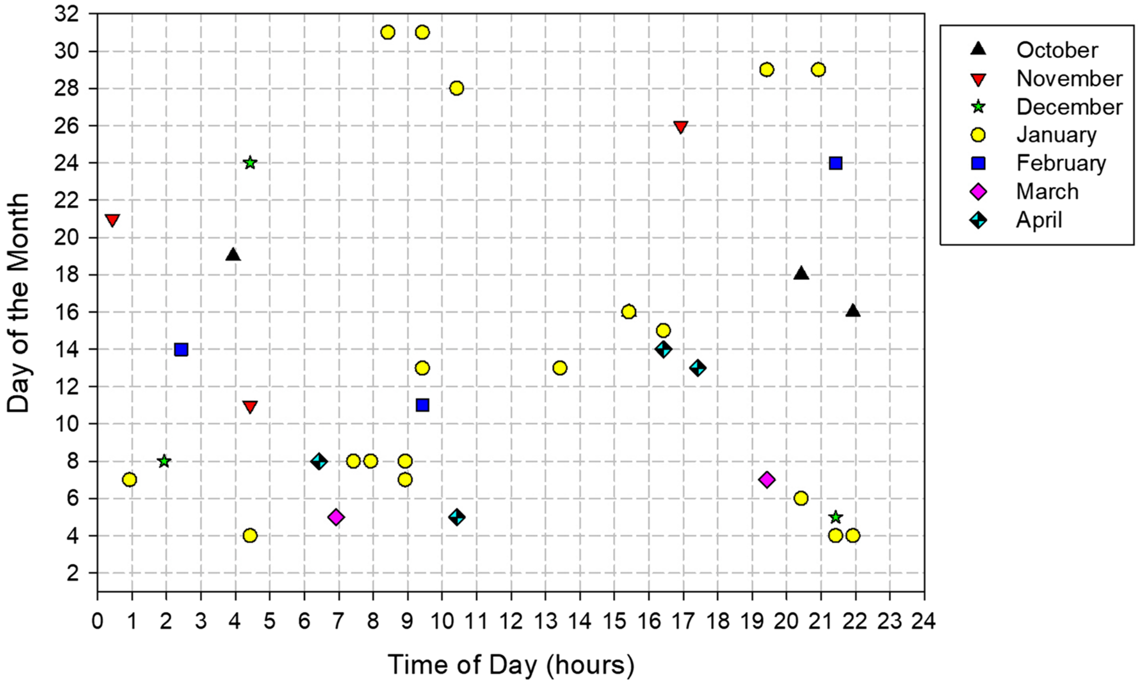


Fig. 3 Date and time of each recorded fish sound over the monitoring period

Table 1 Summary of the acoustic parameters (average ± SD), their recorded location and timing (month recorded) for each call type identified by the cluster analysis

Parameter	Call type		
	Type 1	Type 2	Type 3
Peak frequency (Hz)	152.8 ± 31.0^{a}	294.6 ± 65.1^{b}	266.6 ± 73.4^{b}
Centre frequency (Hz)	168.4 ± 45.7^{a}	300.4 ± 66.0^{b}	324.6 ± 49.3^{b}
90% bandwidth (Hz)	179.8 ± 66.9^{a}	228.3 ± 57.5^{b}	472.9 ± 44.3^{c}
Burst-duration (ms)	453 ± 185^{a}	357 ± 105^{a}	366 ± 22.7^{a}
90% duration (ms)	248 ± 148^{a}	200 ± 118^{a}	200 ± 122^{a}
Pulse rate per call	3–44	7–17	9*
Location	Sachs Harbour ($n = 3$) Ulukhaktok ($n = 28$)	Ulukhaktok ($n = 11$)	Sachs Harbour ($n = 4$) Ulukhaktok ($n = 1$)
Month	October ($n = 1$) November ($n = 2$) December ($n = 6$) January ($n = 14$) February ($n = 1$) March ($n = 2$) April ($n = 5$)	October ($n = 2$) November ($n = 1$) December ($n = 1$) January ($n = 4$) February ($n = 3$)	October ($n = 1$) February ($n = 4$)

Superscripts identify which call type statistically differ within each parameter (Holm-Sidak test, $p < 0.05$)

*Burst-rate only measureable for a single call due to poor signal-to-noise ratio preventing accurate detection of peaks in the waveform above ambient

recorded only during October (at the Ulukhaktok site) and February (at the Sachs Harbour site). No diurnal patterns of the three sound types were identified.

Discussion

Passive acoustic monitoring (PAM) is a widely used tool for tracking the presence and absence of soniferous marine organisms. However, in the Arctic, this technique has been applied to only marine mammals, with no known accounts of recorded marine fish activity. Data analyses

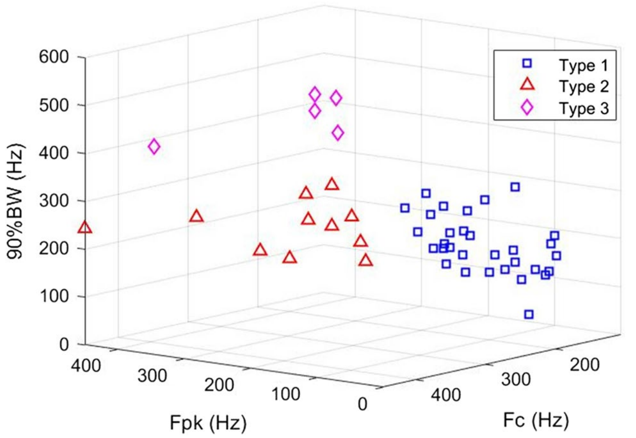


Fig. 4 *K*-means cluster analysis plot showing three clusters (referred to herein as Type 1 through 3) and corresponding 90% bandwidth (BW), peak (Fpk) and centre (Fc) frequencies of each sound

from this study have shown potential spatial differences in the overall detection counts as well as types of fish sounds. This either suggests a different distribution of fish species between the two locations (if each sound type is attributed to a different species); a spatial difference in the repertoire of a single species; or neither, with differences being attributed to the low sample size of calls recorded at the Sachs Harbour site. Over 700 species of fish are considered to be, or potentially be, soniferous and this includes fish species with Arctic distributions (Kaatz 2002; Rountree et al. 2006). The cod family Gadidae includes some of the more prolific soniferous species reported in the literature, some of which have Arctic distributions: Atlantic cod, Arctic cod, saffron cod, walleye pollock, Pacific tomcod, Greenland cod, polar cod, and the freshwater burbot. Of those, the Atlantic cod (Hernandez et al. 2013), polar cod (Riera et al. 2018a) and walleye pollock (Park et al. 1994; Riera et al. 2018b) are known to produce sounds, either from recordings made in the field (such as the Atlantic cod), captivity (such as the polar cod and walleye pollock), or both. Within the ISR, the known cod species include Arctic cod, polar cod, saffron cod and Greenland cod and all have been found around both sites in this study (Stephenson 2004; Renaud 2018). Several other fish species are found around the two monitoring sites, including Arctic char (*Salvelinus alpinus*) and Pacific herring (*Clupea pallasii*) (Stephenson 2004), both of which exhibit air movement sounds [herring: Wahlberg and Westerberg (2003); char: Bolgan et al. (2016)]. However, the data presented herein show no overlapping spectral and temporal characteristics of air movement, which are far higher frequency (between 1 and 4.1 kHz (Bolgan et al. 2016; Wahlberg and Westerberg 2003)).

Several types of sounds have been recorded from gadids, primarily described as grunts and knocks (Kasumyan 2008). The sounds produced by Atlantic cod have been well studied and overlap strongly with those of polar cod (Riera et al. 2018a). Frequency distributions of Atlantic and polar cod calls range between 36 and 851 Hz and 27 and 539 Hz, respectively (Riera et al. 2018a; Hernandez et al. 2013). Peak frequencies around 50 Hz and 103 Hz are known for Atlantic cod grunts with polar cod being around 107 Hz (Riera et al. 2018a). The fish calls found in this study fell into three clusters/types, with 90% bandwidth, peak frequency and centre frequency centroid points of 180, 168 and 142 Hz (Type 1); 218, 300 and 302 Hz (Type 2) and 448, 330 and 259 Hz (Type 3), respectively. All three types were highly likely to be produced by gadids, based on the harmonic components of the calls and presence of multiple pulses within each burst-call [that range between 3 and 44 pulses and typical of cod grunts (Brawn 1961; Hawkins 1993; Rowe and Hutchings 2006; Hernandez et al. 2013)]. Walleye pollock are known to produce sounds during mating with calls below 800 Hz (Park et al. 1994; Riera et al. 2018a). Bandwidths extending up towards 800 Hz were closest to the Type 3 call recorded at both sites, while Type 1 showed similarities with polar cod (peak frequencies between 59 and 234 Hz) calls recorded in captivity by Riera et al. (2018a). However, it is not possible to confirm the species responsible for these calls, although they are highly likely to be a cod, with the majority of the calls matching those of polar cod.

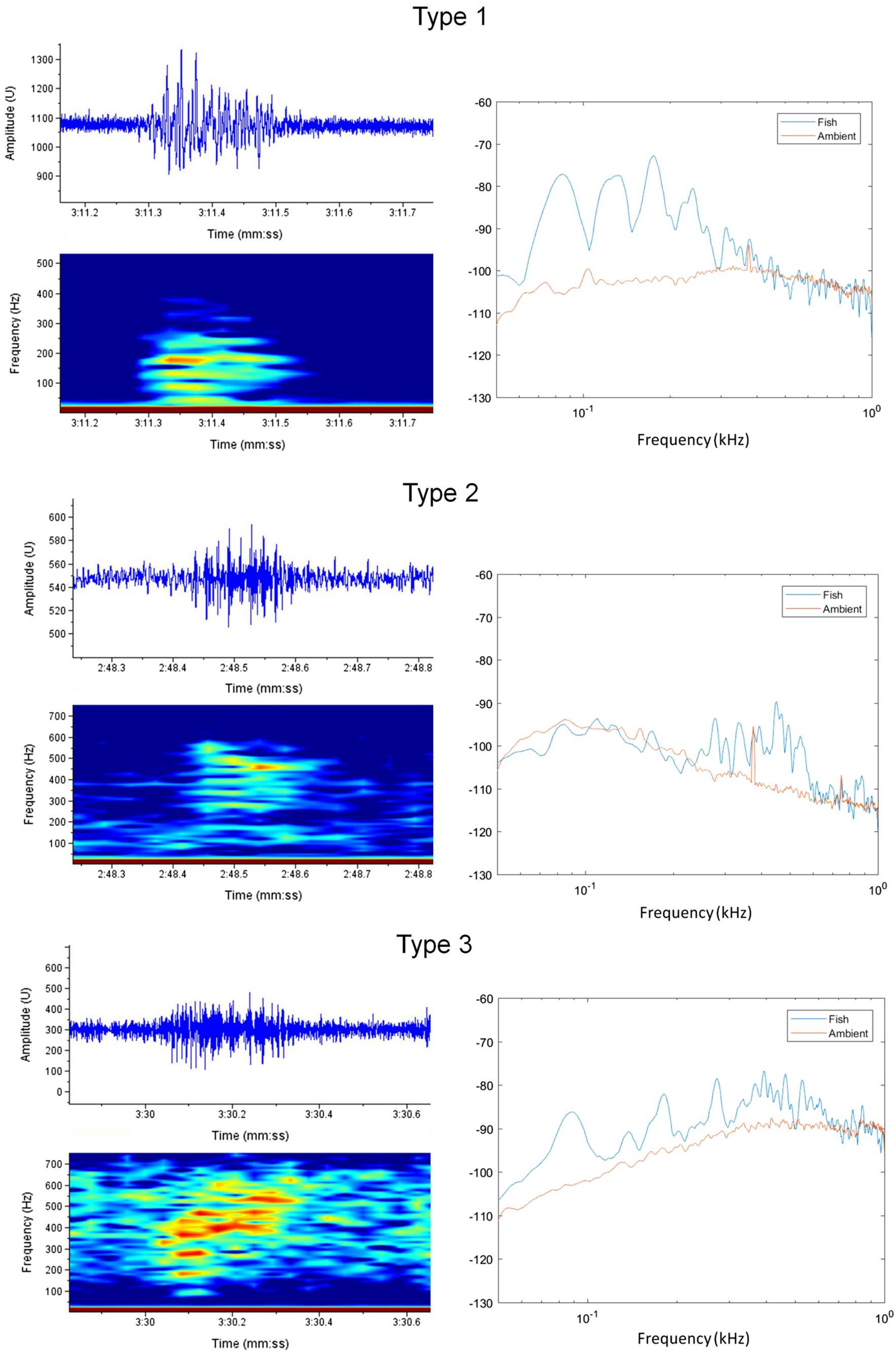
Polar cod and walleye pollock both have their mating seasons during the winter (Kessel et al. 2015). Fish typically vocalise most often during their mating seasons, as they coordinate spawning behaviours, compete for mates or locate conspecifics (Popper and Hawkins 2018). As such, call rates can be expected to peak during spawning. Evidence for which call types are from which species can possibly be obtained by quantifying the temporal variation of certain unidentified fish call rates over certain times of the year (Riera et al. 2018b). For this study, all calls were detected between October and April, with the highest detection rates occurring during peak ice concentration in January, which matches the spawning season of polar cod (Hop and Gjøsæter 2013; Kessel et al. 2015). Broken down into their clusters, the highest detection rates of Type 1 ($n = 14$) and Type 2 ($n = 4$) were during January, while the highest number of Type 3 calls were detected during February ($n = 4$) (Table 1). Since only Type 1 calls match the spectral and temporal characteristics of known polar cod calls, the timing of Type 1 calls during January may further suggest they are from polar cod. However, due to the low sample sizes and limited date range over which the data were collected (i.e. only data between October and April were collected from the Ulukhaktok site), any temporal patterns are preliminary. Furthermore, the reproductive behaviours of the other species inhabiting the study area are also poorly understood.

The detection range of the hydrophones for fish sounds is an important consideration for relying on PAM in studying fish spawning, and may be a factor in why fish calls were not detected more often (also important to note that fish may not be making sounds outside spawning to avoid detection by eavesdropping predators). Detection ranges of hydrophones for any biological signal is highly dynamic and dependent on the surrounding acoustic environment, weather conditions and the source level of the biological signal. While no data on the source levels of polar cod, or other Arctic gadids in the study area, are available, the Atlantic cod and haddock have source levels of approximately 127 and 124 dB re 1 μPa @ 1 m (between 22 and 88 Hz), respectively (Nordeide and Kjellsby 1999; Stanley et al. 2017). These low source levels mean the fish would have to be within a couple of hundred metres [based on the ambient sound level of 75 dB re 1μPa (Insley et al. 2017)], although that number is an approximate estimate based on a simple propagation loss equation (see Pine et al. 2014 for the equation used) and would continuously change. Polar cod form large winter aggregations at depth in the Amundsen Gulf (Benoit et al. 2014), with peak biomasses recorded during April below 140 m (Benoit et al. 2008) within Franklin Bay. Therefore, it may be that the paucity of fish calls in this study could be due to the detection range of the hydrophones being too limiting in these shallow waters to detect sounds from deep-water aggregations. This assumes, of course, that polar cod are quite vocal during spawning—perhaps a reasonable assumption based on the known vocal activity of Atlantic cod during spawning (Stanley et al. 2017) and their similar calls to polar cod (Riera et al. 2018a). Deployment of PAM systems in deeper water near areas where aggregations are known to occur would therefore be advantageous.

Notwithstanding, these data do show temporal variation in fish vocal activity that agree with known winter spawning in polar cod; thereby showing that PAM can provide the same potential insights into their distributions in the same way as for marine mammals. However, while PAM may presently provide some understanding of fish spawning in very remote regions, in order to gain a deeper understanding of fish presence and potential behaviours using PAM in the Arctic, the species responsible for each call type needs to be known. Assigning species to call types with an appropriate level of confidence is the next research step for PAM of fish in the western Canadian Arctic. The most widely used method for assigning sounds recording using PAM is by 'auditioning' fish in captivity and cross-correlating the known species-specific calls with those recorded in situ (Riera et al. 2017). However, acoustic measurements made in captive environments often present challenges in either the data processing (such as filtering out extraneous noise sources from pumps, water filters etc.) or actually encountering natural conditions under which fish would normally vocalise (i.e. would fish produce the same call in a hatchery during spawning when the caller and listener can see each other?). It would therefore be preferable to record the sounds of fish in their natural habitats rather than a laboratory. In situ techniques that can identify fish species have been recently developed that show good promise, such as sound source localisation coupled with cameras (Mouy et al. 2018). The use of red-lights and image processing techniques may also mean that these passive hydrophone/video arrays could be used over the Arctic winter with limited light.

One of the more interesting observations from these data is that Type 2 calls were not noted at the Sachs Harbour site. It is important to consider the possibility that the absence of Type 2 calls at the Sachs Harbour site was, at least in part, due to the poor sample size of calls (although the recording period was a full year compared to half a year at the Ulukhaktok site). Furthermore, substantially fewer calls were recorded overall at the Sachs Harbour site than at the Ulukhaktok site. In the Beaufort and Chukchi Seas, polar cod make up a higher percentage of ringed seal diets than in bearded seals, especially in pups (Crawford et al. 2015). Some overlap in the diets of bearded seals and ringed seals has been reported, although these two ice-associated species are ecologically separated in most aspects (Burns 1981; Reeves 2014). Bearded seals, ringed seals and beluga whales occur at both Sachs Harbour and Ulukhaktok, although far fewer ringed seals occur at Sachs Harbour than at Ulukhaktok (Halliday et al. 2018, 2019). This formed part of the reason why Ulukhaktok was selected as a monitoring site for this study. Recent PAM studies from the Ulukhaktok site show ringed seals to be most prevalent during January (Halliday et al. 2019), coinciding with a peak in fish detections at that site—a possible indication for higher polar cod abundance near Ulukhaktok than Sachs Harbour. At the Sachs Harbour site during the same period, ringed seals were far less common and instead bearded seal activity started during October, peaking between April and June (Halliday et al. 2019). No correlations between bearded seals and fish call rates from Halliday et al. (2018) and the current study were seen, with fish calls being very rare at the Sachs Harbour site (at least during 2015 and 2016). Therefore, the spatial differences in fish call rates between the Sachs Harbour and Ulukhaktok monitoring sites may be related to the spatial differences in seals between the monitoring sites—an observation that would be expected based on these two seals' diets.

The data presented in this study comprise the first analysis of fish calls from two PAM stations within Canada's western Arctic. The analyses reveal fish calls to be relatively rare, with only 47 calls being detected over both sites, despite the monitoring continuing for several months to a complete year.


Type 1
Amplitude (U)
1300
1200
1100
1000
900
Time (mm:ss)
3:11.2
3:11.3
3:11.4
3:11.5
3:11.6
3:11.7
Frequency (Hz)
500
400
300
200
100
Fish
Ambient
-60
-70
-80
-90
-100
-110
-120
-130
10^{-1}
10^{0}
Frequency (kHz)
Type 2
600
580
560
540
520
500
2:48.3
2:48.4
2:48.5
2:48.6
2:48.7
2:48.8
700
600
Type 3
0
3:30
3:30.2
3:30.4
3:30.6

◂**Fig. 5** Representative spectrograms, waveform and power spectra of each call type from the k-means cluster analysis. Spectra were calculated with 9974 sample Hamming window, 50% overlap and no time-averaging

However, fish calls were substantially more commonly identified near Ulukhaktok than at Sachs Harbour, and the peak in calls during January (where ice concentration is highest) coincides with expected polar cod spawning seasons. Based on the apparent reliance of polar cod (a known soniferous fish) and other cod species by ringed seals (Quakenbush et al. 2011; Chambellant et al. 2013), the higher number of fish calls detected at the Ulukhaktok monitoring site could be expected as ringed seal abundance during that time was much higher than at Sachs Harbour. The fact that fish sounds were detectable (with Type 1 calls being potentially from polar cod) and showed spatio-temporal variations that were somewhat expected based on literature indicates that PAM can be useful in monitoring fish populations the same way as for marine mammals. The long-term collection of acoustic data from various sites can therefore provide information on when fish spawn, what areas are important for fish spawning and which regions may require more protection. As species-specific calls of Arctic gadids become better understood, PAM is recommended as a standard tool in monitoring long-term trends. These data therefore provide an important step forward in illustrating the potential usefulness of PAM in Arctic science—particularly at a time when climate change is forcing Arctic nations to better prepare for ecological shifts and understand how such changes will impact certain predator/prey relationships.

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Compliance with ethical standards

Conflict of interest The authors have no conflicts of interest to declare.

Ethical approval This study did not require approval from any ethics committee of the University as fish were passively monitored within their natural habitats, with no human interference. Therefore, the study complied with all ethical standards required by the University.

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