#### **ORIGINAL PAPER**



# Beluga (*Delphinapterus leucas*) and narwhal (*Monodon monoceros*) echolocation click detection and differentiation from long-term Arctic acoustic recordings

Joshua M. Jones<sup>1</sup> · Kaitlin E. Frasier<sup>1</sup> · Kristin H. Westdal<sup>2</sup> · Alex J. Ootoowak<sup>2</sup> · Sean M. Wiggins<sup>1</sup> · John A. Hildebrand<sup>1</sup>

Received: 31 August 2021 / Revised: 10 January 2022 / Accepted: 10 January 2022 © The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

#### Abstract

Beluga (*Delphinapterus leucas*) and narwhal (*Mondon monoceros*) echolocation signals have been described in numerous acoustic studies but reported characteristics of their clicks vary across studies. Here, a year of acoustic recordings was collected in the Chukchi Sea where belugas are abundant, and narwhals are not present. A second year was recorded in Eclipse Sound, Nunavut, where beluga sightings are rare and narwhals abundant. The same calibrated hydrophone was used at both locations to facilitate data comparison. Click detection and signal parameter measurements were carried out using a single analysis method. Peak frequency of detected clicks decreased with peak-to-peak received sound pressure level (RL) for both species. High RL beluga clicks (n=23,946) and narwhal clicks (n=25,433) had a modal peak frequency of 56 kHz. Lower RL modal peak frequency of beluga clicks (n=688,601) was 53 kHz and for narwhal clicks (n=616,536) was 22.5 kHz. Modal inter-click interval (ICI) for beluga clicks (n=872,336) was 49 ms. Narwhal ICI distribution (n=791,905) was bimodal and right skewed with modal values of 4 and 144 ms. Clicks of belugas and narwhals are distinguishable by frequency spectra and ICI distribution. These parameters provide a reliable way to discriminate between the monodontid species in large acoustic datasets. Received sound levels substantially influence measured frequency spectra and must be carefully accounted for in acoustic identification of monodontid echolocation. Frequency-dependent acoustic absorption of seawater results in longer propagation and detection distance predictions for narwhal clicks that show greater energy below 30 kHz than found in beluga click spectra.

Keywords Passive acoustic monitoring · Echolocation · Classification · Monodontidae · Beluga · Narwhal

### Introduction

Toothed whales produce impulsive clicks for navigation, foraging and for social communication. Acoustic characteristics of these echolocation clicks can be used to identify and discriminate among odontocete species in underwater recordings, making them valuable for studies of click-producing species using passive acoustic methods (Morrissey et al. 2006; Baumann-Pickering et al. 2013; Frasier et al.

☑ Joshua M. Jones j8jones@ucsd.edu

<sup>2</sup> Oceans North, 515-70 Arthur Street, Winnipeg, MB R3G 1B7, Canada 2017; Hildebrand et al. 2019). Echolocation characteristics particularly useful for species identification include frequency spectrum, pulse duration, and rate of click production, measured as inter-click-interval (ICI). These features of odontocete sound production have enabled the study of their seasonal movements and distribution using passive acoustic monitoring (PAM) methods in remote locations where other methods of marine mammal research, such as aerial or shipbased observations are problematic or impractical (Trickey et al. 2015). Echolocation click detections also have been used for density estimation where ancillary information such as clicking rates are known (Marques et al. 2009; Küsel et al. 2011; Hildebrand et al. 2015).

The use of PAM for studies of echolocating marine mammals requires an understanding of the differences between the signals emitted by the animals, and what is recorded at the acoustic receiver. Differences in these signals can be

<sup>&</sup>lt;sup>1</sup> Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0205, USA

caused by physiological attributes and swimming behavior of the animals, and environmental effects on sound propagation (Hildebrand et al. 2019). Echolocation clicks with energy > 30 kHz attenuate rapidly due to frequency dependent absorption (Ainslie 2013), potentially lowering the frequency content of the received signals. Odontocetes often exhibit highly directional projection of acoustic energy, with more energy directed forward in the direction the head is oriented (Au 1993). Both horizontal and vertical beam patterns have been measured experimentally in species including narwhals (Monodon monoceros) (Koblitz et al. 2016), beluga whales (Delphinapterus leucas) (Au et al. 1987), bottlenose dolphins (Tursiops truncatus) (Au et al. 1986), Cuviers beaked whale (Ziphius cavirostris) (Gassmann et al. 2015) and False killer whale (*Pseudcorca crassidens*) (Au et al. 1995). Recording system characteristics can also cause differences in recorded signals unrelated to changes in the acoustic behavior of the animals producing the sounds. Hydrophone and recording system sensitivity are needed to translate recorded signals back into sound pressure. These aspects of acoustic monitoring produce challenges that must be addressed to improve the quality of passive acoustic detections as inputs to monitoring methods, such as studies of seasonal presence and acoustic density estimation.

In the Arctic, autonomous passive acoustic monitoring provides opportunities to study odontocete species under conditions that would be difficult to conduct with human observers, such as at night or under ice-cover. Arctic waters present unique challenges to studying behavior and seasonal movements due to the remoteness of much of their range, the inaccessibility to ships during months of sea ice cover, and absence of sunlight during winter. These factors make passive acoustic monitoring with autonomous underwater acoustic packages an important tool that can record data for months in remote areas where other research methods are not practical (Jones et al. 2014; Frouin-Muoy et al. 2017; Seger and Miksis-Olds, 2020).

Belugas (D. leucas) and narwhals (M. monoceros), the two members of the odontocete family Monodontidae, are the only odontocetes endemic to Arctic waters. These deepdiving whales produce high-frequency echolocation clicks with energy between 20 and 120 kHz that have been previously described (Au et al. 1985; Miller et al. 1995; Roy et al. 2010; Rasmussen et al. 2015; Koblitz et al. 2016; Frouin-Mouy et al. 2017; Zahn et al. 2021). Although these studies provide descriptions for the echolocation signals of belugas and narwhals, differences in characteristics of the hydrophones and recording systems, as well as differences in methods used to analyze acoustic recordings, make discriminating between these species challenging. A literature review of beluga and narwhal echolocation signals yielded a range of values for frequency spectra, ICI, and pulse duration (Au et al. 1985; Au et al. 1987; Mohl et al. 1990; Turl et al. 1991; Miller et al. 1995; Roy et al. 2010; Rasmussen et al. 2015; Koblitz et al. 2016; Zahn et al. 2021) (Table 1). More recently, a novel approach to differentiation between the echolocation clicks of the two species was developed, focusing on the frequency spectra of detected clicks (Frouin-Mouy et al. 2017). Narwhal clicks consistently contained significantly more energy than beluga clicks in the 16 and 20 kHz 1/3rd octave band sound pressure levels (SPL). This characteristic, when combined with the increased presence of whistle-type signals from belugas, allowed discrimination between the two species in autonomous acoustic recordings. Likewise, Zahn et al. (2021) present one hour of beluga recordings and ~ eight hours of narwhal recordings that were collected using a hand-deployed hydrophone array in the pack ice of Baffin Bay, West Greenland, during 2013. These data provide information on an estimated 22-36 individual belugas and 63-120 narwhals sampled across seven encounters. Their results suggest that differences exist between the two species echolocation clicks, distinguished by higher frequencies for beluga (>60 kHz) than for narwhal (<60 kHz) with overlap between 40 and 60 kHz.

To improve confidence in identification of beluga and narwhal echolocation signals, we analyzed a large dataset of clicks (beluga ~ 900,000 and narwhal ~ 800,000) detected with the same acoustic sensor and recording system deployed at two Arctic locations where overlap between these species is minimal and their seasonal presence is well known. A full year of recordings were analyzed from one location in the northeast Chukchi Sea where belugas are present, but narwhals are absent. Another year of recordings were analyzed from the Eastern Canadian Arctic in a summering location for narwhals where presence of belugas is minimal. These data allowed characterization of echolocation clicks with attention to the variability in the signals likely caused by animal behavior and environmental effects on sound propagation. This work shows that the clicks of the two species can be reliably differentiated based on frequency spectra and rhythmic patterns in the clicks.

#### Methods

#### Acoustic recording

Acoustic recordings were collected at two locations in the Arctic (Fig. 1), each with only one monodontid species commonly present—either beluga or narwhal. One recording location in the northeast Chukchi Sea (Fig. 1, site CS) was 160 km north-northwest of Pt. Barrow, Alaska at seafloor depth 323 m along the continental slope between the Chukchi Sea shelf and Canada Basin. Beluga annual presence between May and November has been established at this location through acoustic detection of echolocation

Species	Click description	n (clicks)	Peak fre- quency (kHz)	-3 dB bandwidth (kHz)	– 10 dB bandwidth (kHz)	click duration (µs)	Inter-click interval (ms)	Source level (dB re 1µPa <sub>p-p</sub> @ 1 m)	Reference
Beluga	Click trains	1427	[40-60]	[15–25]	-	~100	-	[197.9– 202.1]	Au et al. (1985)
	Click trains	321	[100–120]	[20-40]	_	~ 50	_	$206.5 \pm 5.5$	
Beluga	Mode 1	563	~115	-	_	_	$193 \pm 37$	$218\pm5$	Au et al. (1987)
	Mode 2	1938	_	-	_	_	$44 \pm 12$	$210\pm7$	
	Mode 3	2416	-	-	-	-	$1.7 \pm 1.0$	$206 \pm 6$	
Beluga	Click trains	~40,000	[85–105]	[30–35]	-	-	[16–21]	[200->210]	Turl et al. (1991)
Beluga	All clicks	787	$40.5 \pm 5.5$	$13.4 \pm 4.4$	$29.1 \pm 9.9$	$163 \pm 152$	$22.6 \pm 33$	$164.4 \pm 9.5$	Roy et al. (2010)
	Regular clicks	-	-	-	-	-	$61.5 \pm 41.0$	_	
	Buzzes	-	-	-	_	_	$6.9 \pm 4.8$	_	
Beluga	Echolocation clicks	2537	$68.7 \pm 10.1$	9.2±6.9	$34.3 \pm 15.9$	659.7 ± 479.9	177.9±174.6	-	Zahn et al. (2021)
Narwhal	Clicks	62		~20	~35	~ 50	[5-500]	$195 \pm 17$	Mohl et al. (1990)
Narwhal	Click train	172	$48 \pm 10$	-	71±~6	$29\pm6$	[100-250] (n=160)		Miller et al. (1995)
	Click burst	566	$19 \pm 1$ ( <i>n</i> =88)	-	$41 \pm 3$ ( <i>n</i> =88)	$45 \pm 3$ ( <i>n</i> =51)	[3-9] ( <i>n</i> =566)		
Narwhal	High- frequency clicks	300	69±14	30±11	52±11	23±9	-	-	Rassmus- sen et al. (2015)
Narwhal	Echolocation clicks	11	$71.3 \pm 15.1$	31.1±8.7	$81.5 \pm 25.4$	$18.3 \pm 3.7$	-	$215\pm 6$	Koblitz et al. (2016)
Narwhal	Echolocation clicks	8782	$43.7 \pm 7.8$	$6.5 \pm 3.9$	$26.2 \pm 12.1$	$592.9 \pm 488.0$	$143.5 \pm 70$	-	Zahn et al. (2021)

Table 1 Review of published beluga and narwhal click parameters

Mean and standard deviation listed when available. Values reported as range are listed in brackets. Approximated values from text are noted with ~. Studies included only if two or more parameters reported for a species

clicks and whistles in year-round acoustic recordings and from satellite telemetry locations of tagged animals (Hauser et al. 2017; Stafford et al. 2018). Belugas are the only odontocetes commonly detected in this area, with occasional annual presence of killer whales (Orcinus orca) closer to the north coast of Alaska (Hannay et al. 2013). The second recording site (Fig. 1, site PI) was in northwest Baffin Bay, 60 km east of the north Baffin Island community of Pond Inlet at the eastern entrance to Eclipse Sound at seafloor depth 670 m. Narwhal annual presence occurs in the Eclipse Sound region between July and November, with an estimated summering population of approximately 10,400 narwhal (Doniol-Valcroze et al. 2019). Narwhal are the dominant odontocete species in this region, with occasional presence of sperm whales (Physeter macrocephalus) and killer whales (Frouin-Mouy et al. 2017; Lefort et al. 2020). Both recording locations are covered with sea ice for approximately nine months annually, with freeze-up and break-up occurring in October-Nov and July-Aug, respectively (Tivy et al. 2011; Stroeve et al. 2014).

Acoustic recordings were made using High-frequency Acoustic Recording Packages (HARPs), which are bottommounted acoustic recorders capable of recording broadband (100 kHz) underwater sound for periods of up to a year (Wiggins and Hildebrand 2007). The HARP units recorded at a sampling rate of 200 kHz, with the CS HARP on a schedule of 10 min recording followed by 5 min of nonrecording, for a duty-cycle of 66.7% between May 28 and October 10, 2014, while the PI HARP recorded continuously between May 28 and Nov 1, 2016. The same hydrophone was used during both deployments; these data were selected from among other years of acoustic data collected at the CS and PI locations to simplify comparisons of acoustic measurements between the recording sites. The hydrophone consisted of two stages, one for low-frequency (<25 kHz) and one for high-frequency (>25 kHz). The low-frequency stage



Fig. 1 High-frequency acoustic recording packages (HARPs; yellow squares) were deployed at locations in the northeast Chukchi Sea, northeast Baffin Bay, and Barrow Strait. The Chukchi Sea HARP (CS) was deployed to depth 323 m on the Chukchi Sea outer shelf.

The pond inlet HARP (PI) was deployed to depth 670 m 60 km east of the community of pond inlet, Nunavut, at the eastern entrance to Eclipse Sound

was composed of six cylindrical transducers (Benthos AQ-1) wired in series (3) and parallel (2), providing a hydrophone sensitivity of -187 decibels (dB) re: V/µPa and with an additional 55 dB of preamp gain. The high-frequency stage consisted of a spherical omni-directional transducer (ITC-1042; www.itctransducers.com) with an approximately flat frequency response of -200 dB root mean squared (RMS) re 1 V/µPa between 1 and 100 kHz with an additional 50 dB of preamplifier gain.

#### Signal detection and description

To facilitate data analysis, long-term spectral averages (LTSAs) were calculated from consecutive 5 s averaged sound pressure spectrum levels with 100 Hz frequency bins for all data. Received sound pressure level (SPL) measurements are reported in units of decibels (dB) with reference pressure of 1  $\mu$ Pa, and sound pressure spectrum levels are reported in units of dB re 1  $\mu$ Pa<sup>2</sup>/Hz.

Echolocation clicks were detected and characterized using automated signal detection, confirmed with visual validation. All signal processing was performed using custom software written in MATLAB (Mathworks). Acoustic data were first processed using a band-pass filter between 5 and 90 kHz. Individual echolocation clicks were then detected within the filtered data using a two-stage process. In the first stage, a suite of energy detection criteria were used to identify impulsive signals (Frasier et al. 2017). A 200-sample window was analyzed for each detection, centered on the detected peak. Spectra for each detected impulse were calculated from the 200-sample window using a Hanning window to yield spectrum level measurements with frequency bin spacing of 500 Hz. Inter-click interval (ICI) was estimated from successive window start times. Detections that had peak frequencies between 15 and 90 kHz, received levels greater than 120 dB pp, and inter-click intervals less than 1 s were retained for the second stage of analysis.

In the second stage of analysis, detected signals were classified into impulse types using an unsupervised learning technique based on spectral shape and ICI distributions (Frasier et al. 2017). The process aided in the removal of false detections. Distinct impulse types were identified within 5-min time bins, collected into groups within each time bin, and then using an agglomerative clustering routine similar impulse types were determined across all the time bins (Frasier et al. 2017). The output from this process yielded a set of clusters, each containing impulsive detections with similar spectra and ICI.

Detections from each cluster were examined in the LTSA and recording time series to evaluate whether the cluster contained echolocation clicks. Impulse clusters with no obvious echolocation clicks were discarded. Detections with peak frequency less than 15 kHz within each retained cluster were labeled as false detections. Finally, all echolocation detections for each site were grouped and parameters estimated for click duration, ICI, averaged spectrum, peak and center frequency, and for 3 and 10 dB bandwidth. These parameters were estimated for four amplitude bins: 120–130, 130–140, 140–150, and > 150 dB pp, allowing for an understanding of how click properties may change with received level.

Click duration was estimated by fitting an envelope to the absolute value of the waveform in the 200-sample window for each click (Fig. 2). The start of each selected click was determined to be the point at which energy in the 60-samples prior to the peak reached 5% of total click energy. Click end points were determined from the point at which the energy under the envelope function, starting from 60 samples after



**Fig. 2** Representative click detection window of duration 0.8 ms (ms) centered on the detected echolocation click waveform (blue line). First and last 40 samples of window contain less than 10%, respectively of total energy. Envelope function (orange line) is drawn over the absolute value of all peaks in window. Estimated start and end times of the click (red circles) contain 90% of the total energy within the click window

and moving toward the peak, reached 5% of total energy. This yielded a click duration for 90% of total click energy. Clicks with more than 10% of total envelope energy in the first 40 or the last 40 samples of the window were removed to reduce noise in estimation of click duration.

Click trains were defined as sequences of 10 of more clicks with maximum ICI 0.5 s, which is the largest ICI reported for beluga or narwhal (Table 1). No maximum number of clicks was set for click trains. Events were defined as time periods containing 2 or more click trains with no more than a 15 min gap between trains. After more than 15 min passed with no click train detected, the next set of clicks meeting event criteria was assigned a new event number. Descriptive statistics were calculated for click train and event durations, number of clicks, and trains per event were calculated for each recording location.

# Discriminating between monodontid and other possible odontocete echolocation

The two recording locations provided an opportunity to describe the echolocation of each monodontid species with confidence since they are the only two odontocetes that occupy the high Arctic year-round. Narwhals are found primarily in the Canadian Arctic, off Greenland, Svalbard, and off Franz Josef Land in western Russia (Heide-Jørgensen 2018). Belugas are circumpolar in Arctic and sub-Arctic waters, extending west from the west coast of Greenland to western Russia (O'Corry-Crowe 2018). Both locations are covered with sea ice for ~9 months per year, restricting access for species not adapted to Arctic waters. During open water months there is a possibility of overlap with other occasional or extralimital odontocete species, so a set of criteria were developed to help avoid misidentification. Killer whales seasonally inhabit both the northeast Chukchi Sea and north Baffin Bay, with some evidence of increasing incursions into Pacific and Atlantic sectors of the Arctic (Higdon et al. 2014; Lefort et al. 2020; Willoughby et al. 2020). In addition, there is overlap in the acoustic characteristics of the echolocation clicks of killer whales and monodontids. Killer whale clicks are similar in frequency content among two North Atlantic and three North Pacific ecotypes, with peak frequency lying between 15 and 80 kHz (Barrett-Lennard et al. 1996; Au et al. 2004; Simon et al. 2007; Eskesen et al. 2011; Gassmann et al. 2013). Recording and analysis methods differ among studies of killer whale echolocation, making it difficult to determine a single set of acoustic characteristics diagnostic of their identification. Killer whales making incursions into the northeast Chukchi Sea and north Baffin Bay are known to be mammal eaters (Lefort et al. 2020; Willoughby et al. 2020). The killer whale ecotypes foraging on mammals are known to produce far fewer echolocation clicks than other fish-eating ecotypes (Barrett-Lennard et al. 1996; Deecke et al. 2005; Matkin et al. 2007). Sightings of this species are most often reported during summer months in ice-free conditions or when ice has broken up (Higdon et al. 2014; Stafford 2019). Echolocation clicks were detected in large numbers during times of the year with ice cover and were not accompanied by readily distinguishable social sounds of killer whales. The north Baffin Bay region is occupied seasonally by other odontocete species, including sperm whales, white beaked dolphins, and bottlenose whales (Frouin-Mouy et al. 2017), but echolocation clicks of narwhals are more readily distinguished from these non-monodontid species based on their published acoustic characteristics or their lack of overlap in seasonal distribution with Eclipse Sound narwhal. Similarly, beluga occupy north Baffin Bay but are rarely sighted in the Eclipse Sound region where the acoustic recorder was located. In contrast, the utilization of Eclipse Sound by narwhals as a summering area is well documented (Doniol-Valcroze et al. 2019).

#### **Environmental data acquisition and processing**

Data on sea ice were obtained to evaluate the impact of ice-cover on beluga and narwhal acoustic presence. Daily advanced microwave scanning radiometer 2 (AMSR2) 6.25 km spatial resolution sea ice data were obtained from the University of Bremen (Spreen et al. 2008; Melsheimer and Spreen 2019) and processed using windows image manager (WIM) and windows automation module (WAM) software (Kahru 2001) to produce a time series of mean daily sea ice concentration (SIC) within a 10 km radius about each recording site. The 10 km radius was selected to exclude land near site PI but was large enough to include several grid values in the estimation of daily mean at the recording site. WAM software was used to compute the daily arithmetic mean, variance, and median of the sea ice concentration as a percent of the total mask area.

### Results

#### Acoustic detections of echolocation clicks

Monodontid echolocation clicks were detected at both Arctic recording locations CS and PI. Click detection events followed a similar pattern, with relatively low received levels (RL) at the start of the event increasing to a maximum RL before falling off relatively rapidly (Figs. 3, 4). Within these events, individual click trains were apparent and tended to change RL by 5–10 dB within a click train for clicks with RL less than 140 dB<sub>pp</sub> and by up to 30 dB for clicks with RL greater than 140 dB<sub>pp</sub>. This pattern can be observed in the series of vertically aligned clicks in the RL plots for both sites (Figs. 3a, 4a).

**Fig. 3** Representative beluga echolocation event July 28, 2014 at the Chukchi Sea recording location. Time series plot of n=3505 click received levels (**a**; blue circles) and spectrogram (**b**) show levels increasing as group approaches the recording location. Inter-click interval (**c**) is commonly about 0.06 s throughout the event and becomes saturated as RL reaches maximum. Gray bars indicate scheduled periods of no recording





**Fig. 4** Representative narwhal echolocation event July 18, 2016 at the Pond Inlet recording location. Time series plot of n=1313 click received levels (**a**; blue circles) and spectrogram (**b**) show levels

increasing as group approaches the recording location. Inter-click interval (c) is variable throughout the event and becomes saturated as RL reaches maximum

At site CS, a consistent modal ICI of approximately 0.06 s was apparent in many click events (Fig. 3c). ICI tended to be relatively longer and more variable in events at site PI (Fig. 4c). Presumed narwhal click ICI at site PI was bimodal and right skewed, with the most common interval of less than 0.01 s, likely due to overlapping click trains from multiple animals, and a second mode with a peak at  $\sim$  0.14 s.

A total of 19,342 trains of presumed beluga echolocation clicks were detected at site CS during the May 28 to October 10, 2014, analysis period. Click trains were separated into 495 discrete detection events with mean duration  $23.9 \pm 26.1$  min. Modal and median event durations were 0.1 and 16.6 min. At site PI, 12,143 trains of presumed narwhal clicks were detected, and 286 events identified. Mean narwhal event duration was  $32.6 \pm 49.1$  min. Additional descriptive statistics for click train and event parameters are presented in Table 2.

A two-sample *t*-test was conducted to compare the distributions of click durations at CS and PI (Fig. 5). Beluga click durations at site CS ( $M = 74.9 \ \mu s$ ,  $SD = 14.5 \ \mu s$ , n = 5779) were significantly shorter than durations of narwhal clicks at

site PI ( $M = 80.3 \text{ } \mu\text{s}$ ,  $SD = 21.1 \text{ } \mu\text{s}$ , n = 925); t(6702) = 9.78, p < 0.00001 (Fig. 6).

Among detections at each site, sound pressure spectrum levels changed with received level (Fig. 7a-d). At higher received levels, peak frequencies were relatively higher and pulse durations were shorter (Table 3). As RL decreased, - 3 dB bandwidth became broader for belugas and stayed relatively consistent for narwhal clicks. At site CS, spectra of beluga clicks exhibited a steep increase in received energy above 35 kHz with peak energy at approximately 55-60 kHz (Fig. 7c). Narwhal clicks at site PI also had peak energy at approximately 55 kHz, but with more energy extending below 35 kHz and a secondary peak at 23 kHz (Fig. 7d). At lower received levels, this secondary peak in energy at 23 kHz was more prominent, becoming the peak frequency when RL was below 130  $dB_{pp}$ . Peak frequencies of echolocation clicks with  $RL > 150 dB_{pp}$ (Fig. 7e, f) were between 50 and 60 kHz at both recording locations, with click spectra containing more energy at lower frequencies when RL was less than 150  $dB_{pp}$ . Peak frequency of the received echolocation clicks increased

Beluga	Click trains $(n = 19, 34)$	42)	Click detection events $(n=495)$				
	Clicks per train	Duration (s)	Trains per event	Clicks per event	Duration (min)		
Mean	33	2.1	38	1258	23.91		
Std	43	2.1	48	1860	26.14		
Median	21	1.5	17	483	16.6		
Mode	11	1.2	2	62	0.1		
Range	[11-2089]	[0.1-89]	[2-318]	[22-12309]	[0.05–178.68]		
Narwhal	Click trains $(n=12,14)$	43)	Click detection events $(n=286)$				
	Clicks per train	Duration (s)	Trains per event	Clicks per event	Duration (min)		
Mean	27	3.1	41	1131	32.63		
Std	31	2.6	137	4921	49.1		
Median	19	2.5	10	214	16.31		
Mode	11	2	2	25	0.4		
Range	[11-693]	[0.1–58.2]	[2–1959]	[22–71416]	[0.06–378.66]		

Table 2 Descriptive statistics for beluga and narwhal echolocation click trains and click detection events

Value ranges (minimum and maximum) are listed in brackets





**Fig. 5** Normalized click waveform (panels **a** and **c**) and histogram of click duration (panels **b** and **d**) for select clicks between RL 140 and 160 dB<sub>pp</sub> from the CS (beluga) and PI (narwhal) recording sites.

Mean click durations of beluga and narwhal were  $74.9 \pm 14.5 \ \mu s$  (n = 5779) and  $80.3 \pm 21.1 \ \mu s$  (n = 925) respectively



**Fig. 6** Cumulative distribution functions for duration of clicks at CS (red line; beluga clicks) and PI (blue line; narwhal clicks)

with RL at both recording locations. At all received levels, detected narwhal clicks have more energy than beluga clicks at frequencies below 40 kHz.

Distributions of ICI differed substantially between the two sites. ICI of presumed beluga at site CS was bimodal (Fig. 8a), with the primary mode at 0.05 s and a secondary mode at < 0.005 s. At site PI, ICI was longer and more variable (Fig. 8b), with local maxima at < 0.005 and 0.14 s.

#### Time series of click detections

Beluga clicks were present in 112 of 135 days of recording, including periods with 100% sea ice cover during May and June and throughout the ice-free periods of August-October. An average of 10,000 clicks with RL > 120 dB were detected each day with acoustic presence of beluga echolocation at the CS site (Fig. 9). The highest day of acoustic presence (August 7, 2014) had 38,000 clicks. At site PI, narwhal echolocation clicks were only present in 36 of 121 days analyzed (May–November), primarily during sea ice break-up and formation. An average of 22,000 > 120 dB RL clicks were detected per day with acoustic presence of narwhal (Fig. 10). The highest day of acoustic presence (July 2, 2016) had 150,000 clicks.

Beluga echolocation clicks were detected during all sea ice conditions, including 65 days of open water. Daily counts of click detections were higher during ice-free months than in periods of ice cover. The period of sea ice formation was not recorded at CS, so acoustic detection of belugas at this time was not possible. Acoustic presence of narwhal coincided with sea ice breakup at site PI. Narwhal clicks were not detected during most of the ice-free period, then detections resumed during the 10 days leading up to continuous formation of sea ice and were not detected above 25% ice cover in October.

#### Discussion

# Similarities in beluga and narwhal echolocation clicks

Two consistent patterns are apparent in received levels during beluga and narwhal detection events. Received level variability within individual click trains increases (e.g. Figures 3, 4) and peak frequencies increase (Fig. 7e, f) as a traveling group apparently swims closer to the recorder. As detection events progress, the variability in RL within click trains increases from  $\pm 5$  dB as the running maximum RL of the event reaches 120–125 dB<sub>pp</sub> up to  $\pm$  15 dB for clicks as the maximum event RL exceeds 140  $dB_{pp}$ . The pattern of increased variability in received level within click trains as the overall event RL increases is likely due to scanning movements of the animals' heads coupled with the beam pattern of clicks as they are produced. Beluga and narwhal clicks are directional and the highest energy is directed straight in front of the melon. Within 15 deg off-axis, the click energy is reduced by > 20 dBin both species (Au et al. 1987; Koblitz et al. 2016). As orientation of animals change during dive behavior, RL would be expected to vary at the hydrophone. This pattern of received level variability has been observed in free-ranging narwhal as rapid changes in received level during click trains acoustically tracked to individual animals (Koblitz et al. 2016). The observed smaller range of click RL when the detected group is apparently farther from the hydrophone is consistent with expectations since more distant clicks would need to be closer to on-axis to propagate to the hydrophone. As the group apparently moves closer to the recording location, a larger number of off-axis clicks would have enough energy to reach the hydrophone.

There is a strong relationship between click received level els and frequency content at both locations. As received level decreases, clicks have less relative energy at higher frequencies. This general pattern is likely caused by sound transmission loss due to frequency-dependent absorption by seawater. Measured absorption at 25 kHz in standard seawater is around 3 dB/km, increasing to 10 and 20 dB/km at 50 and 75 kHz, respectively (Mellen 1987; Macaulay et al. 2020). Lower-frequency energy from both species clicks travels farther than the higher frequency components of the clicks. With more energy below 30 kHz than beluga clicks, theoretical absorption spectra predict narwhal click detection will occur at greater ranges from the recorder than beluga clicks.

# Discriminating features of beluga and narwhal clicks

The primary differences between beluga and narwhal clicks are in frequency content and rhythmic patterns of the



**Fig.7** Concatenated spectrograms of detected beluga (**a**) and narwhal (**b**) clicks are sorted by click received level (dB<sub>pp</sub>). Average sound pressure spectrum levels are plotted for beluga (**c**) and narwhal (**d**) clicks in 10 dB received level bins. Colored lines in average sound pressure spectra represent 120–130 dB (purple), 130–130 dB

(orange), 140–150 dB (red) and > 150 dB (blue) peak-to-peak sound pressure level. Bottom plots show normalized counts of peak frequency and received level (dB<sub>20-100 kHz</sub>) for beluga (e) and narwhal (f) clicks

inter-click intervals. Narwhal clicks contain more energy in the 20–30 kHz range and this difference becomes more pronounced as clicks travel away from the source. This difference between the two species has been used to differentiate between beluga and narwhal clicks, but from less than 200 representative clicks for each (Frouin-Mouy et al. 2017) and from recording duration ~ 7.5 h or less (Zahn et al. 2021). By including a much larger set of click detections across a greater range of received levels and environmental conditions, we substantially improve the confidence in using this characteristic for species identification and enable greater spatial context for received clicks. Although peak frequency

Table 3Descriptive statisticsfor beluga and narwhalecholocation clicks

Received	Beluga: Cł	nukchi Sea			Narwhal: Eclipse Sound			
level (dB <sub>pp</sub> )	120–130	130-140	140-150	>150	120–130	130–140	140-150	>150
Pulse duratio	n (µs)							
Mean	87.6	80.3	74.9	74.7	85.3	83.7	78.7	79.3
Std	17.5	16	14.6	15.2	18.6	18.9	19.1	16
Mode	85	75	70	70	75	85	80	70
Median	85	80	75	75	85	85	80	80
n	5452	12,819	5472	265	5267	5646	2582	1069
ICI (ms)								
Mean	77.9	62.3	86.5	77.9	162.4	157.4	159.7	172.8
Std	88.5	55.8	91.1	69.9	137.3	131.6	131.1	143.9
Mode	48.6	49.5	1.6	42.1	4.1	1.6	2.8	4.4
Median	54.1	53.2	58.4	60.6	129.3	128.8	131.5	132.7
n	608,959	155,505	23,380	943	486,262	124,957	21,399	1069
Peak frequen	cy (kHz)							
Mean	53.2	58	63	66	39.1	45.4	51.6	57.6
Std	12.3	11.5	10.9	9.9	13.4	12.5	10.4	9.7
Mode	53	56	56	64.5	22.5	23.5	56	56.5
Median	52	55.5	60.5	64.5	39	48	52.5	56.5
- 3 dB band	width (kHz)							
Mean	12.7	11.1	7.2	7.9	5.2	4.6	4.8	6.9
Std	7.3	6.6	4.9	4.9	5	4.2	4.2	5.8
Mode	3	2.5	2.5	3	2	2	2	2.5
Median	12	11	6	7	3	3	3	4.5
- 10 dB ban	dwidth (kHz	)						
Mean	35.6	33.5	31.1	35.1	17.5	18.1	20.4	30.8
Std	15	15.1	13.4	12.1	14.4	13.8	14.2	14.8
Mode	35	31.5	25.5	25.5	3	3	4.5	40.5
Median	35	33	30	33.5	13	14.5	17	32
п	688,601	158,836	23,946	953	616,536	148,557	25,433	1379



**Fig. 8** ICI of beluga (**a**) and narwhal (**b**) clicks. Distributions of both species bimodal. Beluga clicks primary mode around 60 ms and secondary mode < 10 ms while narwhal ICI are right skewed with modal values primary mode < 10 ms and secondary mode 144 ms

changes with received level for clicks of both species, the patterns are species-specific (Fig. 7e, f) and may be particularly useful in future acoustic studies where the two species may occur at one recording location. It is helpful that the differences in frequency spectra of the two species' clicks are most readily distinguishable at lower received levels, which are likely to be most abundant in detection time series.

ICI differed between beluga and narwhal. Both species ICI distributions were bimodal with one mode below 10 ms, likely due to the presence of buzzes along with overlapping **Fig. 9** Number of beluga echolocation click detections per day (gray bars) at the CS site during the 2014 recording period analyzed. Mean daily sea ice concentration (blue line) decreased from Jul 21 through Aug 7, followed by open water for the reminder of the analysis period

**Fig. 10** Number of narwhal echolocation click detections per day (gray bars) at the PI site during the 2016 recording period analyzed. Mean daily sea ice concentration (blue line) decreased from Jun 1 through Jul 10, followed by open water for the remainder of the analysis period



clicks from multiple animals and a combination of direct path clicks and echoes. Beluga clicks primary modal ICI was around 50 ms. Narwhal ICI was much more variable and right skewed, with the primary mode below 10 ms and a secondary mode at 140 ms. These differences in ICI may relate to species behavior at the recording locations. Buzzes with ICI < 10 ms are commonly produced by belugas and narwhals (Au et al. 1987; Miller et al. 1995; Roy et al. 2010) and have been associated with active foraging in both species (Blackwell et al. 2018; Castellote et al. 2021). In Cook Inlet, Alaska, beluga feeding click trains with terminal buzzes differed in ICI distribution from buzzes made while socializing (Castellote et al. 2021). Social buzzes had longer and more variable ICI. Similarly, narwhal exhibit distinct modes of diving behavior (Ngô et al. 2019) with greater numbers of buzzes produced at depth when foraging than during shallower dives associated with traveling and social behavior (Blackwell et al. 2018).

ICI analysis of a small number of detected clicks may have limited the usefulness for discrimination between the species. This characteristic may be diagnostic in larger sets of clicks where ICI distributions can be determined with confidence over periods long enough to observe a greater range of behavioral states. The use of ICI for discrimination between beluga and narwhal clicks should be investigated further in long-term recordings from a range of locations and behavioral contexts.

A potential improvement could be made by rhythmic analysis to attribute overlapping click trains to individual sources. Time-ICI analyses have been successful in de-interleaving click trains of simultaneous clicking belugas (Le Bot et al. 2015). This time-ICI analysis uses a single hydrophone and can greatly improve the resolution of ICI distributions, especially during high-density click detection events that were common in this study.

#### Detection time series of belugas and narwhals

Narwhal presence at site PI coincided closely with the short periods of sea ice breakup and freeze-up in July and October, respectively. The Eclipse Sound population of narwhal are known to enter Eclipse Sound around the time of sea ice break-up and exit again for the year around freeze-up (Watt et al. 2012; White 2012; Ariak and Olson 2019). Animals in this population spend the ice-free summer months within Eclipse Sound and its interior inlets and bays. The strongly pulsed seasonal signal to narwhal detection matches the expected acoustic presence of the species at the PI site, which is at the eastern entrance to Eclipse Sound. Dates of narwhal entry and exit from eclipse sound are relevant for management of this population with respect to regional shipping and this annual timing may be reliably detected acoustically from the PI recording location.

Beluga presence at CS began in early May during 100% sea ice coverage at the recording site. Belugas were present at this offshore location in > 90% sea ice cover for 1.5 months before the onset of continuous melt occurred. Their seasonal acoustic presence agrees with known movements of two populations of belugas that inhabit the Chukchi Slope region between early sea ice breakup and well into freeze-up in October and November (Hauser et al. 2017). Although click detection spanned May–October, daily click

detection counts were higher during open water periods than with ice cover. This could be due to the scattering effects of sea ice on beluga clicks, which reduces the probability of detection. A similar study on detection probability of echolocation clicks in the Gulf of Mexico demonstrated that propagation loss is a significant factor in detection probability (Frasier et al. 2016). The results of this study confirm that effect of sea ice scattering on beluga and narwhal click detection ranges and detection probability is an area that should be further investigated.

## Conclusions

Echolocation clicks of beluga and narwhal can be detected in long-term acoustic recordings using a relatively simple semi-automated process. These detected clicks can be used to discriminate between the species' signals acoustically, provided a sufficient sample size of clicks are recorded to observe distributions of key characteristics including peak frequency, sound pressure spectrum levels, and inter-click interval. Effects of sound propagation and the behavior and physiology of the animals must be accounted for when evaluating the results of click detection. This is needed to increase confidence in the species identification and make use of passive acoustic recordings as inputs to models for acoustic estimation of population density.

Received level variability in individual click trains may also provide insight into animal dive behavior. If sound propagation is accounted for, these characteristics of recorded echolocation events likely reflect dive behavior (scanning motion) and physiology of sound production (beam pattern). Similarly, increasing understanding of narwhal and beluga dive behavior and underwater movements could improve strength of inference about group composition and behavior from time series of acoustic detections.

Density estimation using acoustic methods requires understanding of the source signal, the effect of propagation on the received signal characteristics, group composition and behavior, and detailed information on the dive behavior, physiology, and rates of sound production in individual animals. A remaining challenge presented by monodontid species, particularly narwhal, is to distinguish between buzzes with short ICI and overlapping click trains of multiple animals. Additionally, most detections in this study occurred during periods of mostly open water or ice-free conditions. The influence of sea ice on received characteristics of echolocation clicks should also be further investigated in the future to help clarify and improve acoustic observations of beluga and narwhal presence in long-term acoustic recordings.

The success in detecting and discriminating between the species using the methods developed in this study will permit additional research using passive acoustic monitoring to study the seasonal movements and distribution of these species. In particular, it would be useful to focus further on developing acoustic methods for beluga and narwhal abundance estimates using echolocation clicks.

Acknowledgements We thank the Mittimatalik Hunters & Trappers Organization, Pond Inlet, Nunavut, Canada, for annual permission to carry out fieldwork and acoustic recording. Acoustic data collection and fieldwork could not have been completed without expert knowledge and technical, logistical, and vessel support provided by Alex J. Ootoowak. We also thank Sheattie Tagak and Tagak Outfitters for additional vessel support. Amanda Joynt of Oceans North was also instrumental in motivating and sustaining this research program. Thanks to Evan Richardson and Environment and Climate Change Canada, for substantial logistical support at the Pond Inlet Research Facility. This project is funded through a private foundation grant to the Marine Physical Laboratory at the Scripps Institution of Oceanography and by Oceans North, with additional support provided by Environment and Climate Change Canada through a grant from the World Wildlife Fund-Canada. We thank members of the Scripps Whale Acoustics Laboratory, including B. J. Thayre, J. Hurwitz, E. O'Neill-Mertz, and S. Wager for assistance with HARP operations and data processing. Special thanks to Dr. Phillip McGillivary, Dr. Julie D. Lee, and Dr. Andrew Mack, who provided helpful comments on this manuscript, as well as W. Halliday and one anonymous reviewer.

Author contributions All authors contributed to the study conception and design. AJO, KHW, JMJ, SMW, and JAH were responsible for data acquisition. KEF contributed substantially to analytical methods for signal processing, detection, and classification. JMJ wrote the manuscript. All authors read and approved the manuscript.

**Funding** Partial funding for this research was received from Ocean North, World Wildlife Fund, and through a gift from a private, non-operating US-based charitable institution wishing to remain anonymous.

**Data availability** The datasets generated during the current study are available from the corresponding author on reasonable request.

#### Declarations

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

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

## References

- Ainslie MA (2013) Neglect of bandwidth of odontocetes echo location clicks biases propagation loss and single hydrophone population estimates. J Acoust Soc Am 134:3506–3512. https://doi.org/10. 1121/1.4823804
- Ariak E, Olson R (2019) Qikiqtani inuit association's tusaqtavut for phase 2 application of the mary river project. Qikiqtani Inuit Association Final Report https://Www.Nirb.Ca/Portal/Dms/

Script/Dms\_Download.Php?Fileid=325450&Applicationid=124701&Sessionid=B83etr131bg3jvioocef51h393

- Au WWL (1993) The sonar of dolphins. Springer-Verlag, New York
- Au WWL, Carder DA, Penner RH, Scronce BL (1985) Demonstration of adaptation in beluga whale echolocation signals. J Acoust Soc Am 77:726–730. https://doi.org/10.1121/1.392341
- Au WWL, Ford JKB, Horne JK, Allman KAN (2004) Echolocation signals of free-ranging killer whales (*Orcinus Orca*) and modeling of foraging for chinook salmon (*Oncorhynchus Tshawytscha*). J Acoust Soc Am 115:901–909
- Au WWL, Moore PWB, Pawloski D (1986) Echolocation transmitting beam of the Atlantic bottlenose dolphin. J Acoust Soc Am 80:688–691. https://doi.org/10.1121/1.394012
- Au WWL, Pawloski JL, Nachtigall PE, Blonz M, Gisner RC (1995) Echolocation signals and transmission beam pattern of a false killer whale (*Pseudorca crassidens*). J Acoust Soc Am 98:51–59. https://doi.org/10.1121/1.413643
- Au WWL, Penner RH, Turl CW (1987) Propagation of beluga echolocation signals. J Acoust Soc Am 82:807–813. https://doi.org/ 10.1121/1.395278
- Barrett-Lennard LG, Ford JKB, Heise KA (1996) The mixed blessing of echolocation: differences in sonar use by fish-eating and mammal-eating killer whales. Anim Behav 51:553–565. https:// doi.org/10.1006/Anbe.1996.0059
- Baumann-Pickering S, Mcdonald MA, Simonis AE, Berga AS, Merkens KP, Oleson EM, Roch MA, Wiggins SM, Rankin S, Yack TM, Hildebrand J (2013) Species-specific beaked whale echolocation signals. J Acoust Soc Am 134:2293–2301. https://doi.org/ 10.1121/1.4817832
- Castellote M, Mooney A, Andrews R, Deruiter S, Lee W, Ferguson M, Wade P (2021) Beluga whale (*Delphinapterus Leucas*) acoustic foraging behavior and applications for long-term monitoring. PLoS ONE 16(11):E0260485. https://doi.org/10.1371/Journal. Pone.0260485
- Deecke VB, Ford JKB, Slater PJB (2005) The vocal behaviour of mammal-eating killer whales: communicating with costly calls. Anim Behav 69:395–405. https://doi.org/10.1016/J.Anbehav. 2004.04.014
- Doniol-Valcroze T, Gosselin J-F, Pike DG, Lawson JW, Asselin NC, Hedges K, Ferguson SH (2019) Narwhal abundance in the Eastern Canadian high Arctic in 2013. Nammco Sci Pub Doi 10(7557/3):5100
- Eskesen IG, Wahlberg M, Simon M, Larsen ON (2011) Comparison of echolocation clicks from geographically sympatric killer whales and long-finned pilot whales (L). J Acoust Soc Am 130:9–12. https://doi.org/10.1121/1.3583499
- Frasier KE, Roch MA, Soldevilla MS, Wiggins SM, Garrison LP, Hildebrand JA (2017) Automated classification of dolphin echolocation click types from the Gulf of Mexico. PloS Comp Biol 13:E1005823. https://doi.org/10.1371/Journal.Pcbi.1005823
- Frasier KE, Wiggins SM, Harris D, Marques TA, Thomas L, Hildebrand JA (2016) Delphinid echolocation click detection probability on near-seafloor sensors. J Acoust Soc Am 140:1918–1930. https://doi.org/10.1121/1.4962279
- Frouin-Mouy H, Kowarski K, Martin B, Bröker K (2017) Seasonal trends in acoustic detection of marine mammals in Baffin bay and Melville bay northwest Greenland. Arctic. https://doi.org/10. 14430/Arctic4632
- Gassmann M, Henderson EE, Wiggins SM, Roch MA, Hildebrand JA (2013) Offshore killer whale tracking using multiple hydrophone arrays. J Acoust Soc Am 134:3513–3521. https://doi.org/ 10.1121/1.4824162
- Gassmann M, Wiggins SM, Hildebrand JA (2015) Three-dimensional tracking of cuvier's beaked whales' echolocation sounds using nested hydrophone arrays. J Acoust Soc Am 138:2483–2494. https://doi.org/10.1121/1.4927417

- Hannay DE, Delarue J, Mouy X, Martin BS, Leary D, Oswald JN, Vallarta J (2013) Marine mammal acoustic detections in the Northeastern Chukchi Sea, September 2007–July 2011. Cont Shelf Res 67:127–146. https://doi.org/10.1016/J.Csr.2013.07.009
- Hauser DD, Laidre KL, Stern HL, Moore SE, Suydam RS, Richard PR (2017) Habitat selection by two Beluga whale populations in the Chukchi and Beaufort seas. PLoS ONE 12:E0172755. https://doi. org/10.1371/Journal.Pone.0172755
- Heide-Jørgensen MP (2018) Narwhal: Monodon monoceros. In: Würsig B, Thewissen JGM, Kovacs KM (eds) Encyclopedia of marine mammals, 3rd edn. Academic Press, Cambridge, pp 627–631
- Higdon JW, Westdal KH, Ferguson SH (2014) Distribution and abundance of killer whales (*Orcinus orca*) in Nunavut, Canada—an Inuit knowledge survey. J Mar Biol Assoc UK 94:1293–1304. https://doi.org/10.1017/S0025315413000921
- Hildebrand JA, Baumann-Pickering S, Frasier KE, Trickey JS, Merkens KP, Wiggins SM, Mcdonald MA, Garrison LP, Harris D, Marques TA, Thomas L (2015) Passive acoustic monitoring of beaked whale densities in the Gulf of Mexico. Sci Rep 5:16343. https://doi.org/10.1038/Srep16343
- Hildebrand JA, Frasier KE, Baumann-Pickering S, Wiggins SM, Merkens KP, Garrison LP, Soldevilla MS, Mcdonald MA (2019) Assessing seasonality and density from passive acoustic monitoring of signals presumed to be from pygmy and dwarf sperm whales in the Gulf of Mexico. Front Mar Sci 6:66. https://doi.org/ 10.3389/Fmars.2019.00066
- Jones JM, Thayre BJ, Roth EH, Mahoney M, Sia I, Merculief K, Jackson C, Zeller C, Clare M, Bacon A, Weaver S, Gentes Z, Stirling I, Wiggins SM, Hildebrand JA (2014) Ringed, bearded, and ribbon seal vocalizations north of barrow, Alaska: seasonal presence and relationship with sea ice. Arctic 67:203–222. https://doi.org/10. 14430/Arctic4388
- Kahru M (2001) Windows image manager: image display and analysis program for microsoft windows with special features for satellite images
- Koblitz JC, Stilz P, Rasmussen MH, Laidre KL (2016) Highly directional sonar beam of Narwhals (*Monodon monoceros*) measured with a vertical 16 hydrophone array. PLoS ONE 11:E0162069. https://doi.org/10.1371/Journal.Pone.0162069
- Küsel ET, Mellinger DK, Thomas L, Marques TA, Moretti D, Ward J (2011) Cetacean population density estimation from single fixed sensors using passive acoustics. J Acoust Soc Am 129:3610–3622. https://doi.org/10.1121/1.3583504
- Le Bot O, Mars JI, Gervaise C, Simard Y (2015) Rhythmic analysis for click train detection and source separation with examples on Beluga whales. J Appl Acoust 95:37–49. https://doi.org/10.1016/J. Apacoust.2015.02.005
- Lefort KJ, Garroway CJ, Ferguson SH (2020) Killer whale abundance and predicted narwhal consumption in the Canadian Arctic. Global Change Biol 26:4276–4283. https://doi.org/10.1111/Gcb. 15152
- Macaulay GJ, Chu D, Ona E (2020) Field measurements of acoustic absorption in seawater from 38 To 360 Khz. J Acoust Soc Am 148:100–107. https://doi.org/10.1121/10.0001498
- Marques TA, Thomas L, Ward J, Dimarzio N, Tyack PL (2009) Estimating cetacean population density using fixed passive acoustic sensors: an example with Blainville's beaked whales. J Acoust Soc Am 125:1982–1994. https://doi.org/10.1121/1.3089590
- Matkin CO, Barrett-Lennard LG, Yurk H, Ellifrit D, Trites AW (2007) Ecotypic variation and predatory behavior among killer whales (*Orcinus orca*) off the Eastern Aleutian Islands, Alaska. Fish Bull 105:74–87
- Mellen R (1987) Global model for sound absorption in sea water. No 7932. Naval Underwater Systems Center

- Melsheimer C, Spreen GL (2019) Amsr2 asi sea ice concentration data, Arctic, Version 5.4 (Netcdf) (July 2012–December 2018). Doi: 10.1594/Pangaea.898399
- Miller LA, Pristed J, Mohl B, Surlykke A (1995) The click-sounds of Narwhals (*Monodon monoceros*) in Inglefield Bay, Northwest Greenland. Mar Mamm Sci 11:491–502. https://doi.org/10.1111/J. 1748-7692.1995.Tb00672.X
- Morrissey R, Ward J, Dimarzio N, Jarvis S, Moretti D (2006) Passive acoustic detection and localization of sperm whales (*Physeter macrocephalus*) in the tongue of the ocean. Appl Acoust 67:1091– 1105. https://doi.org/10.1016/J.Apacoust.2006.05.014
- Møhl B, Surlykke A, Miller LA (1990) High intensity Narwhal clicks.
  In: And TJA, Kastelein RA (eds) Sensory abilities of cetaceans.
  Nato ASI series (Series A: life sciences), vol 196. Springer, Boston
- Ngô MC, Heide-Jørgensen MP, Ditlevsen S (2019) Understanding Narwhal diving behaviour using hidden markov models with dependent state distributions and long range dependence. Plos Comput Biol 15(3):E1006425. https://doi.org/10.1371/Journal. Pcbi.1006425
- O'Corry-Crowe GM (2018) Beluga whale: *Delphinapterus leucas*. In: Würsig B, Thewissen JGM, Kovacs KM (eds) Encyclopedia of marine mammals, 3rd edn. Academic Press, Cambridge, pp 93–96
- Rasmussen MH, Koblitz JC, Laidre KL (2015) Buzzes and high-frequency clicks recorded from Narwhals (*Monodon Monoceros*) at their wintering ground. Aquat Mamm. https://doi.org/10.1578/ Am.41.3.2015.256
- Roy N, Simard Y, Gervaise C (2010) 3d tracking of foraging belugas from their clicks: experiment from a coastal hydrophone array. Appl Acoust 71:1050–1056. https://doi.org/10.1016/J.Apacoust. 2010.05.008
- Seger K, Miksis-Olds JL (2020) A decade of marine mammal acoustical presence and habitat preference in the Bering sea. Polar Biol 43:1549–1569. https://doi.org/10.1007/S00300-020-02727-X
- Simon M, Wahlberg M, Miller LA (2007) Echolocation clicks from killer whales (*Orcinus Orca*) feeding on herring (*Clupea Harengus*). J Acoust Soc Am 121:749–752. https://doi.org/10.1121/1. 2404922
- Spreen G, Kaleschke L, Heygster G (2008) Sea ice remote sensing using Amsr-E 89-Ghz channels. J Geophys Res 113:1–14. https:// doi.org/10.1029/2005jc003384
- Stafford KM (2019) Increasing detections of killer whales (Orcinus Orca), in the Pacific Arctic. Mar Mamm Sci 35:696–706. https:// doi.org/10.1111/Mms.12551
- Stafford KM, Ferguson MC, Hauser DD, Okkonen SR, Berchok CL, Citta JJ, Clarke JT, Garland EC, Jones J, Suydam RS (2018) Beluga whales in the western Beaufort sea: current state of knowledge on timing, distribution, habitat use and environmental drivers. Deep Sea Res Part II 152:182–194. https://doi.org/10.1016/J. Dsr2.2016.11.017
- Stroeve JC, Markus T, Boisvert L, Miller J, Barrett A (2014) Changes in Arctic melt season and implications for sea ice loss. Geophys Res Lett 41:1216–1225. https://doi.org/10.1002/2013gl058951

- Tivy A, Howell SE, Alt B, Mccourt S, Chagnon R, Crocker G, Carrieres T, Yackel JJ (2011) Trends and variability in summer sea ice cover in the Canadian Arctic based on the Canadian ice service digital archive, 1960–2008 and 1968–2008. J Geophys Res. https://doi.org/10.1029/2009jc005855
- Trickey JS, Baumann-Pickering S, Hildebrand JA, Reyes Reyes MV, Melcón M, Iñíguez M (2015) Antarctic beaked whale echolocation signals near South Scotia Ridge. Mar Mamm Sci 31:1265– 1274. https://doi.org/10.1111/Mms.12216
- Turl CW, Skaar DJ, Au WW (1991) The echolocation ability of the beluga (*Delphinapterus Leucas*) to detect targets in clutter. J Acoust Soc Am 89(2):896–901. https://doi.org/10.1121/1.18946 51
- Watt CA, Orr J, Leblanc B, Richard P, Ferguson SH (2012) Staellite tracking Of Narwhals (*Monodon Monoceros*) from admiralty inlet (2009) and eclipse sound (2010–2011). Fisheries and Oceans Canada, Canadian Science Advisory Secretariat [Research Doc. 2012/046]
- White A (2012) A synthesis of Narwhal (*Monodon Monoceros*) scientific advice and inuit knowledge collected during nunavut community consultations (May 25–31, 2011). Fisheries and Oceans Canada, Canadian Science Advisory Secretariat [Research Doc. 2012/001].
- Wiggins SM, Hildebrand JA (2007) High-frequency acoustic recording package (Harp) for broad-band, long-term marine mammal monitoring International Symposium on Underwater Technology 2007 and International Workshop on Scientific use of Submarine Cables & Related Technologies 2007. Institute of Electrical and Electronics Engineers, Tokyo, Japan, Pp 551–557
- Willoughby AL, Ferguson MC, Stimmelmayr R, Clarke JT, Brower AA (2020) Bowhead whale (*Balaena Mysticetus*) and killer whale (*Orcinus Orca*) co-occurrence in the US Pacific Arctic, 2009–2018: evidence from bowhead whale carcasses. Polar Biol 43:1669–1679. https://doi.org/10.1007/S00300-020-02734-Y
- Zahn MJ, Rankin S, Mccullough JL, Koblitz JC, Archer F, Rasmussen MH, Laidre KL (2021) Acoustic differentiation and classification of wild belugas and narwhals using echolocation clicks. Sci Rep 11:1–16. https://doi.org/10.1038/S41598-021-01441-W
- Blackwell SB, Tervo OM, Conrad AS, Sinding MHS, Hansen RG, Ditlevsen S, Heide-Jørgensen MP, Cooper G (2018) Spatial and temporal patterns of sound production in East Greenland narwhals. PLOS ONE 13(6):e0198295. https://doi.org/10.1371/journ al.pone.0198295

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.