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Passive acoustic monitoring reveals year-round marine mammal community composition off Tasiilaq, Southeast Greenland[a]

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ABSTRACT:
Climate-driven changes are affecting sea ice conditions off Tasiilaq, Southeast Greenland, with implications for marine mammal distributions. Knowledge about marine mammal presence, biodiversity, and community composition is key to effective conservation and management but is lacking, especially during winter months. Seasonal patterns of acoustic marine mammal presence were investigated relative to sea ice concentration at two recording sites between 2014 and 2018, with one (65.6°N, 37.4°W) or three years (65.5°N, 38.0°W) of passive acoustic recordings. Seven marine mammal species were recorded. Bearded seals were acoustically dominant during winter and spring, whereas sperm, humpback, and fin whales dominated during the sea ice-free summer and autumn. Narwhals, bowhead, and killer whales were recorded only rarely. Song-fragments of humpback whales and acoustic presence of fin whales in winter suggest mating-associated behavior taking place in the area. Ambient noise levels in 1/3-octave level bands (20, 63, 125, 500, 1000, and 4000 Hz), ranged between 75.6 to 105 dB re 1 μPa. This study provides multi-year insights into the coastal marine mammal community composition off Southeast Greenland and suggests that the Tasiilaq area provides suitable habitat for various marine mammal species year-round.

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I. INTRODUCTION

Located off Southeast Greenland, the Tasiilaq region is considered an area of "heightened ecological significance" providing critical habitat for endemic Arctic marine mammals and seasonally migrating cetaceans (AMAP/CAFF/SDWG, 2013). A total of 22 species of pinnipeds and cetaceans inhabit the waters of Greenland (Ugarte *et al.*, 2020), and 20 of these species have been sighted in or near the Tasiilaq region. However, knowledge on species diversity and on the spatial and temporal (seasonal and inter-annual) distributions of marine mammals in coastal Southeast Greenland are based on a handful of visual surveys (Heide-Jørgensen *et al.*, 2007; Boertmann *et al.*, 2009; Merkel *et al.*, 2010; Boertmann and Rosing-Asvid, 2014; Hansen *et al.*, 2019) and on subsistence hunting reports (e.g., Dietz *et al.*, 1994). These surveys and hunting reports are often strongly seasonally biased towards summer, reflecting the logistic constraints of accessing the area in winter. To date, year-round and multi-year data on the occurrence of marine mammals are lacking entirely for this critical ecological area off Southeast Greenland.

Passive acoustic monitoring (PAM) has become increasingly important to assess the distribution of acoustically active animals in remote (polar) areas and gain long-term insights into acoustic habitat and soundscape characteristics, especially in light of ongoing climatic changes (e.g., Davis *et al.*, 2020; Halliday *et al.*, 2020; Schall *et al.*, 2021). In this study, three years of PAM data were used to study intra- and inter-annual patterns in species diversity, community composition, and spatio-temporal distribution of marine mammals in the coastal waters off Southeast Greenland. Biodiversity measures were applied to explore the relationship between the acoustic marine mammal community composition and sea ice concentration.

Southeast Greenland has already lost a third of its winter sea ice cover, and the number of ice-free summer periods is increasing (Kern *et al.*, 2010; Onarheim *et al.*, 2018; Stroeve and Notz, 2018). The ecological consequences of sea ice loss are diverse and complex (e.g., Lannuzel *et al.*, 2020), including increased primary production (e.g., Lewis *et al.*, 2020), as well as poleward distributional shifts in

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species (e.g., Fossheim *et al.*, 2015; Davis *et al.*, 2020; Ershova *et al.*, 2021). For both marine mammals endemic to the Arctic and seasonally migrating species, habitat loss and changes in food availability drive northward distributional and temporal shifts in the occurrence on feeding grounds, with potential fitness implications (Kovacs *et al.*, 2011; Laidre *et al.*, 2015; Ramp *et al.*, 2015).

Distributional shifts of seasonally migrating baleen whales are increasingly reported for the (sub-)Arctic Ocean (for a review, see Moore *et al.*, 2019). In the Western North Atlantic Ocean, acoustic presence of sei (*Balaenoptera borealis*), fin (*B. physalus*), and blue whales (*B. musculus*) significantly increased in Davis Strait, indicating a northward distributional shift from the North American continental shelf within just one decade (Davis *et al.*, 2020). Blue whales seem to prolong their occurrence in Fram Strait by arriving almost a month earlier (mid-June) in 2015–2018 compared to 2008–2014 (Ahonen *et al.*, 2021). Similarly, sei whales were historically only occasionally observed north of ∼72°N, but recently, they were reported in Fram Strait (∼79°N) (Nieukirk *et al.*, 2020). Furthermore, the distribution of the North Atlantic right whale (*Eubalaena glacialis*) seems to have shifted to the northwest of their historic offshore whaling ground off South Greenland (Mellinger *et al.*, 2011). Moreover, along the continental shelf off Southeast Greenland, fin and humpback whales (*Megaptera novaeangliae*) are increasing in abundance, likely caused by progressing sea ice loss and changing prey distribution related to increasing sea surface temperatures (Jansen *et al.*, 2016; Hansen *et al.*, 2019). Spatial and temporal shifts in distribution of seasonally migrating marine species can affect local community compositions, potentially resulting in increased resource competition with endemic Arctic species (Kovacs *et al.*, 2011; Laidre *et al.*, 2015).

The ecological consequences of sea ice decline and ocean warming in lower Arctic regions such as the Tasiilaq region might reflect future scenarios for higher Arctic regions. Therefore, baseline information on the spatio-temporal distribution and local diversity of marine mammal species is crucial to observe, understand, and monitor shifts in species distribution, community composition, and ecosystem changes.

II. MATERIAL AND METHODS

A. Data collection

Between August 2014 and September 2018 AURAL-M2 recorders (Multi-Électronique, MTE, IN., Canada) were deployed at two sites off the coast of Tasiilaq (former Ammassalik), Southeast Greenland (Fig. 1). The first recording site was located close to the entry of the Sermilik fjord (hereinafter referred to as "SER"; 65.49°N, 38.02°W). The second recording site was located at the entry of Ammassalik fjord close to the village Kulusuk (hereinafter referred to as "KUL"; 65.59°N, 37.40°W). The distance between the recording sites was approximately 30 km. The SER recorders were deployed at a depth of 260 m (water depth: 276 m) and the KUL recorders were moored at 248 m depth (water depth: 338 m).

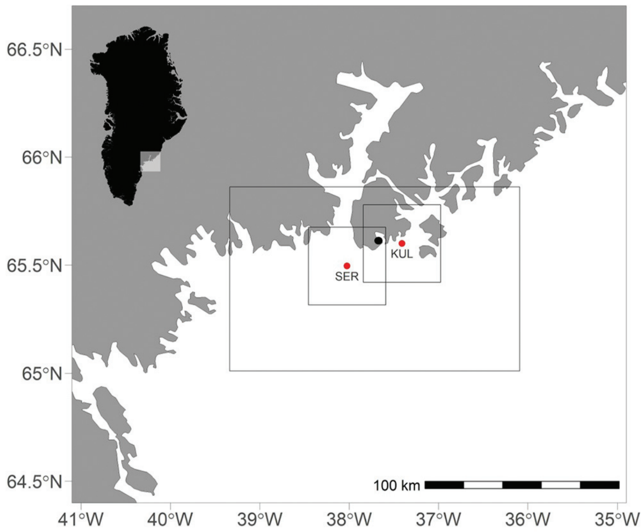

FIG. 1. The study area off Tasiilaq, Southeast Greenland. The red dots mark the recorder position SER (65.49°N, 38.02°W, Sermilik) and KUL (65.59°N, 37.40°W, Kulusuk). The black dot marks the town Tasiilaq. The rectangles around the recorders indicate the areas over which the daily sea ice concentration was averaged (40 × 40 km and 95 × 150 km).

At site SER, data were collected over three years from August 2014 to August 2015 (360 days) and from September 2016 to September 2018 (736 days). At recording site KUL, approximately one year (368 days) of recordings was collected from September 2016 to September 2017 (Table I). The recorders had a sampling rate of 32 768 Hz (effective frequency range: 10–16 384 Hz), 16-bit resolution, and a system peak clipping level of 151 dB re 1 μPa. The hydrophones (HTI-96-Min) had a sensitivity of -165 dB re 1 V/μPa with a flat frequency response from 2 Hz to 30 kHz (High Tech Inc., Long Beach, MS). The recorders were set to sample 30 consecutive minutes every four hours in the 2016/17 deployments and 30 consecutive minutes every two hours during all other deployment years giving a total of 3 and 6 h recorded per day, respectively (see also Table I for details).

A total of 35.3% of days (i.e., 517.4 days corresponding to 2783.5 h) of the overall recorded passive acoustic data (corresponding to 1463.8 days) were analyzed for the daily acoustic presence of marine mammal species (Table I).

Four recorders that were deployed could not be used for data analysis for various reasons and were omitted from the analysis here: SER-2015/16 and KUL-2014/15 ran out of battery and only recorded during a part of the deployment period. KUL-2015/16 showed irregularities in the duty cycle due to an unknown technical failure of the instrument, and KUL-2017/18 was lost, probably to an iceberg.

B. Daily acoustic marine mammal presence

Five-minute-long spectrograms were visually and aurally screened by a trained human operator to assess the daily acoustic presence of marine mammal species, using Raven Pro 1.5.0 (Hanning-window, 50% overlap, gray-scale; Bioacoustics Research Program 2014, Cornell Laboratory of

TABLE I. Overview of the analyzed acoustic data recorded by the AURAL-M2 acoustic recorders deployed off Tasiilaq. All recorders were set to a sampling rate of 32 768 Hz, 16-bit resolution, and preamplifier gain of 20 dB. SER, Sermilik; KUL, Kulusuk.

						Analyzed		
Recording site	Deployed years	Recording period	Duty cycle (min/min)	Days recorded	Analyzing scheme	Days	Hours	Proportion of data
SER	2014/15	27.08.2014 – 21.08.2015	30/120	359.4	Every 7th day	52	312	14.5%
(65.49 °N	2016/17	03.09.2016 – 15.09.2017	30/240	378	Every 7th day	54	162	14.3%
38.02 °W)	2017/18	19.09.2017 – 12.09.2018	30/120	358.4	Every day	358.4	2150.5	100%
KUL	2016/17	03.09.2016 – 05.09.2017	30/240	368	Every 7th day	53	159	14.4%
(65.59 °N								
37.40 °W)								

Ornithology). Only signals which were clearly distinguishable over ambient noise were considered. In this study, "daily acoustic presence" is defined to mean that at least one distinct signature (i.e., one call) attributed to a specific species or sound source was detected during the respective recording day that was analyzed.

For recordings of SER-2017/18, every recorded day was analyzed for marine mammal daily acoustic presence, while every seventh day was analyzed for SER-2014/15, SER-2015/16, and KUL-2016/17 (see Table I).

Detected call types and vocalizations were assigned to species level wherever possible based on species-specific call type characteristics (such as duration, frequency range, spectrographic shape, inter-call intervals, or complexity of songs) described in the literature, such as species-specific trills, moans, or sweeps for bearded seals (*Erignathus barbatus*) (Risch *et al.*, 2007), low-frequency clicks, buzzes, and pulsed calls for narwhals (*Monodon monoceros*) (e.g., Stafford *et al.*, 2012a; Ahonen *et al.*, 2019), regular, slow clicks and creaks emitted by sperm whales (*Physeter macrocephalus*) (e.g., Goold and Jones, 1995; Madsen *et al.*, 2002), and killer whale (*Orcinus orca*) pulsed calls and whistles (e.g., Deecke *et al.*, 2011). Furthermore, the acoustic presence of baleen whales was determined based on the 20 and 130 Hz calls of fin whales (e.g., Simon *et al.*, 2010), species-specific non-patterned calls, call sequences, and song fragments of humpback whales (e.g., Huang *et al.*, 2016; Kowarski *et al.*, 2019), and bowhead whale (*Balaena mysticetus*) simpler call sequences (e.g., Stafford *et al.*, 2012b). Given the similarities in humpback and bowhead whale vocalizations (overlapping frequency range, similar calling structure, and acoustic behavior, including annual changing songs and singing through winter) (e.g., Payne and McVay, 1971; Ljungblad *et al.*, 1982; Herman, 2017; Stafford *et al.*, 2018), we defined humpback whales as acoustically present when a detected call sequence was considered complex (i.e., call sequences consisting of three or more call types), whereas bowhead whales were considered present when the call sequence was simpler (i.e., call sequences consisting of one to two call types). Additionally, online sound databases were used to compare detected species-specific sound signals aurally: NOAA fisheries Sounds in the Ocean (2021), Discovery of Sound in the Sea (2021), and Voices in the Sea (2021).

Recordings were reviewed in a three-stage audio-visual screening process. First, the full frequency spectrum (10–16 384 Hz) was analyzed to capture higher frequency signals (fast Fourier transform, FFT: 8192, time resolution: 0.25 s, frequency resolution: 4 Hz, overlap: 50%). Secondly, the frequency range from 10 to 4000 Hz was screened for signals produced by seals and baleen whales (FFT: 8192, overlap: 50%). Finally, the spectrogram was screened for low-frequency signals using a frequency range from 10 to 500 Hz (FFT: 12 032, time resolution: 0.367 s, frequency resolution: 2.72 Hz, overlap: 50%). For each stage, these settings were kept constant throughout the screening process. If necessary, individual signals were examined for species identification by zooming into the spectrogram and optimizing the spectral display of the signal by adjusting the settings (brightness, contrast, and FFT).

Unidentified biological sound signals were classified into broader groups: unidentified toothed whales (UTW) and unidentified baleen whales (UBW). UTW signals included whistles, pulsed calls, and clicks of toothed whales that could not be assigned to species level. UBW signals mainly contain lower frequency sounds ($<$700 Hz) that could not be attributed to a species with certainty. UBW sounds were classified into sub-categories, based on the aural and visual appearance.

C. Acoustic community composition

We quantified the acoustic marine mammal diversity off Tasiilaq by estimating the monthly effective number of (acoustically active) species (ENS) for every recording period (following Van Opzeeland and Hillebrand, 2020). ENS is an index number of species within a community and provides the true species diversity relative to evenness: As long as all species are equally common, ENS reflects the total number of species in the community; when evenness decreases, so does ENS. However, the decrease is disproportional as rare species only account for a fraction and ENS is primarily influenced by common species. ENS is an ideal measure of diversity given that it is robust to fluctuations in sampling effort or sudden changes in species diversity (Chase and Knight, 2013). Although our data do not contain information on precise species abundance, the relative acoustic presence of species (the sum of days in a month a species was acoustically present divided by the number of days analyzed per month) can be used as a pseudo species abundance (see also Van Opzeeland and Hillebrand, 2020). Thereby, we assume that in a large population the probability of detecting an acoustically active individual is higher and that a larger population has a more consistent acoustic activity, leading to more days with acoustic presence compared to a small population (Van Opzeeland and Hillebrand, 2020). Additionally, the net change in acoustic species richness, as well as considering species identity, was calculated from month to month (Hillebrand *et al.*, 2018; Van Opzeeland and Hillebrand, 2020).

D. Ambient noise level metrics

To assess (relative) trends of ambient noise levels within the communication range of the detected marine mammal species off Tasiilaq, four 1/3-octave levels (TOL) bands centered at 20 Hz (range: 17–22 Hz), 500 Hz (445–561 Hz), 1000 Hz (890–1122 Hz), and 4000 Hz (3563–4489 Hz) were investigated. These bands were selected as they reflect (parts of) the communication range of the species detected in this study (Mellinger *et al.*, 2007; Southall *et al.*, 2008; Erbe *et al.*, 2017). Additionally, background noise levels were assessed within the 63 Hz (55–70 Hz) and 125 Hz (111–140 Hz) TOL bands, according to the recommendations of the Marine Strategy Framework Directive (Van der Graaf *et al.*, 2012). In this study, we use the term "ambient noise" to comprise all recorded sounds, including natural and anthropogenic sounds as well as acoustic self-noise, which is in addition to the ISO (2017) definition of "ambient noise" (ISO 18405:2017, 3.1.5.11) because not all TOL bands analyzed in the present study contained acoustic self-noise (ISO 18405:2017, 3.1.5.10).

For these six TOL bands, received levels were measured over 60 s time intervals using the Noise Band Monitor (filter: Butterworth; filter order: 5) of the software PAMGUARD 1.15.15. Received levels (dB re 1 μPa) were calculated using factory calibration settings of the Aural-M2 recorders, i.e., system sensitivity: -164.1 dB re 1 V/μPa; peak to peak voltage range: ±2 V; preamplifier gain: 20 dB. For each TOL, the daily median sound pressure levels (SPL) were computed, as well as mean, median, 5% percentile, and 95% percentile of the SPLs for each recording period and site.

E. Sea ice concentration data

The daily sea ice concentration (SIC) was provided in a grid resolution of 3.125 × 3.125 km on a polar stereographic grid for South Greenland and obtained from the University of Bremen (Spreen *et al.*, 2008). The daily SIC was spatially averaged for three areas at the recording sites (see Fig. 1) using the R package "raster" by averaging over all pixels within and touched by the defined area boundaries (Hijmans, 2020; R 3.5.2, The R Foundation for Statistical Computing).

The size of the areas over which the daily SIC was averaged, was based on estimated detection ranges of the sounds produced by marine mammals. To our knowledge, there is no published information on local sound propagation characteristics or sound propagation modeling results available for the Tasiilaq region. We used previously published detection ranges for species from other (Arctic) locations (e.g., Cleator and Stirling, 1990; Madsen *et al.*, 2002; Stafford *et al.*, 2007; Ahonen *et al.*, 2021), although detection ranges may differ with site characteristics (such as oceanographic conditions, sea ice cover, bathymetry, ambient noise, and season) (e.g., Au and Hastings, 2008). Bearded seal trills and sperm whale echolocation clicks were assumed to propagate less than 20 km (Cleator and Stirling, 1990; Madsen *et al.*, 2002). Surmising similar and shorter propagation distances for other seal and toothed whale species, an area around the recording site with the size of 40 × 40 km was chosen. The low-frequency calls of baleen whales can propagate more than 100 km in deep water (Stafford *et al.*, 2007; Ahonen *et al.*, 2021). However, in shelf regions, the propagation range is assumed to be shorter, in particular when only distinct individual calls are considered. For bowhead whale calls in the Beaufort Sea, detection ranges were estimated to range up to 35 km (Bonnel *et al.*, 2014). In Fram Strait, close to the East Greenland shelf, the propagation distance for blue and fin whales was estimated to range between 30 and 60 km (Ahonen *et al.*, 2021). Therefore, we chose to average the daily sea ice concentration for a second larger area measuring 95 × 150 km, spanning both recording sites (Fig. 1) to represent the sea ice conditions vocalizing baleen whales recorded off Tasiilaq are likely to experience. Thereby, the southern, western, and eastern box boundary is 60 km from the nearest recorder position. We excluded the main Sermilik fjord, assuming the ice concentration within the fjord does not affect the species presence outside the fjord and that the species within the fjord are not acoustically detectable at the recording site SER.

Given the lower latitude of the Tasiilaq region and its lower sea ice concentrations compared to higher Arctic regions, we used SIC thresholds of $\leq$15% and $\geq$45% for this study to reflect open water and heavier sea ice conditions, respectively (following Laidre *et al.*, 2012). The average daily SIC is calculated as 7-day daily moving mean for all three SIC-area-boxes.

III. RESULTS

PAM off Southeast Greenland revealed the acoustic presence of three marine mammal species endemic to Arctic waters: bearded seals, narwhals, and bowhead whales. Further, four seasonally migrating cetaceans were acoustically present: killer, sperm, humpback, and fin whales. Bearded seals, sperm, humpback, and fin whales showed a strong seasonality in their acoustic presence linked to the seasonal SIC in the study area (Fig. 2). No seasonal trend was evident for narwhals, killer, and bowhead whales, due to their rare detections. In addition, several further (presumably) cetacean sounds were recorded, that could not be identified to species level with certainty.

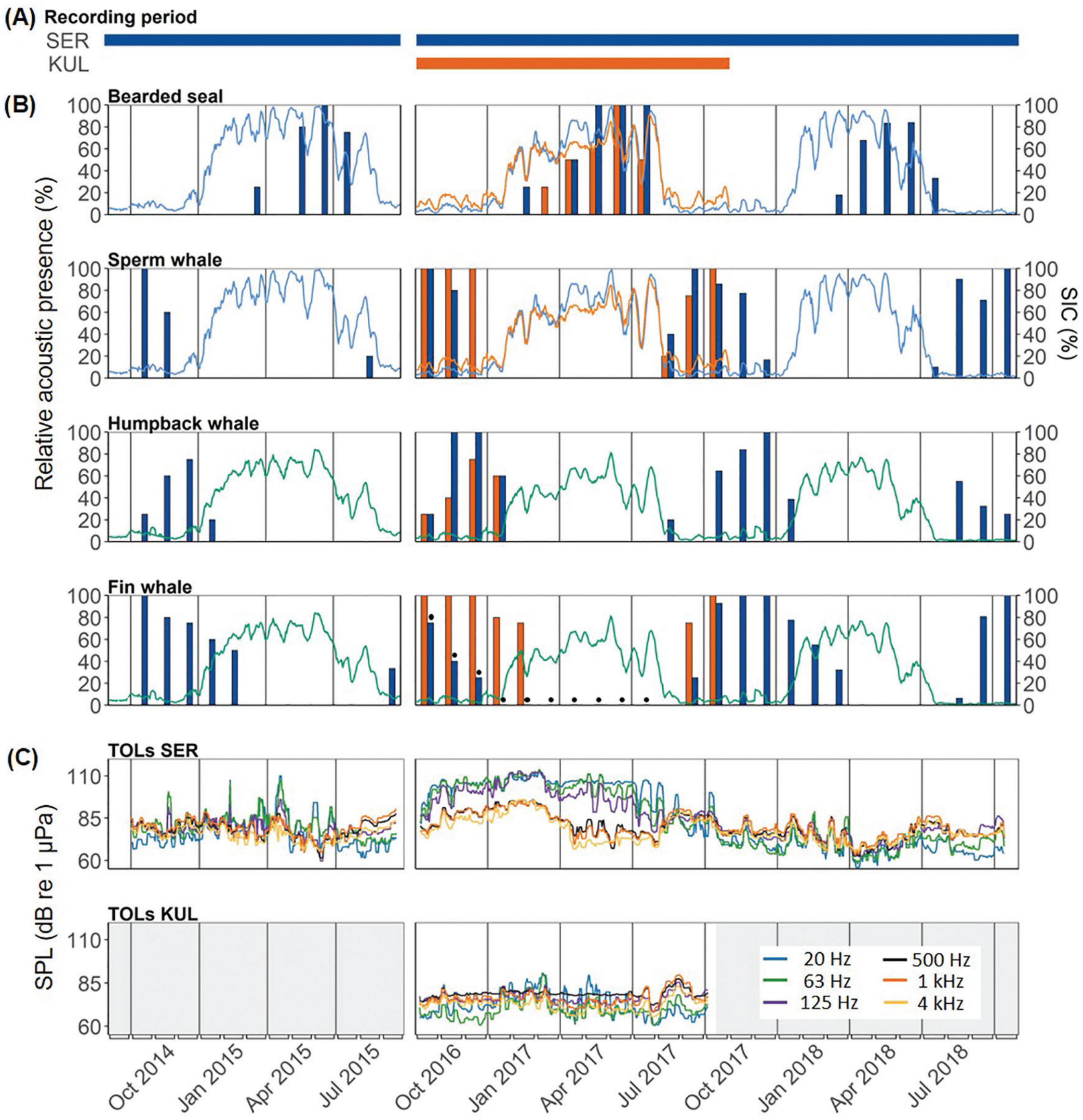

FIG. 2. (A) Recording periods analyzed in this study for site SER (blue horizontal bar) and site KUL (orange horizontal bar). (B) Monthly relative acoustic presence (proportion of days with acoustic presence per month on days analyzed, left *y*-axis) per species and recording site (vertical bars) relative to the SIC given as 7-day daily moving means (right *y*-axis). The blue and the orange line represent the SIC within 40 × 40 km boxes around site SER and site KUL, respectively, for the assumed propagation distance of sounds produced by the species. The SIC spanning the larger Tasiilaq area (95 × 150 km) is represented as the green line, after the assumed propagation distance of sounds produced by baleen whales. Black dots (in the fin whale panel) indicate times of intense mooring-generated strumming potentially masking fin whale 20 Hz pulses. Note that narwhals, killer, and bowhead whales are not represented here, due to their low acoustic presence. (C) SPLs (in dB re 1 μPa) within six 1/3-octave level (TOL) bands as a 7-day daily moving median. Gray shaded areas mark periods that were not analyzed (KUL-2014/15) or of lacking data (KUL-2017/18). The seasons are indicated by the vertical lines: autumn, September–November; winter, December–February; spring, March–May; summer, June–August.

A. Arctic marine mammal species

Bearded seals were acoustically present from January through June, following sea ice formation, with a peak in acoustic presence in May at both recording sites and all years [Fig. 2(b); Information on the total amount of days with species-specific acoustic presence per recording period is given in the supplementary material.[1]] Acoustic activity continued during sea ice retreat and ceased in June when the SIC was around 45%. Overall, 6% of days with bearded seal acoustic presence had open water conditions (≤15% SIC), while 73% of days with bearded seal acoustic presence exhibited heavier SICs (≥45% SIC) up to full sea ice coverage.

Narwhals were acoustically present only at site SER and were detected on two days in spring: on 20 May 2015 and 1 April 2017 when SICs were 86% and 89%, respectively.

Vocalizations (simpler call sequences) of bowhead whales were detected on three days in total. At site SER, bowhead whales were acoustically present on 21 January 2017 and 9 March 2018, when SIC were 30% and 61%, respectively. At KUL, acoustic presence was detected on 26 November 2016 when the SIC reached 45%.

B. Seasonally migrating marine mammal species

Killer whales were acoustically present only at site SER on 23 September 2017 during open water conditions.

Sperm whales were acoustically present from July to October or November, with a peak in acoustic presence in late summer and early autumn (August or September) at both recording sites and all years [Fig. 2(b)]. The acoustic presence of sperm whales slightly decreased in October 2016 at site SER but remained constant at site KUL. At site SER sperm whale acoustic presence was considerably lower in 2014/15 compared to other years. Overall, sperm whales appeared to prefer open water conditions [with 96% of days with sperm whale acoustic presence associated with open water conditions, Fig. 2(b)] but were occasionally acoustically present at SIC up to 37%. The acoustic presence of sperm whales ceased about one month before sea ice formation.

Humpback whales were acoustically present from July to late December and their acoustic presence peaked in October and November in all years and at both recording sites [Fig. 2(b)]. In summer, mainly non-song social calls, including calls associated with foraging, were detected. However, humpback whales were acoustically absent or rarely acoustically present during the summer months. Starting in September/October, song fragments remained present until December. (Vocalizing) humpback whales appeared to prefer open-water conditions [with 92% of days with humpback whale acoustic presence occurring during open water conditions; Fig. 2(b)]. Occasionally, however, humpback whales were acoustically present at SIC up to 45% (4% of days with humpback whale acoustic presence) and up to 75% (3% of days with humpback whale acoustic presence). Despite careful and conservative assessment of humpback whale acoustic presence, the possibility of accidentally misclassifying bowhead whale sounds as humpback whale sounds exists, given similarities in their vocal characteristics.

Of all species, fin whales were acoustically present during most days, displaying a pronounced seasonality in their acoustic presence from June to the end of February with a peak in autumn [Fig. 2(b)]. Their acoustic presence per recording period was similarly distributed over both recording sites and years, except for SER-2016/17, in which mooring-generated strumming noise was present below 100 Hz [Fig. 2(b)]. For fin whales, 75% of days with acoustic presence were during open water conditions [Fig. 2(b)]. Only 15% of days with fin whale acoustic presence were characterized by heavier sea ice concentrations (up to 78%).

C. Unidentified biological sound signals

The recordings made off Tasiilaq contained several signal types that could not be assigned to species-level with certainty and hence, were summarized within two groups: unknown toothed whale sounds (UTW) and unknown baleen whale sounds (UBW). Information on the total relative species-specific acoustic presence per recording period for the unidentified biological sound signals, on temporal patterns in their occurrence, and spectrographic examples are given in the supplementary material.[1]

The group UTW consists of clicks and whistles. The occurrence of UTW signals mainly peaked in autumn at both recording sites, but occasionally occurred in other seasons.

The group UBW includes a variety of sound signals, mainly at frequencies below 700 Hz, that were categorized into five sub-categories (C1–C5) based on their visual and aural characteristics. For calls of categories C1 (faint tonal calling pattern) and C2 (pulsed frequency-modulated downsweeps), a seasonal pattern in their presence was similar to humpback whales and fin whales, respectively. The presence of sounds categorized as C3 (simple sequences of short pulses) did not show a clear seasonal pattern, but these were detected in different seasons during the analyzed recording period. Calls summarized as C4 (frequency modulated arched downsweeps) infrequently occurred in autumn and winter months from 2016 to 2018 and occasionally in combination with calls of category C5 (low-frequency moans and grunts). C5 calls occurred during all seasons, but only at site SER. All other UBW sub-categories were detected at both recording sites.

D. Trends in ambient noise levels

Overall, the abiotic and anthropogenic components of the marine soundscape off Tasiilaq included sounds from sea ice and ships. Moreover, the recordings contained electronic self-noise, as well as mooring generated strumming (<100 Hz) and shackle-noise (i.e., broadband impact sounds).

The annual mean SPLs for each recording period and site ranged from 75.6 to 105 dB re 1 μPa across all TOL bands (Table II). The lowest annual mean SPLs were measured in SER-2017/18 and KUL-2016/17 across all TOL bands, while SER-2016/17 showed the highest annual mean SPLs, mainly reflecting intensive mooring-generated strumming and shackle-noise. Among the TOL bands analyzed here, the highest mean SPLs were always measured in the 20 Hz or 63 Hz TOL band.

No clear seasonal pattern reflecting species' acoustic presence was discernable in the TOLs, recording periods, and recording sites. All TOLs exhibit high intra-annual variability, with KUL-2016/17 and SER-2017/18 showing the lowest daily median SPLs, especially in the 20 and 63 Hz bands [Fig. 2(c), Table II]. Within the recording periods SER-2014/15, SER-2017/18, and KUL-2016/17, the daily median SPLs were similar for all TOLs [Fig. 2(c)]. Mooring-generated strumming noise persisted occasionally in SER-2014/15 and for almost the entire recording period of SER-2016/17. Furthermore, the SER-2016/17 data also contained shackle-noise from October to March.

TABLE II. Annual metrics of the SPL (dB re 1 μPa) of the 1/3-octave level (TOL) bands for each recording period and site.

		TOL bands					
	Recorder	20 Hz	63 Hz	125 Hz	500 Hz	1 kHz	4 kHz
Mean	SER-2014/15	96.1	96.8	95.2	82.9	83.2	79.2
	SER-2016/17	105	103.8	101.3	87.9	87.4	85.6
	SER-2017/18	77.8	84.3	83.4	79.2	80.3	77.8
	KUL-2016/17	83.7	80.6	81	80.7	79.4	75.6
Median	SER-2014/15	74.4	79.5	79.0	79.5	80.8	76.3
	SER-2016/17	105.0	100.9	95.7	85.0	84.9	81.2
	SER-2017/18	68.3	70.3	75.9	75.8	77.1	74.9
	KUL-2016/17	71.3	69.2	76.0	78.8	76.1	72.7
5% percentile	SER-2014/15	57.0	63.6	67.1	64.5	65.8	66.6
	SER-2016/17	70.9	75.8	79.1	71.0	69.9	67.0
	SER-2017/18	54.4	57.5	62.7	62.5	64.3	65.6
	KUL-2016/17	57.9	60.7	71.3	74.2	69.2	65.8
95% percentile	SER-2014/15	112.0	112.2	112.0	92.0	91.4	87.8
	SER-2016/17	111.8	112.8	112.4	96.8	95.9	96.4
	SER-2017/18	86.9	95.5	90.7	87.4	88.9	86.3
	KUL-2016/17	97.1	92.6	88.6	86.9	88.0	84.0

The strumming and shackle-noise are reflected by high SPLs in all TOL bands of SER-2016/17 [Fig. 2(c)].

E. Acoustic community composition

Overall, seven marine mammal species were identified to be acoustically present at site SER and five at site KUL between August 2014 and September 2018. A trend in seasonal variation in the monthly acoustic ENS can be distinguished at both recording sites (Fig. 3, black dots, gray line), particularly at the multi-year recording site SER. The monthly acoustic ENS at both recording sites shows a recurring peak in the autumn, having primarily two to three acoustically active species present, reflecting that the acoustic community is most diverse in autumn. Generally, acoustic marine mammal diversity was highest at both sites during open water conditions and was lowest during sea ice-covered periods when primarily bearded seals were present. The net change of acoustic species richness was fairly neutral over time (Fig. 3, open triangles, dashed gray line), and there was no explicit recurring seasonal cycle of gained or lost numbers of species to consecutive months.

There was no substantial difference in species diversity and community composition at site KUL (one year of available data) compared to the multi-year site SER. Interestingly, the marine mammal acoustic community composition changes completely on a semiannual basis following the sea ice breakup and formation (Fig. 4). In autumn, three species of seasonally migrating cetaceans (i.e., sperm, humpback, and fin whales) mainly constitute the acoustic marine mammal community composition at both recording sites. In winter, the acoustic community composition shifts towards an acoustic community dominated by bearded seals with incidental narwhal and bowhead whale acoustic presence. In summer, the acoustic community again turns over to be acoustically dominated in autumn by seasonally migrating cetacean species (Fig. 4).

IV. DISCUSSION

This study provides insights into the intra- and interannual patterns in marine mammal occurrence and community composition relative to the local SIC for the Tasiilaq area of Southeast Greenland. Such knowledge is of direct relevance to international and intergovernmental initiatives that aim to monitor the status of Arctic marine environments and to coordinate efforts on their protection and sustainable development, such as the Arctic Council, including CAFF (Conservation of Arctic Flora and Fauna), PAME (Protection of the Arctic Marine Environment), AMAP (Arctic Monitoring and Assessment Program), SDWG (Sustainable Development Working Group) or the IQOE (International Quiet Ocean Experiment).

In total, one pinniped species (bearded seal), three baleen whale species (bowhead, humpback, and fin whale), and three toothed whale species (narwhal, killer, and sperm whale) were found to contribute to the local marine soundscape between 2014 and 2018. Despite the small spatial

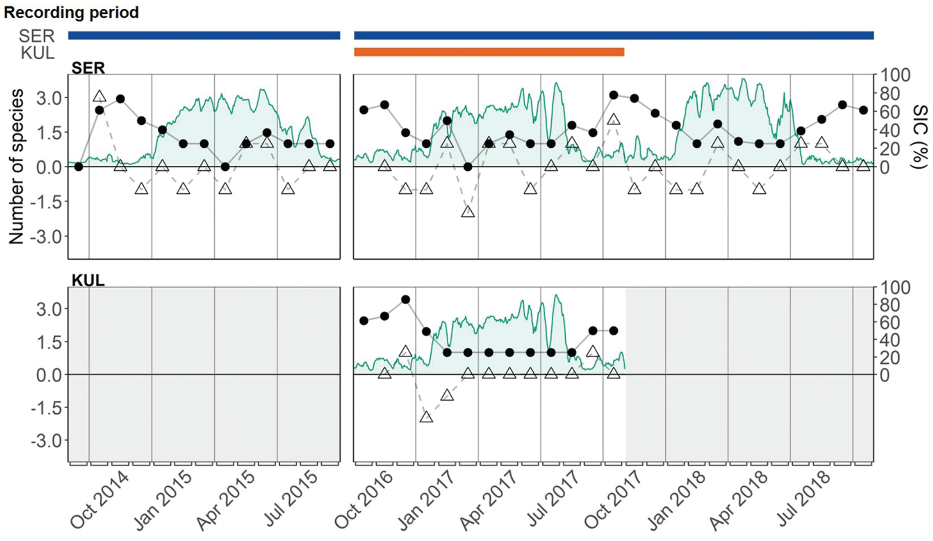

FIG. 3. Monthly acoustic species diversity (left *y*-axis) for recording site SER, and site KUL versus the 7-day daily moving mean SIC (%; green shaded area, right *y*-axis) of the larger area (95 × 150 km) off Tasiilaq. The monthly ENS (black dots, gray line) was calculated from the relative acoustic presence of all species (see Fig. 2). The net change in species richness (triangles, dashed gray line) from any month to the next month. Gray shaded areas mark periods that were not analyzed (KUL-2014/15) or lacking data (KUL-2017/18). The horizontal bars on top of the figure indicate the respective recording periods analyzed for site SER (blue) and site KUL (orange).

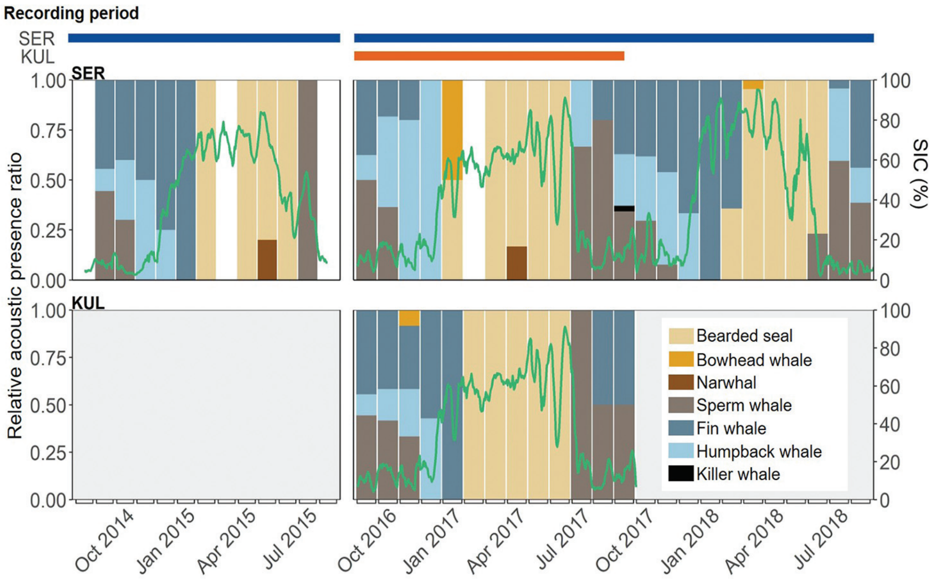

FIG. 4. Acoustic community composition of marine species acoustically present off Tasiilaq, as the relative acoustic presence of a species to the relative acoustic presence of any other species acoustically present within this month (left *y*-axis). The green line shows the 7-day daily moving mean SIC (%; right *y*-axis) of the greater area (95 × 150 km) off Tasiilaq. Gray shaded areas mark periods that were not analyzed (KUL-2014/15) or lacking data (KUL-2017/18). The horizontal bars on top of the figure indicate the respective recording periods analyzed for site SER (blue) and site KUL (orange).

scale of this study, our acoustic data captured 32% of the total marine mammal species richness described for all of Greenland (excluding polar bears, *Ursus maritimus*) (Ugarte *et al.*, 2020), implying the Tasiilaq area is a marine mammal hotspot.

Acoustic studies of marine mammal diversity rely on the species to produce sound and can be affected by the recorder set-up, recording period, and the analysis scheme (Mellinger *et al.*, 2007; Thomisch *et al.*, 2015). Furthermore, species detection is strongly dependent on both species-specific and individual acoustic behavior, such as the highly seasonal vocal activity of male pinnipeds (e.g., Van Parijs *et al.*, 2001; MacIntyre *et al.*, 2015) or context-dependent acoustic behaviors in cetaceans (e.g., Croll *et al.*, 2002; Stafford *et al.*, 2012b; Kowarski *et al.*, 2019). By choosing subsets of data (where applicable) that were evenly distributed over the respective recording period, we aimed to minimize the risk of biased detection results due to species-specific seasonal patterns in acoustic activity.

The effective frequency range of 10–16 384 Hz in this study hampered reliable detection and identification of species producing sounds that (partly) exceed the sampling frequency of the recorders (Mellinger *et al.*, 2007). Additionally, subsampling of data (applied in the recording or analysis process, or both) has been shown to affect the detection likelihood. Such duty cycle effects are most pronounced for species with low or temporally clustered vocal activity (Thomisch *et al.*, 2015), such as narwhals (Blackwell *et al.*, 2018; Ahonen *et al.*, 2019) or killer whales (Deecke *et al.*, 2005). The analysis scheme applied here, i.e., sampling every seventh day entirely, was selected to ensure we capture species that exhibit a diel pattern in their vocal activity. When comparing overall trends from a seventh-day subsampling scheme to the daily analysis, no substantial differences were found in acoustic diversity or seasonal patterns in species-specific acoustic presence, leaving it unlikely that our analysis scheme considerably underrepresents the daily acoustic presence of the different species.

A. Trends in ambient noise levels off Tasiilaq

Off Tasiilaq, the ambient noise levels measured for the TOL bands (centered at 20, 63, 125, 500, 1000, and 4000 Hz) did not show a pronounced reoccurring seasonal pattern in the daily median SPLs.

In Fram Strait, annual mean SPLs of the 63, 125, and 500 Hz TOL bands were higher, ranging from 85.3 to 95.9 dB re 1 μPa (Ahonen *et al.*, 2017). Lower SPLs in the Tasiilaq area, are likely caused by the absence of noise generated by seismic explorations, which contribute considerably to the SPLs in Fram Strait.

Overall, high noise levels can mask signals of interest by reducing the signals' detection ranges (Erbe *et al.*, 2016). Therefore, the actual detection range of vocalizing individuals likely was less for SER-2014/15 and SER-2016/17 than for SER-2017/18 and KUL-2016/17. In SER-2016/17 and occasionally in SER-2014/15, the TOL bands centered at 20, 63, and 125 Hz were affected by mooring-generated strumming noise (mainly below 100 Hz). In SER-2016/17, additionally, shackle-noise was prominent and affected the higher-frequency TOL bands centered at 500, 1000, and 4000 Hz. High SPLs in the 20 Hz TOL band in SER-2016/17 due to strumming noise likely masked 20 Hz fin whale calls, providing a possible explanation for the observed low acoustic presence of fin whales during this recording period. In SER-2014/15, however, strumming did not seem to mask fin whale calls and cause a subsequent underestimation of fin whale acoustic presence. The broadband but transient nature of the recorder shackle-noise allowed for detection of marine mammal vocalizations in the absence of shackle-noise and hence did not seem to compromise results on the overall daily acoustic presence of marine mammals.

B. Arctic marine mammal occurrence in the Tasiilaq area

Of the eight endemic Arctic seal and cetacean species occurring around Greenland (Ugarte *et al.*, 2020), three species were acoustically present in the Tasiilaq area: bearded seals, narwhals, and bowhead whales.

Bearded seal acoustic presence was strongly related to sea ice during winter and spring (from January to June), consistent with findings from other Arctic regions (Van Parijs *et al.*, 2004; MacIntyre *et al.*, 2015; Boye *et al.*, 2020). Male bearded seals are known to vocalize exclusively prior to and during the springtime breeding season (Cleator and Stirling, 1990; Van Parijs *et al.*, 2001). Our findings, therefore, highlight the relevance of the Tasiilaq area as breeding habitat for this species. Although most bearded seals are assumed to retreat into fjords during summer, some individuals remain present along Southeast Greenland (Boertmann and Rosing-Asvid, 2014). Hence, the Tasiilaq area may be of ecological importance for bearded seals year-round, serving as a breeding and molting ground. However, in light of increasing numbers of sea ice-free periods and earlier sea ice break-up, bearded seals might respond to changing sea ice conditions by using land for hauling out (Laidre *et al.*, 2008), using pieces of glacial ice during pupping season (Lydersen *et al.*, 2014), starting breeding earlier in the season, or (seasonally) migrating north into areas that still provide more stable sea ice cover (Kovacs *et al.*, 2011; Laidre *et al.*, 2015).

While Sermilik fjord is a known narwhal summering ground (Dietz *et al.*, 1994; Heide-Jørgensen *et al.*, 2010), narwhals were rarely acoustically detected in our data off Tasiilaq. The Tasiilaq area may be a transit area for narwhals, or they may occur at low densities such that they were not detected by our instruments. Additionally, the duty-cycled recording scheme (with duty cycles of 12.5% or 25%) and the chosen analysis schemes (with about 14% of data analyzed for most recording years) may have negatively affected the accuracy of acoustic presence estimates. Narwhal acoustic behavior is temporally clustered, e.g., they are known to vocalize more intensely during daytime and early evening, including long periods of vocal inactivity (Blackwell *et al.*, 2018; Ahonen *et al.*, 2019). Furthermore, narwhal high-frequency clicks are highly directional and range from about 18 up to 200 kHz (Stafford *et al.*, 2012a; Rasmussen *et al.*, 2015). This might have rendered them undetectable given our sampling rate of 32 768 Hz, thereby adding to an underestimation of narwhal acoustic presence.

The occasional acoustic presence of bowhead whales in our study supports previous observations that bowhead whales do not regularly inhabit the waters of Tasiilaq but move through the area occasionally (Heide-Jørgensen, 2019). Bowhead whales detected off Tasiilaq might belong to the Spitsbergen stock, which has been reported to migrate along the sea ice edge south to the "Southern Whaling Grounds" (70–75.5°N) of the Greenland Sea (Lydersen *et al.*, 2012; Kovacs *et al.*, 2020). In November, the acoustic presence of bowhead and humpback whales overlapped in the Tasiilaq area. Both whale species show similarities in their vocal behaviors, characterized by complex, annually changing songs (Payne and McVay, 1971; Ljungblad *et al.*, 1982; Herman, 2017; Stafford *et al.*, 2018). This might have caused an underestimation of bowhead whale acoustic presence.

C. Seasonally migrating cetacean occurrence in the Tasiilaq area

Four seasonally migrating cetaceans off Greenland were acoustically present. The regular seasonal occurrence of sperm, humpback, and fin whales during summer and autumn indicates summer feeding in the coastal waters of Tasiilaq.

Killer whales have been reported to regularly occur in the Tasiilaq area since 2009, with occurrences linked to sea ice loss in this region (Ugarte *et al.*, 2020). In this study, they were acoustically detected only on one single day in September 2017. Killer whales off Tasiilaq have been observed to prey on seals (Foote *et al.*, 2013). The low acoustic presence observed here may therefore reflect silent hunting strategies used by marine mammal-feeding killer whale ecotypes to avoid startling potential prey (Deecke *et al.*, 2005). Furthermore, the limited sampling rate, as well as duty-cycled sampling and analysis schemes may have affected the likelihood of detection for killer whale calls and highly directional clicks, which exhibit frequency ranges up to 75 kHz (Samarra *et al.*, 2010; Eskesen *et al.*, 2011).

Sperm whales are known to produce clicks for communication and prey localization year-round (e.g., Mellinger *et al.*, 2004), hence their acoustic absence likely reflects actual physical absence. In the Tasiilaq area deep trenches located at the fjord entries (about 400 to 900 m depth) (Sutherland *et al.*, 2014), provide suitable foraging habitats for these deep-diving predators (Watkins *et al.*, 1993). The pronounced seasonality of sperm whale acoustic presence in summer and autumn in the Tasiilaq area, with acoustic absence through winter and spring, contrasts observations of prolonged and year-round acoustic presence in eastern Fram Strait (Klinck *et al.*, 2012) and the Greenland Sea (De Vreese *et al.*, 2018). In contrast to recording sites in Fram Strait and the Greenland Sea, the Tasiilaq area exhibits seasonal sea ice cover, which may cause animals to leave the area in winter. Interestingly, sperm whale acoustic presence off Tasiilaq had already ceased one month before sea ice formation. Therefore, factors other than sea ice concentration alone (e.g., prey availability, changes in water temperature, or light conditions) are likely to trigger the onset of sperm whale departure (Shaw, 2016).

This study indicates that the Tasiilaq area serves as a suitable habitat for humpback and fin whales not only for summer feeding activities but also during winter. In general, both species are negatively associated with sea ice concentration, but fin whales seem to tolerate loose drift ice (Storrie *et al.*, 2018). In other (sub-)Arctic areas that were ice-free year-round, humpback and fin whales were acoustically present throughout winter and into spring (Magnúsdóttir *et al.*, 2014; De Vreese *et al.*, 2018; Fournet *et al.*, 2018). Ahonen *et al.* (2021) and Moore *et al.* (2012) detected fin whale 20 Hz calls in Western Fram strait in spite of sea ice cover. In Davis Strait, advancing sea ice seems to push singing fin whales to migrate further south (Simon *et al.*, 2010). In the Tasiilaq area, the seasonal sea ice cover can be quite variable due to currents and strong katabatic winds creating coastal polynyas (Oltmanns *et al.*, 2014). The presence of coastal polynyas possibly provides ice-free areas for marine mammals during winter and might explain fin whale singing off Tasiilaq until February. Later in the season, the persistent sea ice cover or changing prey availability may cause fin whales to move to sea ice-free areas further offshore (e.g., Irminger Sea, Davis *et al.*, 2020).

Similar to fin whale 20-Hz calls, humpback whale song fragments were recorded from late September into winter months. Songs of humpback whales and 20 Hz pulses of fin whales are most likely produced solely by males in a reproductive context (Croll *et al.*, 2002; Simon *et al.*, 2010; Herman, 2017). Humpback whale songs are mainly recorded at low-latitude breeding grounds, but also occur during migration and on high-latitude feeding grounds (Herman, 2017). Singing during migration and on feeding grounds is assumed to be connected to complex migratory behaviors, such as partial or staggered migration (Clark and Clapham, 2004; Geijer *et al.*, 2016). It also has been suggested as an opportunistic mating strategy of males to access females that failed to conceive during the breeding season or are skipping migration (Clark and Clapham, 2004). Our recordings of humpback whale song-fragments and fin whale 20 Hz pulses on a feeding ground during autumn and winter months thereby add to a growing body of evidence of complex migratory behaviors in baleen whales (Clark and Clapham, 2004; Simon *et al.*, 2010; Geijer *et al.*, 2016).

D. Unidentified biological sounds

The biological soundscape further contained several cetacean sounds that could often be attributed to family or genus but not to species level, including clicks, whistles, grunts, moans, frequency-modulated downsweeps, and simpler call sequences. The occurrence of these sounds might indicate a greater acoustic marine mammal diversity off Tasiilaq, potentially including white-beaked dolphin (*Lagenorhynchus albirostris*), blue, sei, and North Atlantic right whales.

Sounds of unknown origin, recorded at frequencies below 700 Hz, were recognized in all years in the waters off Tasiilaq. Some of these sounds, i.e., call categories C1 and C2, show similarities in the temporal patterns of acoustic presence to that observed for humpback and fin whales. Category C3 (simple call sequences of short pulses) occurred in winter and spring 2018 and might be produced by bowhead whales or by North Atlantic right whales, which have been reported and observed off Southeast Greenland (Mellinger *et al.*, 2011; AMAP/CAFF/SDWG, 2013). Both species produce spectrographically similar calls in the same frequency range (e.g., Laurinolli *et al.*, 2003; Stafford *et al.*, 2012b). However, the presence of C3 calls during heavier sea ice conditions might indicate that these calls are produced by bowhead whales. Calls categorized as C4 (frequency-modulated arched downsweeps) are known to be produced by blue (e.g., Mellinger and Clark, 2003; Schall *et al.*, 2020) and sei whales (e.g., Nieukirk *et al.*, 2020), and both species are reported to occur along Southeast Greenland (Heide-Jørgensen *et al.*, 2007; AMAP/CAFF/SDWG, 2013; Hansen *et al.*, 2019). Nieukirk *et al.* (2020) note that sei whale calls can be misidentified with similar calls of other baleen whales, requiring a highly conservative approach in confirming downsweeping vocalizations on species-level. Furthermore, the absence of the lower-frequency AB calls of blue whales (Mellinger and Clark, 2003), prevents an unequivocal assignment of the C4 calls to blue whales. Humpback whales tend to produce moans and grunts during feeding activities and social interactions (Dunlop *et al.*, 2008; Stimpert *et al.*, 2011). However, several baleen whales can produce such moans and grunts categorized here as C5, preventing an assignment to any specific species.

E. Acoustic community composition

In polar regions, strong seasonal fluctuations in environmental conditions, such as sea ice cover, are assumed to be reflected in species richness and community composition patterns (Van Opzeeland and Hillebrand, 2020). The acoustic species richness off Tasiilaq exhibited a highly seasonal dynamic, peaking during the sea ice-free late summer and autumn and dropping to mainly one species in winter when the sea ice concentration increased. Off Tasiilaq, a strong and complete semi-annual turnover and recovery of the acoustic species community composition linked to the seasonal sea ice cover was observed. Furthermore, there was no substantial difference in the acoustic species diversity and acoustic community composition at site KUL compared to site SER, even though only one year was analyzed for site KUL. Unidentified cetacean sounds, potentially reflecting the acoustic presence of additional species, were not included in the diversity analyses. In turn, the actual acoustic species richness and the acoustic community composition turnover off Tasiilaq might be higher and more complex than assumed.

With increasing sea ice loss, species turnover dynamics might change over time due to changing community composition and species dominance (Van Opzeeland and Hillebrand, 2020). Sea ice decline facilitates the occurrence of killer whales in the Tasiilaq area, potentially increasing the predation risk for seals and narwhals in the area (Westdal *et al.*, 2013; Breed *et al.*, 2017), which may add pressure to move to areas that still provide steady sea ice cover. With ongoing sea ice loss, seasonal migrants may arrive earlier on (sub-)polar summering grounds or extend their stay into winter (Ramp *et al.*, 2015; Ahonen *et al.*, 2021). Fin and humpback whales have a similar feeding ecology, foraging on the same pelagic prey species, such as euphausiids, copepods, and small schooling fish species (Aguilar and García-Vernet, 2018; Clapham, 2018). By trophic niche partitioning, however, they might avoid direct prey competition, possibly facilitating co-occurrence of these species in the Tasiilaq area (Gavrilchuk *et al.*, 2014).

V. CONCLUSION

Overall, the waters off Tasiilaq provide year-round habitat for endemic Arctic marine mammals and seasonally migrating cetaceans, supporting the classification of the region as an area of "heightened ecological significance" (AMAP/CAFF/SDWG, 2013). Strong seasonal dynamics in acoustic marine mammal richness and acoustic community composition linked to the local sea ice concentrations reflect the species-specific seasonal habitat suitability. Prospective PAM studies should consider recording continuously (rather than duty-cycled recording schemes) to gain insights into the habitat use of rare species or those exhibiting temporally clustered vocal activities, such as narwhal and killer whales, by increasing the likelihood of acoustically capturing these species. Furthermore, the availability of fully recorded call sequences and songs could greatly benefit the classification of the recorded sounds on species-level, e.g., by facilitating the distinction between bowhead and humpback whales.

Climate change-related, ongoing alterations in species distribution and community composition in the Arctic Ocean highlight the need for large-scale and long-term, internationally coordinated efforts to assess, understand and monitor the *status quo* of, as well as future trends in, already vulnerable Arctic environments.

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[1] See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0009429 for an overview of the total relative species-specific acoustic presence per recording period and for examples of unidentified biological sound signals and their temporal occurrence.

Aguilar, A., and García-Vernet, R. (**2018**). "Fin Whale: *Balaenoptera physalus*," in *Encyclopedia of Marine Mammals*, edited by B. Würsig, J. G. M. Thewissen, and K. M. Kovacs (Academic Press, New York), pp. 368–371.

Ahonen, H., Stafford, K. M., de Steur, L., Lydersen, C., Wiig, Ø., and Kovacs, K. M. (**2017**). "The underwater soundscape in western Fram Strait: Breeding ground of Spitsbergen's endangered bowhead whales," Mar. Pollut. Bull. **123**, 97–112.

Ahonen, H., Stafford, K., Lydersen, C., Berchok, C., Moore, S., and Kovacs, K. (**2021**). "Interannual variability in acoustic detection of blue and fin whale calls in the Northeast Atlantic High Arctic between 2008 and 2018," Endanger. Species Res. **45**, 209–224.

Ahonen, H., Stafford, K. M., Lydersen, C., de Steur, L., and Kovacs, K. M. (**2019**). "A multi-year study of narwhal occurrence in the western Fram Strait—detected via passive acoustic monitoring," Polar Res. **38**, 3468.

AMAP/CAFF/SDWG (**2013**). "Identification of Arctic marine areas of heightened ecological and cultural significance: Arctic Marine Shipping Assessment (AMSA) IIc," Arctic Monitoring and Assessment Programme, Oslo, Norway, p. 114.

Au, W. W. L., and Hastings, M. C. (**2008**). "Acoustic propagation," in *Principles of Marine Bioacoustics* (Springer US, New York), pp. 87–120.

Blackwell, S. B., Tervo, O. M., Conrad, A. S., Sinding, M. H. S., Hansen, R. G., Ditlevsen, S., and Heide-Jørgensen, M. P. (**2018**). "Spatial and temporal patterns of sound production in East Greenland narwhals," PLoS One **13**, 1–23.

Boertmann, D., Merkel, F., and Durinck, J. (**2009**). "Bowhead whales in East Greenland, summers 2006–2008," Polar Biol. **32**, 1805–1809.

Boertmann, D., and Rosing-Asvid, A. (**2014**). "Seabirds and seals in Southeast Greenland. Results from a survey in July 2014," Scientific Report from Danish Centre for Environment and Energy, Aahrus University, Aahrus, Denmark, p. 42.

Bonnel, J., Thode, A. M., Blackwell, S. B., Kim, K., and Michael Macrander, A. (**2014**). "Range estimation of bowhead whale (*Balaena mysticetus*) calls in the Arctic using a single hydrophone," J. Acoust. Soc. Am. **136**, 145–155.

Boye, T. K., Simon, M. J., Laidre, K. L., Rigét, F., and Stafford, K. M. (**2020**). "Seasonal detections of bearded seal (*Erignathus barbatus*) vocalizations in Baffin Bay and Davis Strait in relation to sea ice concentration," Polar Biol. **43**, 1493–1502.

Breed, G. A., Matthews, C. J. D., Marcoux, M., Higdon, J. W., LeBlanc, B., Petersen, S. D., Orr, J., Reinhart, N. R., and Ferguson, S. H. (**2017**). "Sustained disruption of narwhal habitat use and behavior in the presence of Arctic killer whales," Proc. Natl. Acad. Sci. U.S.A. **114**, 2628–2633.

Chase, J. M., and Knight, T. M. (**2013**). "Scale-dependent effect sizes of ecological drivers on biodiversity: Why standardised sampling is not enough," Ecol. Lett. **16**, 17–26.

Clapham, P. J. (**2018**). "Humpback whale: *Megaptera novaeangliae*," in *Encyclopedia of Marine Mammals*, edited by B. Würsig, J. G. M. Thewissen, and K. M. Kovacs (Academic Press, 3rd ed., 489–492.

Clark, C. W., and Clapham, P. J. (**2004**). "Acoustic monitoring on a humpback whale (*Megaptera novaeangliae*) feeding ground shows continual singing into late spring," Proc. R. Soc. London, Ser. B **271**, 1051–1057.

Cleator, H. J., and Stirling, I. (**1990**). "Winter distribution of bearded seals (*Erignathus barbatus*) in the Penny Strait area, Northwest Territories, as determined by underwater vocalizations," Can. J. Fish. Aquat. Sci. **47**, 1071–1076.

Croll, D. A., Clark, C. W., Acevedo, A., Tershy, B., Flores, S., Gedamke, J., and Urban, J. (**2002**). "Only male fin whales sing loud songs," Nature **417**, 809–811.

Davis, G. E., Baumgartner, M. F., Corkeron, P. J., Bell, J., Berchok, C., Bonnell, J. M., Bort Thornton, J., Brault, S., Buchanan, G. A., Cholewiak, D. M, Clark, C. W., Delarue, J., Hatch, L. T., Klinck, H., Kraus, S. D., Martin, B., Mellinger, D. K., Moors-Murphy, H., Nieukirk, S., Nowacek, D. P., Parks, S. E., Perry, D., Pegg, N., Read, A. J., Rice, A. N., Risch, D., Scott, A., Soldevilla, M. S., Stafford, K. M., Stanistreet, J. E., Summers, E., Todd, S., and Van Parijs, S. M. (**2020**). "Exploring movement patterns and changing distributions of baleen whales in the western North Atlantic using a decade of passive acoustic data," Glob. Chang. Biol. **26**, 4812– 4840.

Deecke, V. B., Ford, J. K. B., and Slater, P. J. B. (**2005**). "The vocal behaviour of mammal-eating killer whales: Communicating with costly calls," Anim. Behav. **69**, 395–405.

Deecke, V. B., Nykänen, M., Foote, A. D., and Janik, V. M. (**2011**). "Vocal behaviour and feeding ecology of killer whales *Orcinus orca* around Shetland, UK," Aquat. Biol. **13**, 79–88.

De Vreese, S., van der Schaar, M., Weissenberger, J., Erbs, F., Kosecka, M., Solé, M., and André, M. (**2018**). "Marine mammal acoustic detections in the Greenland and Barents Sea, 2013–2014 seasons," Sci. Rep. **8**, 16882.

Dietz, R., Heide-Jørgensen, M. P., Born, E. W., and and Glahder, C. M. (**1994**). "Occurrence of narwhals (*Monodon monoceros*) and white whales (*Delphinapterus leucas*) in East Greenland," East Greenl. Meddelelser om Grønland, Biosci. **39**, 69–86.

Discovery of Sound in the Sea (**2021**). "Audio Gallery," https://dosits.org/galleries/audio-gallery/ (Last viewed 10/1/2019).

Dunlop, R. A., Cato, D. H., and Noad, M. J. (**2008**). "Non-song acoustic communication in migrating humpback whales (*Megaptera novaeangliae*)," Mar. Mamm. Sci. **24**, 613–629.

Erbe, C., Dunlop, R., Jenner, K. C. S., Jenner, M.-N. M., McCauley, R. D., Parnum, I., Parsons, M., Rogers, T., and Salgado-Kent, C. (**2017**). "Review of underwater and in-air sounds emitted by Australian and Antarctic marine mammals," Acoust. Aust. **45**, 179–241.

Erbe, C., Reichmuth, C., Cunningham, K., Lucke, K., and Dooling, R. (**2016**). "Communication masking in marine mammals: A review and research strategy," Mar. Pollut. Bull. **103**, 15–38.

Ershova, E. A., Kosobokova, K. N., Banas, N. S., Ellingsen, I., Niehoff, B., Hildebrandt, N., and Hirche, H.-J. (**2021**). "Sea ice decline drives biogeographical shifts of key Calanus species in the central Arctic Ocean," Glob. Chang. Biol. **27**, 2128–2143.

Eskesen, I. G., Wahlberg, M., Simon, M., and Larsen, O. N. (**2011**). "Comparison of echolocation clicks from geographically sympatric killer whales and long-finned pilot whales (L)," J. Acoust. Soc. Am. **130**, 9–12.

Foote, A. D., Newton, J., Ávila-Arcos, M. C., Kampmann, M.-L., Samaniego, J. A., Post, K., Rosing-Asvid, A., Sinding, M.-H. S., and Gilbert, M. T. P. (**2013**). "Tracking niche variation over millennial timescales in sympatric killer whale lineages," Proc. R. Soc. London, Ser. B **280**, 20131481.

Fossheim, M., Primicerio, R., Johannesen, E., Ingvaldsen, R. B., Aschan, M. M., and Dolgov, A. V. (**2015**). "Recent warming leads to a rapid borealization of fish communities in the Arctic," Nat. Clim. Chang. **5**, 673–677.

Fournet, M. E. H., Gabriele, C. M., Culp, D. C., Sharpe, F., Mellinger, D. K., and Klinck, H. (**2018**). "Some things never change: Multi-decadal stability in humpback whale calling repertoire on Southeast Alaskan foraging grounds," Sci. Rep. **8**, 13186.

Gavrilchuk, K., Lesage, V., Ramp, C., Sears, R., Bérubé, M., Bearhop, S., and Beauplet, G. (**2014**). "Trophic niche partitioning among sympatric baleen whale species following the collapse of groundfish stocks in the Northwest Atlantic," Mar. Ecol. Prog. Ser. **497**, 285–301.

Geijer, C. K. A., Notarbartolo di Sciara, G., and Panigada, S. (**2016**). "Mysticete migration revisited: Are Mediterranean fin whales an anomaly?," Mamm. Rev. **46**, 284–296.

Goold, J. C., and Jones, S. E. (**1995**). "Time and frequency domain characteristics of sperm whale clicks," J. Acoust. Soc. Am. **98**, 1279–1291.

Halliday, W. D., Pine, M. K., Mouy, X., Kortsalo, P., Hilliard, R. C., and Insley, S. J. (**2020**). "The coastal Arctic marine soundscape near Ulukhaktok, Northwest Territories, Canada," Polar Biol. **43**, 623–636.

Hansen, R. G., Boye, T. K., Larsen, R. S., Nielsen, N. H., Tervo, O., Nielsen, R. D., Rasmussen, M. H., Sinding, M. H. S., and Heide-Jørgensen, M. P. (**2019**). "Abundance of whales in West and East Greenland in summer 2015," NAMMCO Sci. Publ. **11**, 32.

Heide-Jørgensen, M. P. (**2019**). (personal communication).

Heide-Jørgensen, M. P., Laidre, K. L., Burt, M. L., Borchers, D. L., Marques, T. A., Hansen, R. G., Rasmussen, M., and Fossette, S. (**2010**). "Abundance of narwhals (*Monodon monoceros*) on the hunting grounds in Greenland," J. Mammal **91**, 1135–1151.

Heide-Jørgensen, M. P., Simon, M. J., and Laidre, K. L. (**2007**). "Estimates of large whale abundance in Greenlandic waters from a ship-based survey in 2005," J. Cetacean Res. Manag. **9**, 95–104.

Herman, L. M. (**2017**). "The multiple functions of male song within the humpback whale (*Megaptera novaeangliae*) mating system: Review, evaluation, and synthesis," Biol. Rev. **92**, 1795–1818.

Hijmans, R. J. (**2020**). "raster: Geographic data analysis and modeling. R package version 3.4-5," https://rspatial.org/raster/ (Last viewed 2/10/2022).

Hillebrand, H., Blasius, B., Borer, E. T., Chase, J. M., Downing, J. A., Eriksson, B. K., Filstrup, C. T., Harpole, W. S., Hodapp, D., Larsen, S., Lewandowska, A. M., Seabloom, E. W., Wan de Wall, D. B., and Ryabov, A. B. (**2018**). "Biodiversity change is uncoupled from species richness trends: Consequences for conservation and monitoring," J. Appl. Ecol. **55**, 169–184.

Huang, W., Wang, D., and Ratilal, P. (**2016**). "Diel and spatial dependence of Humpback song and non-song vocalizations in fish spawning ground," Remote Sens. **8**, 712.

International Organization for Standardization (**2017**). "ISO 18405:2017(en) - Underwater acoustics — Terminology;" available at https://www.iso.org/standard/62406.htm.

Jansen, T., Post, S., Kristiansen, T., Óskarsson, G. J., Boje, J., MacKenzie, B. R., Broberg, M., and Siegstad, H. (**2016**). "Ocean warming expands habitat of a rich natural resource and benefits a national economy," Ecol. Appl. **26**, 2021–2032.

Kern, S., Kaleschke, L., and Spreen, G. (**2010**). "Climatology of the Nordic (Irminger, Greenland, Barents, Kara and White/Pechora) Seas ice cover based on 85 GHz satellite microwave radiometry: 1992–2008," Tellus A Dyn. Meteorol. Oceanogr. **62**, 411–434.

Klinck, H., Nieukirk, S. L., Mellinger, D. K., Klinck, K., Matsumoto, H., and Dziak, R. P. (**2012**). "Seasonal presence of cetaceans and ambient noise levels in polar waters of the North Atlantic," J. Acoust. Soc. Am. **132**, EL176–EL181.

Kovacs, K. M., Lydersen, C., Overland, J. E., and Moore, S. E. (**2011**). "Impacts of changing sea-ice conditions on Arctic marine mammals," Mar. Biodivers. **41**, 181–194.

Kovacs, K. M., Lydersen, C., Vacquiè-Garcia, J., Shpak, O., Glazov, D., and Heide-Jørgensen, M. P. (**2020**). "The endangered Spitsbergen bowhead whales' secrets revealed after hundreds of years in hiding," Biol. Lett. **16**, 20200148.

Kowarski, K., Moors-Murphy, H., Maxner, E., and Cerchio, S. (**2019**). "Western North Atlantic humpback whale fall and spring acoustic repertoire: Insight into onset and cessation of singing behavior," J. Acoust. Soc. Am. **145**, 2305–2316.

Laidre, K., Heide-Jørgensen, M. P., Stern, H., and Richard, P. (**2012**). "Unusual narwhal sea ice entrapments and delayed autumn freeze-up trends," Polar Biol. **35**, 149–154.

Laidre, K. L., Stern, H., Kovacs, K. M., Lowry, L., Moore, S. E., Regehr, E. V., Ferguson, S. H., Øystein, W., Boveng, P., Angliss, R. P., Born, E. W., Litovka, D., Quakenbush, L., Lydersen, C., Vongraven, D., and Ugarte, F. (**2015**). "Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century," Conserv. Biol. **29**, 724–737.

Laidre, K. L., Stirling, I., Lowry, L. F., Wiig, Ø., Heide-Jørgensen, M. P., and Ferguson, S. H. (**2008**). "Quantifying the sensitivity of arctic marine mammals to climate-induced habitat change," Ecol. Appl. **18**, S97–S125.

Lannuzel, D., Tedesco, L., van Leeuwe, M., Campbell, K., Flores, H., Delille, B., Miller, L., Stefels, J., Assmy, P., Bowman, J., Brown, K., Castellani, G., Chierici, M., Crabeck, O., Damm, e., Else, B., Fransson, A., Fripiat, F., Geilfus, N.-X., Jacques, C., Jones, E., Kaartokallio, H., Kotovitch, M., Meiners, K., Moreau, S., Nomura, D., Peeken, I., Rintala, J.-M., Steiner, N., Tison, J.-L., Vancoppenolle, M., Van der Linden, F., Vichi, M., and Wongpan, P. (**2020**). "The future of Arctic sea-ice biogeochemistry and ice-associated ecosystems," Nat. Clim. Chang. **10**, 983–992.

Laurinolli, M. H., Hay, A. E., Desharnais, F., and Taggart, C. T. (**2003**). "Localization of North Atlantic right whale sounds in the Bay of Fundy using a sonobuoy array," Mar. Mammal Sci. **19**, 708–723.

Lewis, K. M., Van Dijken, G. L., and Arrigo, K. R. (**2020**). "Changes in phytoplankton concentration now drive increased Arctic Ocean primary production," Science **369**, 198–202.

Ljungblad, D. K., Thompson, P. O., Diego, S., and Moore, S. E. (**1982**). "Underwater sounds recorded from migrating bowhead whales, *Balaena mysticetus*, in 1979," J. Acoust. Soc. Am. **71**, 477–482.

Lydersen, C., Assmy, P., Falk-Petersen, S., Kohler, J., Kovacs, K. M., Reigstad, M., Steen, H., Strøm, H., Sundfjord, A., Varpe, Ø., Wlaczowski, W., Weslawski, J. M., and Zajaczkowksi, M. (**2014**). "The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway," J. Mar. Syst. **129**, 452–471.

Lydersen, C., Freitas, C., Wiig, Ø., Bachmann, L., Heide-Jørgensen, M. P., Swift, R., and Kovacs, K. M. (**2012**). "Lost highway not forgotten: Satellite tracking of a bowhead whale (*Balaena mysticetus*) from the critically endangered Spitsbergen stock," Arctic **65**, 76–86.

MacIntyre, K. Q., Stafford, K. M., Conn, P. B., Laidre, K. L., and Boveng, P. L. (**2015**). "The relationship between sea ice concentration and the spatio-temporal distribution of vocalizing bearded seals (*Erignathus barbatus*) in the Bering, Chukchi, and Beaufort Seas from 2008 to 2011," Prog. Oceanogr. **136**, 241–249.

Madsen, P. T., Wahlberg, M., and Møhl, B. (**2002**). "Male sperm whale (*Physeter macrocephalus*) acoustics in a high-latitude habitat: Implications for echolocation and communication," Behav. Ecol. Sociobiol. **53**, 31–41.

Magnúsdóttir, E. E., Rasmussen, M. H., Lammers, M. O., and Svavarsson, J. (**2014**). "Humpback whale songs during winter in subarctic waters," Polar Biol. **37**, 427–433.

Mellinger, D. K., and Clark, C. W. (**2003**). "Blue whale (*Balaenoptera musculus*) sounds from the North Atlantic," J. Acoust. Soc. Am. **114**, 1108–1119.

Mellinger, D. K., Nieukirk, S. L., Klinck, K., Klinck, H., Dziak, R. P., Clapham, P. J., and Brandsdóttir, B. (**2011**). "Confirmation of right whales near a nineteenth-century whaling ground east of southern Greenland," Biol. Lett. **7**, 411–413.

Mellinger, D. K., Stafford, K. M., and Fox, C. G. (**2004**). "Seasonal occurrence of sperm whale (*Physeter macrocephalus*) sounds in the Gulf of Alaska, 1999-2001," Mar. Mammal Sci. **20**, 48–62.

Mellinger, D. K., Stafford, K. M., Moore, S. E., Dziak, R. P., and Matsumoto, H. (**2007**). "An overview of fixed passive acoustic observation methods for cetaceans," Oceanography **20**, 36–45.

Merkel, F. R., Rasmussen, L. M., and Rosing-Asvid, A. (**2010**). "Seabirds and marine mammals in South and Southeast Greenland, June 2008," Technical Report, Pinngortitaleriffik, Greenland Institute of Natural Resources, Nuuk, Greenland, p. 57.

Moore, S. E., Haug, T., Víkingsson, G. A., and Stenson, G. B. (**2019**). "Baleen whale ecology in arctic and subarctic seas in an era of rapid habitat alteration," Prog. Oceanogr. **176**, 102118.

Moore, S. E., Stafford, K. M., Melling, H., Berchok, C., Wiig, Ø., Kovacs, K. M., Lydersen, C., and Richter-Menge, J. (**2012**). "Comparing marine mammal acoustic habitats in Atlantic and Pacific sectors of the High Arctic: Year-long records from Fram Strait and the Chukchi Plateau," Polar Biol. **35**, 475–480.

Nieukirk, S. L., Mellinger, D. K., Dziak, R. P., Matsumoto, H., and Klinck, H. (**2020**). "Multi-year occurrence of sei whale calls in North Atlantic polar waters," J. Acoust. Soc. Am. **147**, 1842–1850.

Oltmanns, M., Straneo, F., Moore, G. W. K., and Mernild, S. H. (**2014**). "Strong downslope wind events in Ammassalik, Southeast Greenland," J. Climate **27**, 977–993.

Onarheim, I. H., Eldevik, T., Smedsrud, L. H., and Stroeve, J. C. (**2018**). "Seasonal and regional manifestation of Arctic sea ice loss," J. Climate **31**, 4917–4932.

Passive Acoustic Research Group (2021). "Sounds in the Ocean," https://www.fisheries.noaa.gov/national/science-data/sounds-ocean (Last viewed 10/1/2019).

Payne, R. S., and McVay, S. (**1971**). "Songs of humpback whales," Science **173**, 585–597.

Ramp, C., Delarue, J., Palsbøll, P. J., Sears, R., and Hammond, P. S. (**2015**). "Adapting to a warmer ocean—Seasonal shift of baleen whale movements over three decades," PLoS One **10**, e0121374.

Rasmussen, M. H., Koblitz, J. C., and Laidre, K. L. (**2015**). "Buzzes and high-frequency clicks recorded from narwhals (*Monodon monoceros*) at their wintering ground," Aquat. Mamm. **41**, 256–264.

Risch, D., Clark, C. W., Corkeron, P. J., Elepfandt, A., Kovacs, K. M., Lydersen, C., Stirling, I., and Van Parijs, S. M. (**2007**). "Vocalizations of male bearded seals, *Erignathus barbatus*: Classification and geographical variation," Anim. Behav. **73**, 747–762.

Samarra, F. I. P., Deecke, V. B., Vinding, K., Rasmussen, M. H., Swift, R. J., and Miller, P. J. O. (**2010**). "Killer whales (*Orcinus orca*) produce ultrasonic whistles," J. Acoust. Soc. Am. **128**, EL205–EL210.

Schall, E., Di Iorio, L., Berchok, C., Filún, D., Bedriñana-Romano, L., Buchan, S. J., Van Opzeeland, I., R. Sears, and R. Hucke-Gaete (**2020**). "Visual and passive acoustic observations of blue whale trios from two distinct populations," Mar. Mammal Sci. **36**, 365–374.

Schall, E., Thomisch, K., Boebel, O., Gerlach, G., Mangia Woods, S., El-Gabbas, A., and Van Opzeeland, I. (**2021**). "Multi-year presence of humpback whales in the Atlantic sector of the Southern Ocean but not during El Niño," Commun. Biol. **4**, 790.

Shaw, A. K. (**2016**). "Drivers of animal migration and implications in changing environments," Evol. Ecol. **30**, 991–1007.

Simon, M., Stafford, K. M., Beedholm, K., Lee, C. M., and Madsen, P. T. (**2010**). "Singing behavior of fin whales in the Davis Strait with implications for mating, migration and foraging," J. Acoust. Soc. Am. **128**, 3200–3210.

Southall, B., Bowles, A., Ellison, W., Finneran, J., Gentry, R., Greene, C., Jr., Kastak, D., Ketten, D., Miller, J., Nachtigall, P., Richardson, W., Thomas, J., and Tyack, P. (**2008**). "Marine mammal noise-exposure criteria: Initial scientific recommendations," Aquat. Mamm. **33**, 411–512.

Spreen, G., Kaleschke, L., and Heygster, G. (**2008**). "Sea ice remote sensing using AMSR-E 89-GHz channels," J. Geophys. Res. Oceans **113**, C02S03, https://doi.org/10.1029/2005JC003384; available at www.seaice.uni-bremen.de.

Stafford, K. M., Laidre, K. L., and Heide-Jørgensen, M. P. (**2012a**). "First acoustic recordings of narwhals (*Monodon monoceros*) in winter," Mar. Mammal Sci. **28**, E197–E207.

Stafford, K. M., Lydersen, C., Wiig, Ø., and Kovacs, K. M. (**2018**). "Extreme diversity in the songs of Spitsbergen's bowhead whales," Biol. Lett. **14**, 20180056.

Stafford, K. M., Mellinger, D. K., Moore, S. E., and Fox, C. G. (**2007**). "Seasonal variability and detection range modeling of baleen whale calls in the Gulf of Alaska, 1999–2002," J. Acoust. Soc. Am. **122**, 3378–3390.

Stafford, K. M., Moore, S. E., Berchok, C. L., Wiig, Ø., Lydersen, C., Hansen, E., Kalmbach, D., and Kovacs, K. M. (**2012b**). "Spitsbergen's endangered bowhead whales sing through the polar night," Endanger. Species Res. **18**, 95–103.

Stimpert, A. K., Au, W. W. L., Parks, S. E., Hurst, T., and Wiley, D. N. (**2011**). "Common humpback whale (*Megaptera novaeangliae*) sound types for passive acoustic monitoring," J. Acoust. Soc. Am. **129**, 476–482.

Storrie, L., Lydersen, C., Andersen, M., Wynn, R. B., and Kovacs, K. M. (**2018**). "Determining the species assemblage and habitat use of cetaceans in the Svalbard Archipelago, based on observations from 2002 to 2014," Polar Res. **37**, 1463065.

Stroeve, J., and Notz, D. (**2018**). "Changing state of Arctic sea ice across all seasons," Environ. Res. Lett. **13**, 103001.

Sutherland, D. A., Straneo, F., and Pickart, R. S. (**2014**). "Characteristics and dynamics of two major Greenland glacial fjords," J. Geophys. Res. Ocean. **119**, 3767–3791, https://doi.org/10.1002/2013JC009786.

Thomisch, K., Boebel, O., Zitterbart, D. P., Samaran, F., Van Parijs, S., and Van Opzeeland, I. (**2015**). "Effects of subsampling of passive acoustic recordings on acoustic metrics," J. Acoust. Soc. Am. **138**, 267–278.

Ugarte, F., Rosing-Asvid, A., Heide-Jørgensen, M. P., and Laidre, K. L. (**2020**). "Marine mammals of the Greenland seas," in *Encyclopedia of World's Biomes*, edited by M. I. Goldstein and D. A. DellaSala (Elsevier, Amsterdam), pp. 575–586.

Van der Graaf, A. J., Ainslie, M. A., André, M., Brensing, K., Dalen, J., Dekeling, R. P. A., Robinson, S., Tasker, M. L., Thomsen, F., and Werner, S. (**2012**). "European marine strategy framework directive good environmental status (MSFD GES): Report of the technical subgroup on underwater noise and other forms of energy," (TSG Noise and Milieu Ltd, Brussels), p. 75.

Van Opzeeland, I., and Hillebrand, H. (**2020**). "Year-round passive acoustic data reveal spatio-temporal patterns in marine mammal community composition in the Weddell Sea, Antarctica," Mar. Ecol. Prog. Ser. **638**, 191–206.

Van Parijs, S. M., Kovacs, K. M., and Lydersen, C. (**2001**). "Spatial and temporal distribution of vocalising male bearded seals—Implications for male mating strategies," Behaviour **138**, 905–922.

Van Parijs, S. M., Lydersen, C., and Kovacs, K. M. (**2004**). "Effects of ice cover on the behavioural patterns of aquatic-mating male bearded seals," Anim. Behav. **68**, 89–96.

Voices in the Sea (2021). https://voicesinthesea.ucsd.edu/ (Last viewed 10/1/2019).

Watkins, W. A., Daher, M. A., Fristrup, K. M., Howald, T. J., and di Sciara, G. N. (**1993**). "Sperm whales tagged with transponders and tracked underwater by sonar," Mar. Mammal Sci. **9**, 55–67.

Westdal, K. H., Higdon, J. W., and Ferguson, S. H. (**2013**). "Attitudes of Nunavut Inuit toward killer whales (*Orcinus orca*)," Arctic **66**, 247–387.