| | |
|---|---|
| **Brevdato** | 30-05-2024 |
| **Afsender** | Talea Weissang (Talea.Weissang@wwf.dk) |
| **Modtagere** | Officiel post til APN (Postkasse, Departementet for Fiskeri, Fangst og Landbrug) |
| **Akttitel** | WWF Høringssvar til ny bekendtgørelse om beskyttelse og fangst af hvid- og narhvaler |
| **Identifikationsnummer** | 24236263 |
| **Versionsnummer** | 1 |
| **Ansvarlig** | Masaana Dorph |
| **Vedlagte dokumenter** | WWF Høringssvar til ny bekendtgørelse om beskyttelse og fangst af hvid- og narhvaler<br>WWF Høringssvar APN ny BKG Narhval og hvidhval 2024 DOKUMENT IKKE MEDTAGET<br>Trevo et al 2021 narwhal response to underwater noise<br>Marine Mammal Science - 2022 - Martin - Exposure and behavioral responses of tagged beluga whales Delphinapterus leucas<br>Lancaster, Winsor, Dumbrille_excerpt underwater noise book chapter |
| **Dokumenter uden PDF-version (ikke vedlagt)** | |
| **Udskrevet** | 06. jun 2024 |

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**Titel:** WWF Høringssvar til ny bekendtgørelse om beskyttelse og fangst af hvid- og narhvaler
**Sendt:** 30-05-2024 20:37
**Bilag:** WWF Høringssvar APN ny BKG Narhval og hvidhval 2024.pdf; Trevo et al 2021 narwhal response to underwater noise.pdf; Marine Mammal Science - 2022 - Martin - Exposure and behavioral responses of tagged beluga whales Delphinapterus leucas.pdf; Lancaster, Winsor, Dumbrille_excerpt underwater noise book chapter.pdf;

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Vi står gerne til rådighed hvis der opstår spørgsmål ifm. vores høringssvar og vil altid gerne indgå i en konstruktiv, løsningsorienteret dialog.

Med venlig hilsner

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**Cite this article:** Tervo OM, Blackwell SB, Ditlevsen S, Conrad AS, Samson AL, Garde E, Hansen RG, Mads Peter H-J. 2021 Narwhals react to ship noise and airgun pulses embedded in background noise. *Biol. Lett.* **17**: 20210220.
https://doi.org/10.1098/rsbl.2021.0220

Received: 22 April 2021
Accepted: 18 October 2021

**Subject Areas:**
behaviour

**Keywords:**
narwhal, noise, airgun, arctic, foraging, disturbance

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Electronic supplementary material is available online at https://doi.org/10.6084/m9.figshare.c.5674554.

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Animal behaviour

# Narwhals react to ship noise and airgun pulses embedded in background noise

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Anthropogenic activities are increasing in the Arctic, posing a threat to niche-conservative species with high seasonal site fidelity, such as the narwhal *Monodon monoceros*. In this controlled sound exposure study, six narwhals were live-captured and instrumented with animal-borne tags providing movement and behavioural data, and exposed to concurrent ship noise and airgun pulses. All narwhals reacted to sound exposure with reduced buzzing rates, where the response was dependent on the magnitude of exposure defined as 1/distance to ship. Buzzing rate was halved at 12 km from the ship, and whales ceased foraging at 7–8 km. Effects of exposure could be detected at distances > 40 km from the ship.At only a few kilometres from the ship, the received high-frequency cetacean weighted sound exposure levels were below background noise indicating extreme sensitivity of narwhals towards sound disturbance and demonstrating their ability to detect signals embedded in background noise. The narwhal's reactions to sustained disturbance may have a plethora of consequences both at individual and population levels. The observed reactions of the whales demonstrate their auditory sensitivity but also emphasize, that anthropogenic activities in pristine narwhal habitats needs to be managed carefully if healthy narwhal populations are to be maintained.

## 1. Introduction

The break-up of sea-ice in the spring as well as calving from glacial fronts and breakdown of icebergs create variable and temporally unpredictable background noise conditions in the Arctic environment that challenge detection and discrimination of acoustic signals [1–3]. Masking of acoustic signals refers to background noise re with the detection of signals of interest, either simultaneously in the frequency domain or in the time domain. Simultaneous masking hinges on the width of the critical band that determines the ability of an individual to discriminate between two nearby frequencies and on the ratio of signal power to noise spectrum level at masked thresholds [4,5]. Directional hearing also plays a role in determining the ability of an animal to localize a sound source in the presence of background noise [6].

Marine mammals use sound for gaining information about their surroundings, including prey, and are, together with echolocating bats, the mammalian groups most specialized to use sound (e.g. [6,7]). Masking studies performed on a handful of species in captivity have demonstrated the extraordinary auditory aptitudes and the complexity of the odontocete sensory system (see [6] for review). Studies of captive whales do not, however, fully address the ability of signal detection in free-ranging whales. Controlled sound exposure studies in the wild in which received sound levels are recorded by animal-borne sensors can be used to determine sound exposure thresholds for behavioural responses. Since the received level at the animal depends on a number of factors including the environment's sound speed profile, and the depth and behaviour of the animal, measuring the received level can be challenging, but studies of behavioural responses can still be used as invaluable indicators of signal detection [8,9].

For the major part of the year, the Arctic is relatively pristine in terms of man-made noise [10,11]. This is changing as a result of a global warming-induced decrease in sea-ice coverage that is making the Arctic more accessible to anthropogenic activities, in both space and time [12–14]. The narwhal, *Monodon monoceros*, is an Arctic toothed whale species that inhabits fjords with erratic ambient noise levels during summer and quieter offshore pack-ice habitats during winter. All studied populations exhibit high-site fidelity towards summer and winter grounds, thereby apparently lacking the plasticity in migratory patterns [15] that is critical for avoiding sustained disturbance. Narwhals must therefore be considered particularly vulnerable to changes in their habitat.

In a controlled sound exposure study, we combined movement and behavioural data from animal-borne tags on narwhals during ship noise and airgun pulse sound exposure trials. We used this information to assess the sensitivity of narwhals to sound exposure in a pristine Arctic soundscape by quantifying sound exposure thresholds for a behavioural response connected to feeding.

## 2. Material and methods

Six male narwhals were live-captured in August 2018 in the Scoresby Sound fjord system in East Greenland in collaboration with local Inuit hunters and instrumented with backpack FastLoc GPS-receivers (Wildlife Computers (Redmond, Seattle, WA, USA) collecting an unrestricted number of FastLoc snapshots through August ([9,15–17] for details on deployment methods and data), and Acousonde™ acoustic and orientation recorders (www.acousonde.com, [18] for details on deployment method) (table 1). Acousondes were set to collect triaxial acceleration and orientation, depth (sampling rate 100 Hz and 10 Hz, respectively), and acoustics. Acoustics were sampled continuously with a 25 811 Hz sampling rate (HTI-96-MIN hydrophone, nominal sensitivity −201 dB re 1 V/µPa, preamp gain 14 dB, an anti-aliasing filter with 3-dB reduction at 9.2 kHz and 22-dB reduction at 11.1 kHz, 16-bit resolution).

The seismic program was operated from an offshore patrol vessel HDMS *Lauge Koch* equipped with a Reson Seabat 7160 multibeam echo sounder (MBES) (nominal operating frequency 41–47 kHz), that ran continuously. The airgun set-up included a cluster of two Sercel G-guns (17.0 l (1040 in$^3$) in total) towed at 6 m depth and operated at a mean pressure of 125 bar. The guns in the cluster were fired synchronously every 80 s during trials, lasting 3–8 h, while the ship's GPS navigation system recorded the location of every shot. Drifting SoundTrap ST202 autonomous recorders (flat frequency response from 20 Hz to 60 kHz, sampling rate 96 kHz, depth 10 m) were used to describe received levels of airgun pulses, ship noise and background noise as a function of range. Background noise levels, measured 10–45 km from the ship, consisted of 1 s samples (10 Hz–48 kHz bandwidth, three-term Blackman–Harris window, NFFT 96000, 50% overlap) selected 3 s before the actual onset of each airgun pulse, as long as the pulses were detectable, and every 80 s thereafter. Airgun pulses were also analysed from Acousonde records on the whales when possible (figure 1; see electronic supplementary material for details on the analyses; see [9] for more information).

Time–depth records were down-sampled to 1 Hz and time-synchronized with GPS positions. Additional GPS positions were created for each second between successive positions through linear interpolation [9]. Buzzes were used as a proxy for foraging attempts [6] and were detected from the Acousonde acoustic data using a custom-written detector (Matlab, The MathWorks Inc., USA) and verified manually.

When the sound source and animal were within line of sight (determined visually from maps showing the positions of the ships and whales aligned in time), distance between the whale and the sound source was determined for each second. Exposure was defined as 1/distance to ship (in km) resulting in higher exposure with decreasing distance to the ship. Exposure was denoted zero before the experiment began representing undisturbed behaviour. The effect of exposure on the buzzing rate (presence/absence of buzz start at 1 s time bins) was modelled using a generalized linear mixed model in R [19] (glmer, package *lme4*, [20]) with a Poisson response distribution with a log-link, where exposure was entered nonlinearly as an explanatory variable using natural cubic splines with three degrees of freedom (ns, package *splines*) with internal knots located at the 33th and 66th percentiles of the non-zero exposure values. Individual was included as a random effect allowing each animal to have a unique baseline (intercept) in their sound production rate. Moreover, the model included an autoregressive memory component of order 63 s to account for autocorrelation in the

**Table 1.** Duration and percentage of observations in distance categories and the number of separate exposures by individual (whale ID). The maximum distance where whales were observed during sound exposure trials was 63 km.

| distance category | whale ID | contribution (%) | no. separate exposures |
|---|---|---|---|
| 0–20 km (64 h) | B1 | 13 | 4 |
| | B2 | 13 | 4 |
| | B3 | 5 | 2 |
| | B4 | 13 | 2 |
| | B5 | 27 | 4 |
| | B6 | 29 | 6 |
| 20–40 km (24.6 h) | B1 | 15 | 2 |
| | B2 | 17 | 3 |
| | B3 | 19 | 1 |
| | B4 | 7 | 1 |
| | B5 | 22 | 4 |
| | B6 | 20 | 3 |
| >40 km (7.4 h) | B1 | 13 | 1 |
| | B2 | 41 | 1 |
| | B3 | 19 | 1 |
| | B4 | 4 | 1 |
| | B5 | 23 | 1 |

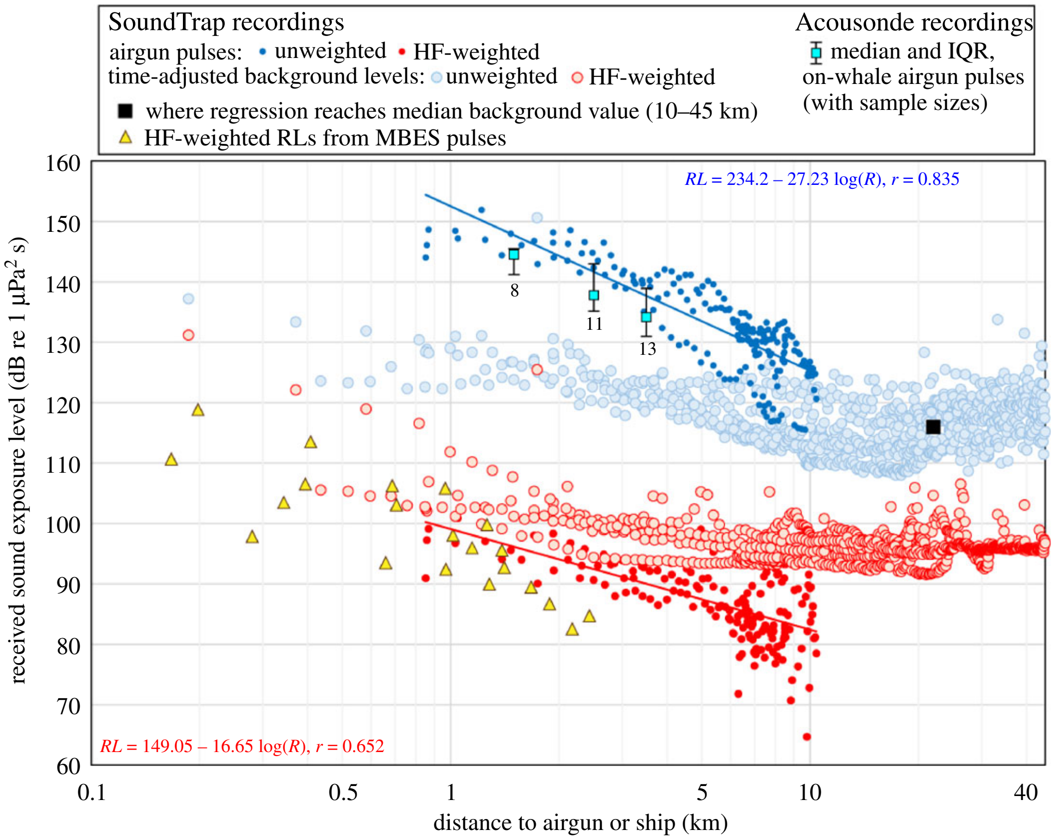


**Figure 1.** Received SELs of sound from airgun and MBES pulses as compared to background levels, as a function of distance from the sound source. Logarithmic regression fits and their equations are shown for the ST airgun pulse analyses (RL is the received level, $R$ is range in $m$ and $r$ is the correlation coefficient). To enable placing background levels on the same plot as pulse SELs, the 1 s background sample values were adjusted to the mean duration of the airgun pulses (1.34 ± s.d. 0.56 s). This added 10 LOG (1.34) = 1.3 dB to what would have been a 1 s SPL (or SEL) value. See electronic supplementary material for details on analyses [22].

**Table 2.** Distances from the sound source (km) at which, compared with undisturbed behaviour, there was a population-level decrease of 25%, 50%, 75% and 100% in the buzzing rate during sound exposure trials i.e. ship noise and airgun pulses (*a*–*d*, figure 2). The estimated SEL at these distances are given both as unweighted and HF-weighted [23] values (figure 1). The cells highlighted with grey represent ranges where the computed SELs that the whales were reacting to were below background noise level. The values in the grey cells indicate the maximum background levels measured at these ranges. The interquartile range of background levels at these ranges were 113–119 dB re 1 µPa$^2$-s in unweighted data and 95–97 dB re 1 µPa$^2$ s in HF-weighted data. Background levels were adjusted to the mean duration of the airgun pulses (1.34 ± s.d. 0.56 s, figure 1).

| decrease in buzzing rate (%) | distance to sound source (km) | unweighted SEL (dB re 1 µPa$^2$ s) | HF-weighted SEL (dB re 1 µPa$^2$ s) |
|---|---|---|---|
| 25 | 16 (a) | <134 | <107 |
| 50 | 12 (b) | | |
| 75 | 10 (c) | | |
| 100 | approximately 7–8 (d) | <135 | |

buzzing activity [21]. Details of the model and model testing are specified in the electronic supplementary material [22].

## 3. Results and discussion

A log fit on received sound exposure levels (SELs) of airgun pulses reached the median background noise level, 115.9 dB re 1 µPa$^2$ s, 22.1 km from the sound source (figure 1). Received levels of airgun pulses ($n$ = 32) measured from whale-borne Acousonde recorders ($n$ = 3), 1–4 km from the airgun, showed reasonable overlap with levels obtained from ST recordings (figure 1). High-frequency cetacean (HF) weighting [23], which provides a better estimate of actual levels perceived by the whales, lowered the airgun pulse SELs and background noise SELs less than 10 km by 28–61 and 9–32 dB, respectively, compared with unweighted values (figure 1). Near the ship, HF-weighted background SELs approached unweighted values (minimum difference was 6 dB) in part due to the presence of the MBES signals (figure 1, see [9] for more details). Within approximately 3 km of the source, MBES signals were therefore part of the sound exposure the whales were experiencing, but beyond this distance, the whales were presumably reacting to a combination of airgun pulses and ship noise (figure 1).

The six male narwhals in this study showed clear behavioural responses to the exposure of concurrent ship noise, MBES pulses and airgun pulses, with a significant effect on the buzzing rate ($p < 0.0001$; table 2 and figure 2).

All individuals ceased foraging within approximately 7–8 km of the ship at received HF-weighted airgun pulse

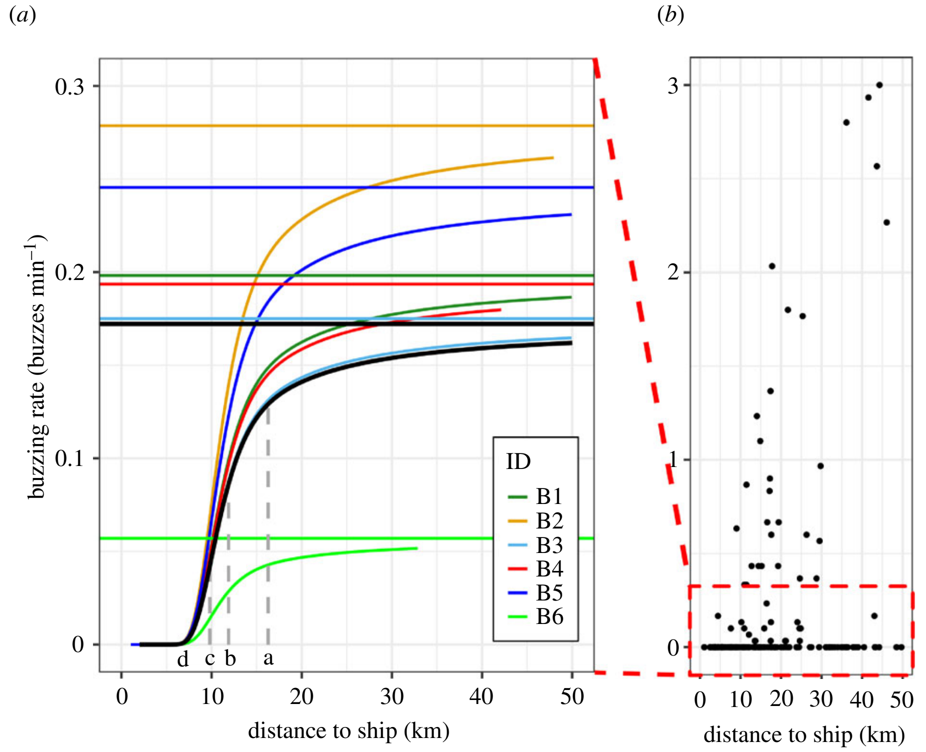


**Figure 2.** The effect of sound exposure on the buzzing rate as a function of distance to the sound source as model outputs (*a*) and raw data (*b*). The curved black line indicates the population-level estimate of the effect and the horizontal black line indicates the undisturbed buzzing rate on a population level. Individual estimates and the corresponding undisturbed buzzing rates are given in different colours. The vertical grey dashed lines indicate the distances (*a*–*d*) at which the population-level buzzing rate decreased by 25%, 50%, 75% and 100% as an effect of exposure (table 2).

SELs below background noise levels of 107 dB (interquartile range 95–97 dB) re 1 µPa$^2$ s (figure 2 and table 2). At this distance, noise from the ship was also buried in the background, but was difficult to quantify (see [9]); the unweighted airgun pulse SELs were less than 135 dB re 1 µPa$^2$ s (table 2). Compared with undisturbed behaviour, a 25% and 50% decrease in buzzing rate occurred at 16 and 12 km from the source, respectively (figure 2). At these distances, the estimated received SELs—both unweighted and HF-weighted—were below background levels, further demonstrating the ability of the whales to detect signals embedded in background noise (table 2). Each of the six individuals, during independent trials, contributed 5–29% of the 64 h of data in range-category ‘0–20 km’ (table 1) supporting that the modelled reduction in buzzing rate predicts a true behavioural response within the population (figure 2).

The effect of sound exposure on buzzing rate could be detected out to the range-category ‘greater than 40 km’ (figure 2). This category, however, only represented 7.4 h of data and individual B2 contributed almost half of that duration (table 1). The response at these remote distances may therefore be driven by individual variation, spatial or behavioural context, and can be used as a proof of sensitivity only in a limited context. Although our data cannot be used to determine signal detection range in narwhals in the Scoresby Sound fjord system, our results imply detection at ranges greater than 40 km from the source. Narwhals have been shown to react to icebreaker noise at greater than 55 km in Lancaster Sound [24,25]. Although the acoustic environment in northern Baffin Bay is different from Scoresby Sound, the observations corroborate our finding of narwhals reacting to low SELs.

Other studies have found that exposure to airgun pulses at levels of 146 and 162 dB re 1 µPa (*p*–p) and 131 dB re 1 µPa$^2$ s (SEL) did not elicit observable reactions in sperm whales *Physeter macrocephalus*, neither in a semi-pristine high latitude habitat nor in a highly trafficked area, respectively [26,27], possibly implying robustness towards disturbance by this species. In the other extreme are the beaked whales *Ziphiidae* sp., which are regarded as one of the most sensitive cetaceans to sound disturbance. They have been shown to decrease or cease foraging as a reaction to low sonar signal levels ranging between 98 and 140 dB re 1 µPa (unweighted) [28–30]. Also harbour porpoises *Phocoena phocoena* have been shown to react to high-frequency ship noise at SPL levels as low as 98 dB re 1 µPa by reduced feeding [31]. Although direct comparisons between SPLs eliciting responses in these studies are not valid due to different signal types, our results of reduced foraging are comparable, placing narwhals among the most sensitive cetaceans to sound disturbance.

## 4. Conclusion

This study showed narwhals to be highly sensitive to anthropogenic noise. The whales clearly reacted to sound disturbance embedded in the highly variable background noise of their environment, as far as greater than 40 km from the sound source, by first reducing, then eliminating their buzzing activity. This likely leads to reduced foraging success, and will, if combined with sustained disturbance over longer periods, have energetic costs at the population level. If healthy, undisturbed narwhal populations are to be maintained, the whales’ extreme sensitivity to man-made sounds needs to be considered when assessing and regulating anthropogenic activities in the Arctic.

Data accessibility. Data on exposure and behavioural responses of narwhals: Dryad https://doi.org/10.5061/dryad.000000046 [17]. The data are provided in the electronic supplementary material [22].

Authors' contributions. O.T. participated in the design of the study, collected field data, carried out data analysis and interpretation of data, participated in the statistical analyses and drafted the manuscript; S.B.B. designed the study, collected field data, carried out data analysis and interpretation of data and helped draft the manuscript; S.D. and A.L.S. drafted the electronic supplementary material, carried out the statistical analyses and interpretation of data, and critically revised the manuscript; A.S.C. carried out data analysis and interpretation of data, and critically revised the manuscript; E.G. participated in the design of the study, collected field data, participated in data analysis and critically revised the manuscript; R.G.H. participated in the design of the study, collected field data and critically revised the manuscript; M.P.H.J. conceived of the study, designed the study, coordinated the study, collected field data and critically revised the manuscript. All authors gave final approval for publication and agree to be held accountable for the work performed therein.

Competing interests. At the time of the study, S.B.B. and A.S.C. were employed by Greeneridge Sciences, Inc., which also produces Acousonde behavioural tags used in this study. The authors declare no other competing interests.

Funding. Funding was provided by the Greenland Environmental Agency for Mineral Resource Activities.

Acknowledgements. We thank the hunters from Ittoqqortoormiit and the crew of HDMS Lauge Koch for assistance in the field. Seven anonymous reviewers improved the manuscript.

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Received: 27 August 2021 | Accepted: 5 September 2022

DOI: 10.1111/mms.12978

Marine Mammal Science

ARTICLE

# Exposure and behavioral responses of tagged beluga whales (*Delphinapterus leucas*) to ships in the Pacific Arctic

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## Abstract

Arctic marine mammals face a multitude of challenges linked to climate change, including increasing anthropogenic noise from ship traffic. The beluga whale (*Delphinapterus leucas*), a predominately Arctic endemic cetacean, relies heavily on acoustic communication, with documented overlap between their vocalizations and hearing range and ship noise. Some belugas migrate through areas with the highest levels of ship traffic in the Pacific Arctic and exposure to ship noise is highly probable. Here, we document the responses of nine satellite-tagged Eastern Beaufort Sea belugas to encounters with ships in the Beaufort, Chukchi, and Bering Seas during July–December 2018. We report 177 occasions when ships were within 125 km of tagged belugas and quantified changes in lateral and vertical movements to investigate individual behavioral responses to ship approaches within 50 km ($n = 23$). Belugas' swim speed was negatively correlated with ship distance, showing possible changes in swim speed up to 79 km away. Changes in lateral and vertical movements, indicating disruption of

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**Funding information**
Crown-Indigenous Relations and Northern Affairs Canada; Fisheries and Oceans Canada, Grant/Award Numbers: Canada Nature Fund for Aquatic Species at Risk, Intergovernmental Strategy, National Conservation Plan, Strategic Program for Ecosystem-based Research and; Fisheries Joint Management Committee; Mitacs, Grant/Award Number: Mitacs Accelerate Postdoctoral Fellowship; Natural Resources Canada; The Weston Family Foundation

behavior, were observed when some ships passed within 50 km. These findings corroborate previous studies that have shown behavioral responses of belugas to ships at distances far beyond visual range, implying belugas react to low-amplitude ship noise near ambient levels.

**KEYWORDS**
acoustic disturbance, anthropogenic noise, Arctic, automatic identification system, avoidance behavior, behavioral response, beluga whale, bio-logging tags, cetacean, disturbance threshold, ship traffic

## 1 | INTRODUCTION

The relatively pristine acoustic marine environment of the Arctic is changing rapidly at least in part as a result of expanding anthropogenic activities (Protection of the Arctic Marine Environment [PAME], 2019). Historically characterized by extensive ice cover, strong winds and low anthropogenic pressure, the Arctic was often a relatively quiet environment as a result of sea ice contributing to extremely low ambient underwater sound levels (median levels [50–1000 Hz band] <75 dB re 1 μPa under solid sea ice and ~ 95 dB re 1 μPa in the summer open water season sensu Diachok, 1976; Halliday, Barclay, et al., 2021; Insley et al., 2017; Kinda et al., 2013; Roth et al., 2012; Yang & Votaw, 1981). Due to economic, geopolitical, and drastic environmental changes occurring as a result of the pronounced rate of climate change in the region, where warming is two to three times faster than the global mean (Council of Canadian Academics, 2019; Meredith et al., 2019), ship traffic and its subsequent noise footprint have markedly increased over the past few decades (Dawson et al., 2018; Intergovernmental Panel on Climate Change, 2022), and continued increases are projected as trans-Arctic shipping routes become more reliably ice-free (Bennett et al., 2020; Mudryk et al., 2021; Zeng et al., 2020).

The naturally low levels of underwater sound have allowed marine animals to hear anthropogenic noise from farther away than in non-Arctic regions due to reduced acoustic masking by background conditions (Halliday et al., 2020a; Pine et al., 2018). The traditionally lower levels of anthropogenic activity in most areas of the Arctic pair with a lower exposure history to anthropogenic noise for Arctic species compared to non-Arctic species (PAME, 2019). Thus, Arctic marine animals may be more sensitive to anthropogenic noise (e.g., Finley et al., 1990; Halliday et al., 2020a) and noise intensification could have disproportionate effects on Arctic species. As a result, noise impacts on Arctic species may need to be treated as a special case.

For most marine mammals, especially cetaceans, hearing is considered to be their primary sensory modality and they use sound for essential biological functions such as communication, foraging, navigation, and predator avoidance (Tyack, 1986). Underwater ambient noise is generated by both natural (biophony and geophony) and anthropogenic sources. There have been numerous studies documenting negative effects of underwater anthropogenic noise on marine species, with the greatest research focus on marine mammals (e.g., Duarte et al., 2021; PAME, 2019; Southall et al., 2007, 2019). Anthropogenic noise affects marine mammals mainly through acoustic masking or behavioral disturbance. Acoustic masking is defined as the overlap in frequency of anthropogenic signals which interfere with detection of important biological or nonvocal sounds produced by these species (Clark et al., 2009; Payne & Webb, 1971). Disturbance occurs when noise elicits a reaction or a change in behavior (e.g., Finley et al., 1990). However, variability exists across species and among individuals within populations due to a variety of factors, including age, sex, behavioral context, and prior exposure, thereby resulting in variable thresholds of disturbance (see Gomez et al., 2016 for a review; Richardson et al., 1995). Ocean noise from shipping and other maritime activities is now recognized as an acute and chronic, habitat-level stressor (Chou et al., 2021; Duarte et al., 2021; Williams et al., 2020).

Acoustic masking and behavioral disturbance from ship noise (<1 kHz) affect taxa with high hearing sensitivity at lower frequencies (i.e., baleen whales, most pinnipeds, fish, and invertebrates). However, high amplitude ship noise levels do not require high hearing sensitivity at lower frequencies to elicit masking and disturbance. Ship noise can also occur at higher frequencies (1–30 kHz; Veirs et al., 2016), which are especially relevant for odontocete hearing sensitivity (Aguilar Soto et al., 2006; Arveson & Vendittis, 2000; Götz et al., 2009; Vergara et al., 2021). Estimates of detection distances for ship noise vary by frequency, vessel, background noise conditions, and receiving species. The focal species of this study is the beluga whale (*Delphinapterus leucas*), an endemic Arctic odontocete species that has a reduced hearing sensitivity to sounds below 1 kHz (Awbrey et al., 1988; Johnson et al., 1989; Ridgway et al., 2001; White, 1978). However, higher frequency components of ship noise could be audible to belugas at long distances because ship source levels can be relatively high even at above 1 kHz, and belugas hear well at those frequencies (Castellote et al., 2014; Cosens & Dueck, 1993; Mooney et al., 2018, 2020; Popov et al., 2013). Understanding hearing abilities at the species level is essential to determine the effects of noise impacts such as masking, disturbance, and (at high received levels) noise-induced hearing loss.

Belugas generally are gregarious, traveling in pods ranging from a few individuals to hundreds of whales (Jefferson et al., 1993), and are considered to be highly sensitive and vulnerable to ecosystem change (Hauser et al., 2018). In the Pacific Arctic, belugas are an important traditional food source for Inuvialuit and Iñupiat subsistence hunters (Frost & Suydam, 2010; Harwood & Smith, 2002). Belugas in the Pacific Arctic migrate through United States, Canadian, and Russian waters, passing through areas with elevated levels of ship traffic and potentially are exposed annually to a high number of acoustic disturbance events (Halliday, Pine, et al., 2021). A recent review of underwater noise and Arctic marine mammals (Halliday et al., 2020a) showed that belugas can be disturbed by ship-related noise and temporarily displaced. A few studies have examined the impacts of underwater noise on the behavior of wild belugas, and in some cases noise from outboard motors, icebreakers, tugs, barges, seismic air guns, and drilling evoked an avoidance/startle (i.e., flee) response at varying received levels (Blevins, 2015; Cosens & Dueck, 1988; Finley et al., 1990; Fraker, 1977, 1978; Koski et al., 1995; Krasnova et al., 2009; Miller et al., 2005; Richardson et al., 1995; Stewart et al., 1982, 1983). Belugas showed the strongest reported reactions to icebreaker ships with avoidance responses occurring at 35–50 km distance from the icebreaker where received noise levels ranged from 94 to 105 dB re 1 μPa [20–1,000 Hz band] (Cosens & Dueck, 1993; Finley et al., 1990). The events involving icebreaker ships resulted in the displacement of all belugas from the region for periods of 1–2 days and by up to 80 km (Finley et al., 1990; LGL & Greeneridge, 1986). Further, Miller et al. (2005) suggested that belugas avoided areas with ships conducting seismic operations by distances of 10–20 km. A recent study by Halliday et al. (2019) showed that beluga vocalizations decreased when ships traveled within 5 km of a moored acoustic recorder. This reduction was either caused by belugas decreasing their calling rates or fleeing the area in response to the ship; the latter is supported from observations by Inuvialuit (Halliday et al., 2019). In addition, noise from manned aircraft and unmanned aerial vehicles (UAVs) flown near the water in some cases has caused a flee response in belugas in the Arctic (e.g., Fraker, 1978; Palomino González et al., 2021; Patenaude et al., 2002), further supporting beluga heightened sensitivity to anthropogenic noise compared to other species of marine mammals.

Avoidance behaviors by animals exposed to threatening stimuli are generally grouped into two categories: "fight or flight" reactions and "freeze" reactions (Gabrielsen & Smith, 1995; Roelofs, 2017). Fleeing mammals display physiological responses characteristic of exercise (i.e., tachycardia, increased metabolic rate, increased swim speed; Ford & Reeves, 2008), while mammals demonstrating freeze responses experience bradycardia and metabolic slowdowns (Roelofs, 2017; Steen et al., 1988). However, a paradoxical physiological response was reported in tagged narwhal displaying simultaneous bradycardia with increased fluke stroke and respiration rates (Williams et al., 2022). Previous research suggests that belugas are more prone to exhibit a flee response to a perceived threat compared to a fight (e.g., aggressive approach) or freeze response. The flee response of belugas has been described as large herds undertaking long dives, where pod integrity breaks down into small, scattered groups and diving becomes asynchronous (Blevins, 2015; Finley et al., 1990; Palomino González et al., 2021). Krasnova et al. (2009) found that female belugas with calves are usually the first group members to flee from anticipated danger. Fleeing also causes the individual or group to cease its current behavioral state (e.g., foraging, nursing, resting, transiting), thereby disrupting important daily activities. Interruptions of behavior, even if short-term, have the potential to negatively impact individual belugas if they are repeated (Tyack, 2009). Thus, while fleeing can afford survival from a presumed threat, it can have short- and longer-term impacts on an individual's fitness, which could lead to a reduction in the overall health of individuals and a population. Previous studies that examined beluga reactions to noise describe diving as a common avoidance response but lacked the technology to quantitatively assess changes in dive behavior paired with surface observations. Modern telemetry methods using animal-borne tags allow researchers to capture the full 3-dimensional movements of marine mammals to provide a more thorough examination of behavioral responses to disturbance events (Hussey et al., 2015).

The current study reports location data from satellite-linked time and depth tags attached to male Eastern Beaufort Sea (EBS) belugas in conjunction with ship location data, and summarizes the number of ships encountered by tagged individuals. We then assess data on beluga lateral surface movements, and where possible, dive behavior including identified dive types associated with certain functional behaviors (e.g., foraging, travel, and recovery; Storrie et al., 2022) to characterize potential behavioral responses to vessels. The scope of this study encompasses beluga behavioral responses from near-continuous monitoring over a vast area of the Pacific Arctic including both coastal and offshore waters in three marginal seas. Given the logistical difficulties in performing a controlled vessel-disturbance study involving belugas in the Arctic, and the cultural and ecological importance of this susceptible species, the encounters presented here provide evidence about how belugas may respond to ship noise, as well as information useful in defining hypotheses for future testing to address this issue.

## 2 | MATERIALS AND METHODS

### 2.1 | Study area and focal animals

This study focuses on the Pacific Arctic region, from the northern Bering Sea to the Amundsen Gulf in the western Canadian Arctic, and includes the Bering, Chukchi, and Beaufort Seas (Figure 1). During July 3–12, 2018, 10 adult male belugas from the EBS stock were instrumented with back-mounted tags using a live capture method (Orr et al., 2001) at Hendrickson Island within Kugmallit Bay of the Mackenzie River estuary, Northwest Territories, Canada (Table 1; Storrie et al., 2022). One beluga's (LC2018#9) tag transmitted for only approximately 1 week and consequently those data were excluded from the following analyses. For the remaining whales, three were fitted with SMRU CTD-SRDL tags (Sea Mammal Research Unit, University of St. Andrews, Scotland) and six were fitted with SPLASH10-F-238 tags (Wildlife Computers Inc., Redmond, WA; Table 1). Both tag types recorded Argos and Fastloc Global Positioning System (GPS) satellite-derived locations and contained time depth recorders (TDRs) for assessing time series dive behavior. Data for the current study were constrained to satellite locations and diving behavior obtained from these nine tagged belugas during the period July–December 2018 (Figure 1a).

Argos satellite tags have been widely used to track large-scale animal movements; however, tags provide relatively coarse quality locations typically with an accuracy of several hundred meters to several kilometers. Each Argos location is assigned a location accuracy designated by a number or letter dependent on the number of orbiting satellites via which the transmission is received, among other factors (https://www.argos-system.org; accuracy categories: GPS [<100 m], 3 [<250 m], 2 [250–500 m], 1 [500–1,500 m], 0 [>1,500 m], A and B [unbounded], Z [invalid]). Consideration of these location accuracies is important when examining fine scale encounters such as individual animals with ships or conspecifics. A Fastloc GPS receiver on a tag can take a snapshot of up to 10 GPS satellites to provide location accuracies of 10s of meters that are then transmitted via standard Argos transmissions (Dujon

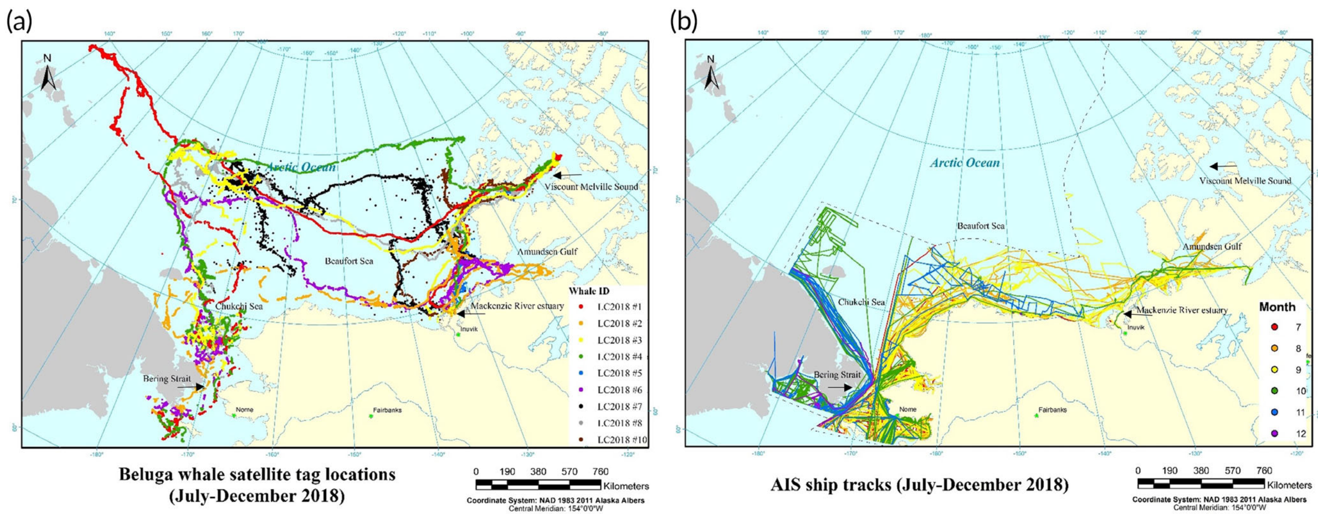



**FIGURE 1** (a) Map of the satellite telemetry locations of the nine tagged belugas during July–December 2018. Whales are color coded by individual. (B) Map of the ship track-lines derived from automatic identification systems (AIS) data during July–December 2018. Ship track-lines are color coded by month. AIS data were derived from ships located within the Exclusive Economic Zones (EEZs) of Canada, the United States and a portion of Russia shown in (b) as the region inside of the dashed gray line.

**TABLE 1** Summary of tagged belugas and their numbers of known encounters with ships within a radius of 125 km during July–December 2018. Tag type "Splash" represents a SPLASH10-F-238 tag and "SMRU" represents a SMRU CTD-SRDL tag. Ship encounters denotes the closest distance of approach to a given ship on a given day after removal of duplicates when an encounter spanned past midnight. The three closest points of approach (CPA) to ships as well as the average (± *SD*) CPA distance are provided per whale. A maximum time difference of 1 hr between the paired whale location and AIS ship location was used to calculate the CPAs. Beluga LC2018#5 was not known to encounter any ships within a radius of 125 km in this study.

| | | | | | | | Ships encountered July–December 2018 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Length | | | Duration | | Distance bins (km) | | | | | Closest point of approach (km) | | | |
| Whale ID | Tag ID | (cm) | Tag on | Tag off | (days) | Tag type | 0-50 | 51-75 | 76-100 | 101-125 | Total | 1st | 2nd | 3rd | Avg (*SD*) |
| LC2018#1 | 174965 | 420 | Jul 3, 2018 | Jan 2, 2019 | 182.7 | Splash | 1 | 2 | 0 | 3 | 6 | 43.8 | 54.8 | 57.3 | 79.6 (± 30.7) |
| LC2018#2 | 174967 | 470 | Jul 4, 2018 | Jun 19, 2019 | 349.9 | Splash | 18 | 7 | 10 | 22 | 57 | 6.8 | 12.6 | 13.1 | 75.2 (± 39.4) |
| LC2018#3 | 174962 | 406 | Jul 6, 2018 | Dec 15, 2018 | 161.2 | Splash | 0 | 2 | 3 | 3 | 8 | 55.0 | 60.7 | 77.7 | 86.9 (± 22.4) |
| LC2018#4 | 174963 | 444 | Jul 8, 2018 | Jun 7, 2019 | 334 | Splash | 3 | 2 | 6 | 4 | 15 | 24.4 | 35.1 | 40.8 | 81.2 (± 30.9) |
| LC2018#5 | 175284 | 419 | Jul 8, 2018 | Jul 25, 2018 | 17.1 | SMRU | 0 | 0 | 0 | 0 | 0 | — | — | — | — |
| LC2018#6 | 174966 | 440 | Jul 8, 2018 | Jun 29, 2019 | 355.7 | Splash | 8 | 14 | 21 | 28 | 71 | 13.4 | 14.3 | 20.9 | 86.7 (± 27.4) |
| LC2018#7 | 175278 | 370 | Jul 9, 2018 | Oct 13, 2018 | 96.1 | SMRU | 0 | 1 | 0 | 1 | 2 | 60.3 | 114.5 | — | 87.4 (± 38.3) |
| LC2018#8 | 174969 | 425 | Jul 9, 2018 | Dec 19, 2018 | 162.2 | Splash | 1 | 2 | 6 | 4 | 13 | 25.2 | 61.1 | 66.9 | 84.9 (± 24.8) |
| LC2018#10 | 175282 | 434 | Jul 12, 2018 | Aug 28, 2018 | 46.7 | SMRU | 0 | 1 | 2 | 2 | 5 | 72.3 | 89.7 | 90.4 | 97.1 (± 19.3) |

et al., 2014). Although Argos derived locations are coarser than those of Fastloc GPS, they require less energy (i.e., battery power) and typically can be determined for a longer duration.

In the current study, locational information was used from both Argos and Fastloc GPS derived locations, preferentially using Fastloc GPS locations when available. Tags were programmed with an Argos transmission rate of 25 s, and to collect Fastloc GPS locations every 7–30 min; however, temporal gaps between satellite-derived locations were often longer than this as a result of transmissions only occurring when the animal surfaces and tag programming (e.g., fewer transmissions from October or November onwards, see Storrie et al., 2022).

We improved location estimates for each animal using a continuous-time Correlated Random Walk (CRW) model developed by Johnson et al. (2008) and implemented in package "crawl," version 2.2/1 (Johnson & London, 2018), in R (R Core Team, 2021). CRW models are limited by the assumption that the errors follow a normal distribution. In general, Argos location data are close to normal except for the presence of extreme outliers. The CRW algorithm performs poorly when Argos position error greatly exceeds measured position values and CRW model priors. Consequently, extreme outliers were removed by passing the raw location data through the *sdafilter* in the R package "argosfilter" (Freitas, 2012; Freitas et al., 2008). We used the default speed threshold of 2 m/s, which is greater than the maximum published speed for belugas of 1.78 m/s (Richard et al., 2001). The filter can also be specified to remove outliers which create acute angles in the path of movement (i.e., "spikes"). We used default values for specifying the angular components of the filter; specifically, we removed values that formed angles <15° when they were >2.5 km from the previous location and angles <25° when they were >5 km from the prior location. Furthermore, the estimated locations and tracklines were visually verified to ensure the data were not being "pulled" towards low-quality locations that marginally passed the filter. Bayesian state-space switching models do not require prefiltering of Argos locations; however, these are discrete time-step models which typically only estimate a location 1–2 times per day. Those intervals are not frequent enough to pair with ship data to assess whale behavioral responses. Hence, it was necessary to use a continuous-time movement model in this study.

The CRW model treats movement as a velocity process with two parameters, $\beta$, the autocorrelation in velocity and $\sigma$, the variation in velocity. Location error was assumed to be normally distributed with a mean of 0 and a standard deviation equal to that declared by the system operator, Collecte Localisation Satellites (CLS), for least-squares location classes GPS, 3, 2, and 1 (CLS, 2016). We treated error for the remaining three location classes as parameters to be estimated and fitted them to half normal distributions with semi-informative priors. Locations with classes 0, A, and B should have more error than those with a class of 1 ($SD = 1,500$ m). Hence, our half normal distributions had a lower bound of 1,500 m. Using data from Vincent et al. (2002), our priors had a mean error of 1,500 m and a standard deviation of 5,000 m for location classes 0 and A, and 7,500 m for location class B. We also set a Laplace prior (double exponential) for $\beta$ and $\sigma$. The Laplace prior had a mean of 3 and a variance of 0.5 on a natural log scale, which is approximately the value of $\beta$ and $\sigma$ observed for most species. Note that this is only significant when tracks have few location data. This is the same model and error estimation used for belugas in Citta et al. (2018, 2020). We used the model to better estimate beluga location at preexisting Argos locations; we did not use the model to predict where a beluga might be located between preexisting Argos locations. In effect, the model was only used to reduce location error. The CRW modeled whale locations, hereafter referred to as "whale locations."

## 2.2 | Spatial and temporal analysis of belugas and ships

The main shipping season for the study region occurs from July to October during the predominantly ice-free period, but can extend to November and December near the Bering Strait. Ship tracks from July to December 2018 were derived from preprocessed satellite Automatic Identification System (AIS) data (exactEarth Ltd., Cambridge, ON, Canada) in the Pacific Arctic spanning from the Chukchi Sea and Bering Strait in the west to the Amundsen Gulf in the east (Figure 1b). AIS transponders transmit signals which show the geographic coordinates and other information about individual ships at regular intervals (e.g., every 2–120 s, depending on ship behavior and context), and these signals can be received by dedicated satellites and land-based receivers. Internationally, only a subset of vessels are required to carry AIS transponders, specifically all ships ≥300 gross tonnes on international voyages, cargo ships ≥500 gross tonnes on domestic voyages, and all passenger ships with >12 passengers (International Maritime Organization, 2014). Other ship types such as barges, tugs, recreational vessels, and research ships are not required to carry AIS voluntary transponders; however, many of these ships use AIS transponders for safety reasons, particularly in the Arctic. Vessel traffic in the Pacific Arctic consists of a variety of vessels including bulk carriers, community supply vessels (barges and tugs), container ships, cruise ships, government icebreakers and research vessels, tankers, military vessels, seismic survey vessels, recreational vessels, and local community traffic for subsistence activities (see Dawson et al., 2018).

We used satellite AIS data to calculate the number of unique vessels that encountered individual tagged belugas in the study area. We acknowledge this may be a conservative estimate if additional ships were present and not transmitting AIS data. When a ship track overlapped in time and space with a tagged beluga, AIS data were used to calculate the range of distances between the ship and the whale including the closest point of approach (CPA) during encounters.

Several steps were taken to calculate the number of unique vessels that encountered individual tagged whales as well as the CPA for each encounter. A spatial and temporal analysis was completed in ArcGIS using ArcMap 10.8 (Environmental Systems Research Institute, Redlands, CA). The first step of the analysis created a buffer radius of 125 km around each individual satellite-derived whale location acquired during July–December 2018. We selected a 125 km radius as modeling has suggested that ship noise can be greater than ambient levels at distances over 100 km in the region (Halliday et al., 2017). Ship noise can theoretically contribute to ambient sound >125 km away, although it is difficult to quantify at this distance (Aulanier et al., 2017). Next, we separated whale location and AIS ship location data by "day" and paired these data sets in space and time. Individual whale and ship data from the same day occurring within a radius of 125 km were then extracted and designated as encounter events. This process was completed separately for each individual whale to ensure that all possible encounters between whales and ships were included in the analysis. Next, the derived paired whale and ship locations within each event were sorted by time to generate time series of consecutive potential encounters while retaining all underlying data and geographic positional information. The maximum allowed delta time between a paired whale and AIS location was 1 hr and the majority had a delta time of <3 min. The "Points to Line" tool in ArcMap 10.8 was used to calculate the distance (meters) between the closest aligned whale and AIS locations as they approached each other within each event. For each encounter occurring within a radius of 125 km on a given day, the CPA was calculated as the shortest distance observed between the whale and ship.

In order to quantify if multiple ships came within 125 km of an individual whale during an encounter event, the CPAs from each whale-ship encounter were compiled and sorted by date and time. This also allowed manual removal of duplicate encounters that resulted from an encounter spanning past midnight where it was included twice based on the original subsetting of data by "day." Once duplicates were removed, all encounters were sorted by the CPA distance and summarized by whale ID (Table 1).

At a finer scale, we chose to investigate all encounter events between whales and ships with a CPA ≤50 km (Table 2) based on the findings of Finley et al. (1990) where belugas showed strong avoidance reactions to ships approaching at distances of 35–50 km. For each encounter event with a CPA ≤50 km, approximately 72 hr of consecutive whale locations and AIS ship locations centered around the CPA were extracted. To examine whale behavior in the theoretical absence of vessels, a control period (24 hr) containing no known ships within 125 km was identified from within the same week for each encounter event. Where possible, this control period was taken from the 24 hr before or after a ship came within 125 km of the whale. Whale locations were extracted for each control period and control dates were used only once (Table 2). For individual whales that came within 125 km of multiple ships on the same day, all unique cases of ship and whale locations were aligned in time to assess each ship's location from the whale's perspective to identify if and when more than one ship was located within 50 km of the whale. For

**TABLE 2** Summary of 23 encounters with the closest point of approach (CPA) < 50 km distance between a ship and a tagged beluga. Under the column "Behavior," "NLR" stands for no lateral response, "A" stands for potential avoidance behavior, "UND" stands for undetermined behavior, and "DD" stands for data deficient. Integer values in the "Behavior" column correspond to the encounter description in the Results section. The estimated broadband received level (RL) in dB re 1μPa of ship noise (maximum in water column) is provided for the CPA, and delta time (seconds) is the time difference between the paired whale location and AIS ship location used to calculate the CPA. Ship speed (knots) is provided for the CPA. For encounters with multiple ships, the delta time, CPA distance and ship speed are provided for the closest ship which is listed first under "Ships present," and RL is a combined estimate for all ships present.

| Whale ID | Date | Time (UTC) | Latitude | Longitude | Ships present | CPA (km) | Δ time (s) | RL (dB) | Ship speed (knots) | Behavior | Control date |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LC2018#1 | Dec 28, 2018 | 02:03 | 63°45′01.22″N | 173°58′00.80″W | *Boris Sokolov* | 43.8 | 103 | 103.4 | 8.2 | DD | Dec 26, 2018 |
| LC2018#2 | Aug 7, 2018 | 22:27 | 70°15′22.06″N | 126°34′54.79″W | *Frosti + Sir Wilfrid Laurier* | 19.1 | 43 | 97.8 | 5.5 | A 1 | Aug 5, 2018 |
| LC2018#2 | Aug 9, 2018 | 09:31 | 69°58′23.66″N | 131°21′17.15″W | *Fathom Wave + Kelly Ovayuak* | 13.9 | 16 | 158.7 | 4.4 | UND 1 | Aug 4, 2018 |
| LC2018#2 | Aug 18, 2018 | 02:34 | 69°58′13.74″N | 120°13′57.19″W | *Sir Wilfrid Laurier* | 23.6 | 533 | 113.4 | 11.1 | NLR 1 | Aug 16, 2018 |
| LC2018#2 | Aug 10, 2018 | 14:58 | 69°32′04.43″N | 118°14′17.54″W | *Kelly Ovayuak* | 12.6 | 61 | 126.5 | 10.0 | A 2 | Aug 14, 2018 |
| LC2018#2 | Aug 22, 2018 | 10:24 | 69°59′36.60″N | 118°28′41.27″W | *Sir Wilfrid Laurier + BBC Oregon* | 39.4 | 34 | 119.0 | 11.1 | UND 2 | Aug 30, 2018 |
| LC2018#2 | Aug 25, 2018 | 03:48 | 70°18′49.80″N | 122°42′25.66″W | *Frosti + Sir Wilfrid Laurier + High Progress* | 13.1 | 9 | 118.9 | 9.3 | A 3 | Aug 29, 2018 |
| LC2018#2 | Sep 22, 2018 | 20:23 | 70°41′38.53″N | 141°54′02.49″W | *Frosti + David Thompson* | 25.5 | 1 | 108.3 | 9.6 | UND 3 | Sep 21, 2018 |
| LC2018#2 | Nov 5, 2018 | 04:49 | 69°46′58.14″N | 179°36′18.64″E | *Andrey Pervozvanniy* | 6.8 | 65 | 123.5 | 12.4 | UND 4 | Nov 3, 2018 |
| LC2018#2 | Nov 8, 2018 | 04:56 | 68°02′51.89″N | 175°40′24.25″W | *Arkadiy Chernyshev* | 46.7 | 132 | 104.0 | 11.4 | NLR 2 | Nov 6, 2018 |
| LC2018#2 | Nov 12, 2018 | 04:21 | 66°53′25.67″N | 171°39′21.46″W | *St. Confidence* | 44.5 | 2281 | 97.3 | 8.9 | DD | Nov 11, 2018 |
| LC2018#2 | Nov 19, 2018 | 03:27 | 66°41′12.12″N | 171°21′38.89″W | *Georgiy Brusilov* | 45.8 | 12 | 126.1 | 18.1 | DD | Nov 18, 2018 |
| LC2018#2 | Nov 22, 2018 | 20:37 | 66°26′13.62″N | 169°58′52.92″W | *Rudolf Samoylovich* | 19.8 | 26 | 123.5 | 13.3 | UND 5 | Nov 29, 2018 |
| LC2018#4 | Oct 11, 2018 | 23:18 | 71°37′11.01″N | 174°58′54.55″W | *Vladimir Vize* | 24.4 | 6 | 126.2 | 15.6 | UND 6 | Oct 10, 2018 |
| LC2018#4 | Nov 1, 2018 | 10:49 | 68°24′55.04″N | 174°02′03.65″W | *Nordic Olympic* | 35.1 | 1 | 112.8 | 11.5 | UND 7 | Oct 29, 2018 |
| LC2018#4 | Nov 8, 2018 | 07:27 | 68°13′00.54″N | 173°05′02.49″W | *Arkadiy Chernyshev* | 40.8 | 48 | 104.8 | 11.2 | A 4 | Nov 7, 2018 |

(Continues)

**TABLE 2** (Continued)

| Whale ID | Date | Time (UTC) | Latitude | Longitude | Ships present | CPA (km) | Δ time (s) | RL (dB) | Ship speed (knots) | Behavior | Control date |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LC2018#6 | Aug 12, 2018 | 06:32 | 70°28′10.80″N | 123°16′57.56″W | *Fathom Wave* + *Sir Wilfrid Laurier* | 43.1 | 15 | 98.9 | 6.0 | A 5 | Aug 13, 2018 |
| LC2018#6 | Aug 24, 2018 | 04:33 | 71°14′04.27″N | 133°51′51.36″W | *High Progress* | 39.3 | 5 | 112.1 | 12.1 | NLR 3 | Aug 23, 2018 |
| LC2018#6 | Aug 29, 2018 | 09:15 | 70°34′00.77″N | 140°40′58.20″W | *David Thompson* | 20.9 | 16 | 100.2 | 9.4 | A 6 | Aug 28, 2018 |
| LC2018#6 | Sep 12, 2018 | 08:44 | 72°25′06.22″N | 156°28′08.20″W | *Sikuliaq* + *High Progress* | 14.3 | 9 | 111.7 | 9.5 | A 7 | Sep 14, 2018 |
| LC2018#6 | Nov 4, 2018 | 00:30 | 67°50′33.88″N | 173°45′05.99″W | *Rubin* | 41.3 | 35 | 116.8 | 8.7 | DD | Nov 3, 2018 |
| LC2018#6 | Nov 19, 2018 | 06:16 | 67°22′27.50″N | 171°27′59.54″W | *Georgiy Brusilov* | 13.4 | 11 | 133.1 | 17.7 | A 8 | Nov 17, 2018 |
| LC2018#8 | Nov 23, 2018 | 03:07 | 69°06′22.72″N | 169°18′43.03″W | *Mirai* | 25.2 | 76 | 118.0 | 11.6 | DD | Nov 21, 2018 |

each encounter event with a CPA ≤50 km, an animation was created in ArcMap 10.8 by pairing the whale and ship AIS locations by time using the animation toolbar (see Supplementary Materials). If multiple ships were present in an encounter event, they were included in a single animation. Animations provided a moving visual perspective of the encounter from a bird's eye view and were used in part to identify evidence of lateral responsive movement by a whale in response to ships during events.

## 2.3 | Estimation of received level of ship noise

In this study, ship noise refers to sound created by propeller cavitation, engine noise, and other sounds accompanying normal ship operations. We do not address noise from air guns, sonar, or other noises associated with military or resource exploration activities. To estimate the received level (RL) of ship noise during instances where ships came within 50 km of a tagged beluga, first the source levels (SL) of underwater ship noise were estimated using the JOMOPANS-ECHO source level model (Table 3; MacGillivray & de Jong, 2021). SL is defined as the sound pressure level at 1 m from an ideal point source emitting the same amount of sound as the ship or other distributed source using 1 μPa as the reference pressure (Au, 1993). The JOMOPANS-ECHO model calculates the ship SL spectrum in decidecade bands as a function of frequency, speed, ship length, and AIS ship type. Vessel classification and length were obtained from the MarineTraffic.com web service based on the maritime mobile service identity (MMSI) number. The statistical uncertainty, reported as the standard deviation of the deviation between model and measurement in the predicted source level spectra of the model, is estimated to be 6 dB (MacGillivray & de Jong, 2021). The propagation loss of underwater noise from different classes of vessels that were transiting the area was estimated based on modeled SLs (dB re 1 μPa), and then applied to actual ship tracks and measured ship speeds (derived from AIS data). RL is the result of the SL minus the transmission loss (TL; Urick, 1983) such that

$$\mathrm{RL} = \mathrm{SL} - \mathrm{TL} \tag{1}$$

Approximate transmission loss for ships is estimated assuming a combination of spherical and cylindrical spreading plus frequency-dependent attenuation caused by absorption (Au & Hastings, 2008) such that.

$$\mathrm{TL} = 15\log_{10}(R) + \alpha R \tag{2}$$

where $R$ is the distance to the ship and $\alpha$ is a constant defined as the frequency dependent absorption (Francois & Garrison, 1982). The geometric spreading coefficient of $15\log_{10}(R)$ was used based on previous acoustic propagation modeling in the Pacific Arctic (Halliday, Pine, et al., 2021). $R$ was calculated continuously as the distance between a whale's location and a ship over the duration of the encounter event using the “Points to Line” tool in ArcMap 10.8. For encounters where more than one ship was located within 50 km of the whale, an estimated combined RL was calculated by converting received level for each individual ship to pressure, summing received pressure levels of all individual ships within 50 km, and then converting the total back to decibels. The calculated RL values apply to a receiver well below the surface, and are roughly the maximum RL in the water column; levels of ship noise (especially the lower frequency components) received by any belugas close to the surface will be reduced by pressure release effects (Urick, 1983). We did not account for the vertical location of the receiver in the water column and acknowledge there are uncertainties involved in these approximate estimates of RL; the RL estimate is intended to provide context for encounters, rather than serving as an absolute RL. We caution against using modeled values for estimating absolute RL, especially for data sets that might be used to establish thresholds for disturbance.

**TABLE 3** Summary of ship metrics for ships involved in known encounters with belugas at distances less than 50 km. Source levels (broadband SL; dB at 1 m μPa) were modeled using the JOMOPANS-ECHO source level model using recordings of ship noise from the Port of Vancouver's ECHO program (MacGillivray & de Jong, 2021). Decidecade band source levels (dB re 1 μPa) were estimated in the 10 Hz–32 kHz band and ship speed was set at a value of 10 knots only for this Table's comparison.

| Vessel name | MMSI | Vessel type | Length (m) | SL (dB) | Encounters (<50 km) | *n* Whales |
|---|---|---|---|---|---|---|
| *Andrey Pervozvanniy* | 273414670 | Tanker | 169 | 175.6 | 1 | 1 |
| *Arkadiy Chernyshev* | 273359930 | Cargo | 113 | 171.0 | 2 | 2 |
| *BBC Oregon* | 305462000 | Cargo | 139 | 172.8 | 1 | 1 |
| *Boris Sokolov* | 209387000 | Tanker | 214 | 177.7 | 1 | 1 |
| *David Thompson* | 316001090 | Research/Government | 29 | 167.0 | 2 | 2 |
| *Fathom Wave* | 316032737 | Tug | 19 | 180.1 | 2 | 2 |
| *Frosti* | 316001821 | Fishing | 39 | 174.4 | 3 | 1 |
| *Georgiy Brusilov* | 212770000 | Tanker | 299 | 180.6 | 2 | 2 |
| *High Progress* | 636012730 | Tanker | 183 | 176.3 | 3 | 2 |
| *Kelly Ovayuak* | 316004160 | Tug | 45 | 187.6 | 2 | 1 |
| *Mirai* | 431939000 | Research/Government | 128 | 179.9 | 1 | 1 |
| *Nordic Olympic* | 356986000 | Cargo | 225 | 177.0 | 1 | 1 |
| *Rubin* | 273189700 | Tug | 58 | 189.8 | 1 | 1 |
| *Rudolf Samoylovich* | 311000627 | Tanker | 299 | 180.6 | 1 | 1 |
| *Sikuliaq* | 338417000 | Research/Government | 79 | 175.7 | 1 | 1 |
| *Sir Wilfrid Laurier* | 316052000 | Research/Government | 83 | 176.1 | 5 | 2 |
| *St. Confidence* | 273443870 | Cargo | 98 | 169.8 | 1 | 1 |
| *Vladimir Vize* | 477194200 | Tanker | 299 | 180.6 | 1 | 1 |

## 2.4 | Statistical and qualitative analyses

All whale locations where one or more ships were less than 50 km from a tagged beluga were classified as an "impact" time segment. Whale locations were grouped together in time series based on consecutive locations when a ship was within 50 km of a tagged beluga and included an equivalent or near equivalent number of whale locations both before and after the "impact" time segments based on the duration of the "impact" segment. These files were then categorized as "before," "during," and "after"; where the "before" segment was the period where the ship was approaching the 50 km radius, the "during" segment was the period where the ship was within 50 km of the tagged whale, and the "after" segment was the subsequent period where the ship was beyond the 50 km distance radius to a tagged whale.

An equal number of control time series were selected where all ships were over 125 km away from a tagged whale to control for natural variation in beluga movement behavior in the absence of vessels. These two sets of series, the ship series and the control series, allowed us to perform a pseudo before-after control-impact analysis. For the control series, whale locations were selected at equivalent times and for the same durations as the ship series (before, during, and after) for each paired encounter. A minimum of three consecutive whale locations were used to represent each before, during, and after segment for both the ship and control series. By comparing the control time series with the ship time series, natural variation in beluga movements can be compared with beluga movements during exposure to ships.

The impact of the distance of ships on beluga swim speed and bearing was analyzed using a before-after control-impact design. Beluga swim speed was estimated from the CRW modeled locations by calculating the distance (meters) between consecutive whale locations and dividing by delta time (seconds). Beluga delta bearing was estimated by calculating the difference in bearing between consecutive whale locations. We acknowledge that variable times between spatially corrected original time stamped data points could bias estimates of actual swim speed and turning angle. Linear mixed effects models in R (package: lme4; function: lme; Bates et al., 2015; R Core Team, 2021) were fitted separately with beluga swim speed or delta bearing as dependent variables, and the logarithm ($\log_{10}$) of ship distance relative to the whale (meters) as a continuous independent variable. The $\log_{10}$ distance of 125,000 m was applied to control series since 125 km was the distance threshold used to identify ship presence. Ship noise received level was included as an alternate continuous independent variable and 90 dB was applied to control series, since 90 dB is roughly the lower boundary of broadband (50–1,000 Hz) ambient sound levels during the open water period (Halliday et al., 2017; Halliday, Barclay, et al., 2021; Insley et al., 2017). Ship count (number of ships within 50 km involved in the encounter), ship class and encounter exposure time (minutes) were included as additional covariates. A categorical variable was included that identified the time series as control (ship absent) or impact (ship present). Individual whale ID and a chronological encounter number were included as nested random effects. We fitted additional linear mixed effects models accounting for the interaction between ship presence/absence and time segment (i.e., before, during, after) and removed the ship distance variable as it was correlated to the impact time segments. To account for potential temporal autocorrelation within time series, an encounter specific random effect was also included and modeled to follow a continuous time autoregressive process within each time series.

A generalized additive mixed model (GAMM) was fitted in R to identify inflection points in the relationship between ship distance and whale speed or delta bearing (package: gamm4; function: gamm; Wood & Scheipl, 2020). Residual diagnostic plots with normalized randomized quantile residuals were used to assess model fit and assumptions, and correlation tests and plots of the lagged residuals for up to 30 lags were assessed for temporal autocorrelation. Models accounting for autocorrelation were compared to those not adjusting for autocorrelation by using Akaike's information criterion (AICc) corrected for small sample sizes (package: qpcR; function: AICc; Spiess, 2014).

Beluga behavioral responses to ships were broadly grouped by visual examination of satellite location data tracks where spatial resolution permitted. Animations for each encounter event contain whale locations which were color coded by before, during, after, and control segments for ease of interpretation. Each encounter event's animation was reviewed independently by three authors (M.J.M., W.D.H., L.S.) and grouped into one of three broad behavioral response categories: potential avoidance, no lateral response and undetermined. Potential avoidance behavior was characterized as a notable change (>35°) in the direction of travel occurring in the before or during segment of a ship encounter. No lateral response was characterized as no notable change in the direction of travel occurring in the before or during segment of a ship encounter. Encounters where whale directional movement was unclear due to sparse surrounding locations or close proximity to shore (and therefore no space to swim away from the ship) were categorized as "undetermined." For each encounter, we checked that the movement trajectory was real and not an artefact of the CRW model and/or location error by removing the remaining lowest accuracy locations (Argos classes 0, A and B), refitting the CRW models and confirming that the movement trajectory associated with the CPA was reproduced.

We tested the ability to subjectively group beluga responses to encounters with ships by visual assessment of the animations using linear mixed effect models to identify relationships between behavioral response type and changes in whale bearing. Models fitted in R (package: lme4; function: lme; Bates et al., 2015; R Core Team, 2021) incorporated beluga delta bearing as a dependent variable, and behavioral response type as a categorical predictor variable which included "control," "potential avoidance response," "no lateral response," and "undetermined response" as factors. Individual whale ID and a chronological encounter number were included as nested random effects. To account for potential temporal autocorrelation within time series, an encounter specific random effect was also included and modeled to follow a continuous time autoregressive process within each time series. We also assessed models that used beluga swim speed as the dependent variable. Residual diagnostic plots with normalized randomized quantile residuals were used to assess model fit and assumptions, and correlation tests and plots of the lagged residuals for up to 30 lags were assessed for temporal autocorrelation. Models accounting for autocorrelation were compared to those not adjusting for autocorrelation by using Akaike's information criterion (AICc) corrected for small sample sizes (package: qpcR; function: AICc; Spiess, 2014).

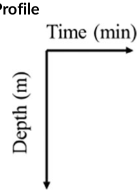
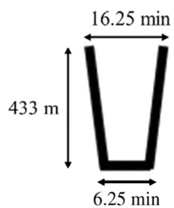
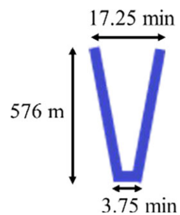
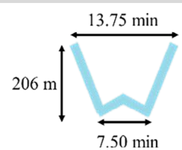
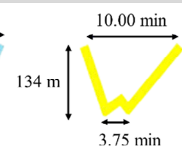
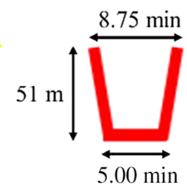
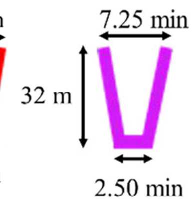
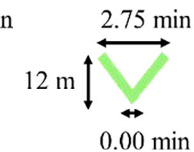
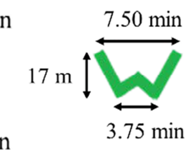
The main relationship of interest is that between behavioral response type and whale bearing. However, we accounted for the possible need to control for the time segment (i.e., before, during, after) as well as the interaction between behavioral response type and time segment. We used likelihood ratio tests (LRT) to test for the effects of the time segment and removed this variable and the interaction of behavior with time segment when there was a lack of evidence for such effects. A pairwise comparisons test using least-squares means (package: lsmeans; Lenth, 2016) was used to compare differences in whale bearing across behavioral response types.

## 2.5 | Beluga dive profiles

For encounter events between belugas and ships at distances less than 50 km, whale dive data were examined from the SPLASH10-F-238 tags for a 24 hr period centered around the time of CPA for each encounter. TDRs sampled depth at a 1 s frequency, and transmitted the data subsampled at a 75 s frequency. There were occasional 1 hr or greater time gaps in the dive profiles resulting from 1 hr time blocks where the TDR failed to transmit any dive data to the satellite (i.e., one message equates to one hr of continuous data). For periods with dive data, individual dives were characterized by time and depth metrics and classified into eight dive types according to the methods of Storrie et al. (2022; Table 4) which used the program *divebomb* (Nunes, 2019) in Python v3.7.1 (Van Rossum & Drake, 2009). *Divebomb* was used to measure dive parameters and categorize any dive made below a depth of 5 m. Storrie et al. (2022) defined eight dive types based on 90,211 dives reported from the 2018 tagged whales in this study (91.6% of reported dives) and seven additional EBS belugas tagged in 2019 (8.4% of reported dives). Seafloor depth for each dive was estimated from the International Bathymetric Chart of the Arctic Ocean (IBCAO) version 3.0 (Jakobsson et al., 2012) and the General Bathymetric Chart of the Oceans (GEBCO Bathymetric Compilation Group, 2020). Identified dives along with their measured parameters (i.e., dive duration, descent rate, ascent rate, bottom duration, maximum depth) were incorporated into each whale-ship encounter event and sorted by time. Dive data were not assessed quantitatively due to nonnegligible data gaps during most encounter events. Due to dive data gaps and known variability in EBS beluga dive behavior (Storrie et al., 2022), we cannot be certain whether changes in dive behavior represent disturbance responses to ships or natural behavior. The dive profiles are provided as additional context and to generate hypotheses on beluga behavior during ship encounters (see Figures S1–S18).

Storrie et al. (2022) proposed the function of classified beluga dives based on time and depth structure, foraging theory, beluga physiology, and published literature on marine mammal dive behavior. In short, EBS belugas exhibit a number of dives suggestive of foraging due to their depth, long bottom durations, and rapid descent rates, including benthic dives (Deep Benthic, DB; Intermediate Benthic, IB) and pelagic dives (Deep Pelagic V, DPV; Deep Pelagic W, DPW) (Table 4). EBS belugas frequently made Shallow V-shaped dives (SV) after deep foraging type dives, with the shallow nature and slow rates of vertical movement for this dive type supporting its use in recovery or transiting behavior (Fahlman et al., 2021; Hooker et al., 2009; Lemieux Lefebvre et al., 2018; Vacquié-Garcia et al., 2019). Other dive types were variable in form (Intermediate Pelagic, IP; Shallow W, SW) and likely represent a number of behaviors including but not limited to recovery, transiting, pelagic foraging, social behaviors, and/or navigating through ice (Table 4; Loseto et al., 2006; Martin et al., 1994; Quick et al., 2017). A final dive type, Deep Pelagic Skew (DPS), was recorded only infrequently, and may represent a pelagic foraging dive with vertical pursuit of prey or an energy efficient drift dive (Lemieux Lefebvre et al., 2018; Simon et al., 2009). Full details on dive classification, sources of error, and hypotheses on dive functions are provided in Storrie et al. (2022).

**TABLE 4** Summary of EBS beluga dive types and proposed functions derived from Storrie et al. (2022, see Table 2) which uses the same tagged individuals as this study and additional belugas tagged in 2019. Mean dive depth, bottom duration, and overall dive duration values are provided for each dive type. **References:** [a] Doniol-Valcroze et al. (2011); [b] Irvine et al. (2017); [c] Lemieux Lefebvre et al. (2018); [d] Martin et al. (1998); [e] Arce et al. (2019); [f] Simon et al. (2009); [g] Fahlman et al. (2021); [h] Castellini et al. (1988); [i] Quick et al. (2017); [j] Hill et al. (2015); [k] Loseto et al. (2006); [l] Hornby et al. (2016).

| Dive type | Deep Benthic (DB) | Deep Pelagic V (DPV) | Deep Pelagic W (DPW) | Deep Pelagic Skew (DPS) | Intermediate Benthic (IB) | Intermediate Pelagic (IP) | Shallow V (SV) | Shallow W (SW) |
|---|---|---|---|---|---|---|---|---|
| **Profile**   |   |   |   |   |   |   |   |   |
| **Likely functions and rationale** | a. **Benthic foraging:** deep, fast descent rate, long bottom phase[a,b,c] at the seafloor | a. **Pelagic foraging:** deep, fast descent rate[a,b,c], bottom phase in mid-water column | a. **Pelagic foraging with vertical search/ pursuit of prey:** Fast descent rate, long bottom phase with vertical movements[a,d] | a. **Pelagic foraging with vertical search/ pursuit of prey:** Fast descent rate, bottom phase with vertical movements[a,d]<br>b. **Drift dive:** skewed shape with longer ascent phase than descent phase[e,f] | a. **Benthic foraging:** Long bottom phase at the seafloor[a,c] | a. **Recovery, resting:** Slow descent and ascent rate, frequently occurred after deep dives[g,h]<br>b. **Social behaviors:** Possibly too deep to benefit transiting, proposed in other odontocetes.[i] This dive type had high variability. | a. **Transiting, recovery, resting:** Slow descent followed immediately by slow ascent, frequently occurred after deep dives and throughout the year, shallow[c,g,h]<br>b. **Social behaviors:** Only described in shallow depths by belugas[c,j] | a. **Transiting, recovery, resting:** Slow descent and ascent rate, frequently occurred after deep dives[c,g,h]<br>b. **Locating breathing holes in ice:** Occurred at times when EBS belugas are in areas with high sea ice coverage[k,l] |

# 3 | RESULTS

## 3.1 | Summary of beluga encounters with ships

During July–December 2018, there were a total of 177 encounters between eight of the nine tagged belugas and ships within a radius of 125 km (Table 1, Figure 2). Whale LC2018#5 (referred to hereafter by whale identification number only, e.g., #5) did not encounter a ship within this distance radius; however, this animal's tag only transmitted for 17 days. The remaining eight whales' tags transmitted for longer periods (46–355 days; Table 1). These eight whales varied in their number of encounters with ships ranging from 2 to 71 (Table 1, Figure 2). Two whales (#2 and #6) had notably higher numbers of encounters with ships with 57 and 71 encounters, respectively. This was due to the near-shore migration routes traveled by those individuals (Figure 1a). Whales #2 and #6 also had the nearest CPAs to ships of all the tagged individuals examined (Table 1). During the month of November in the Chukchi Sea, the highest number of encounters with ships ($n = 49$) occurred, where six tagged belugas each had between 6 and 13 encounters (Table 1, Figure 2). August also contained a high number of encounters ($n = 47$) between ships and four tagged belugas in the Amundsen Gulf and eastern Beaufort Sea (Table 1, Figure 2). July and December 2018 were the months with the lowest numbers of encounters, likely due to seasonally reduced accessibility of this region to ships.

For each tagged whale, the average CPA to a ship <125 km away was at a distance >75 km; however, there were five individuals which experienced CPAs to ships at distances ≤50 km (Table 1). When considering behavioral

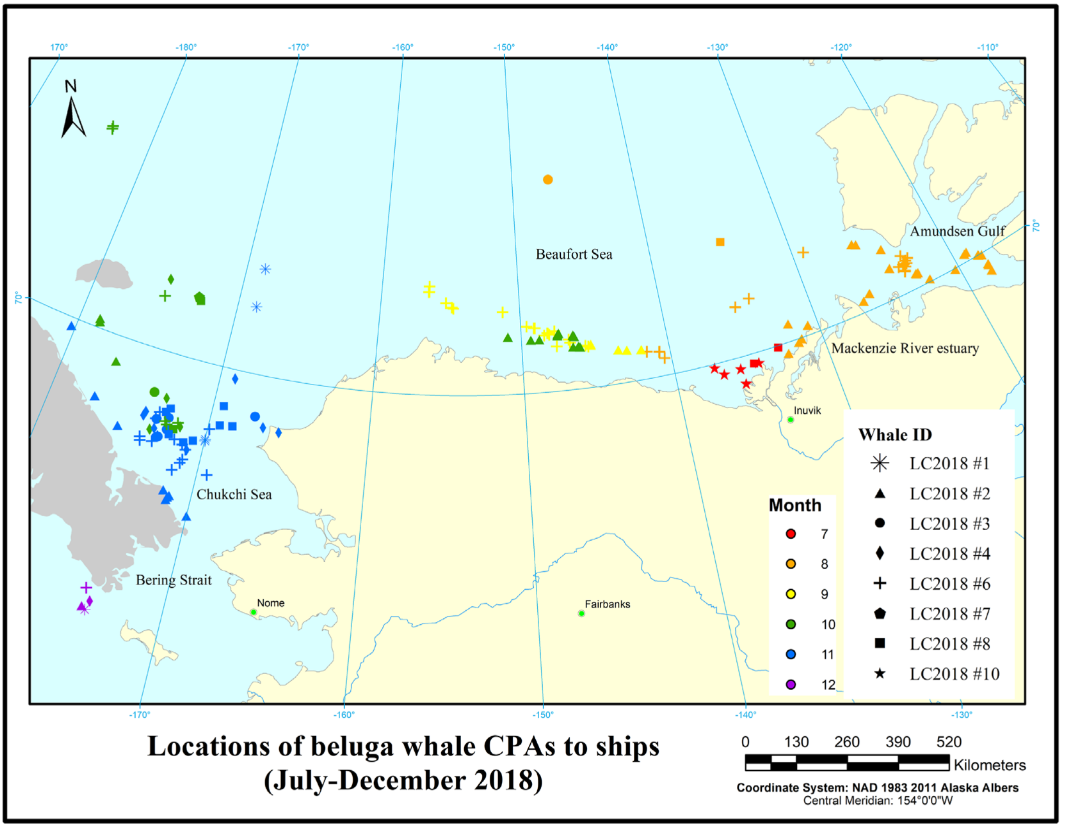



**FIGURE 2** Map of the 177 closest points of approach (CPA) for all encounters between tagged belugas and ships within a radius of 125 km. CPAs are color coded by month and shape coded by individual tagged beluga.

responses of belugas to ships located within 50 km, a total of 23 unique encounters occurred with one or more ships (Table 2). Of these encounters, three showed no indication of a lateral behavioral response (Figure 3a), eight displayed signs of potential avoidance responses (Figure 3b), and seven were categorized as undetermined. The remaining five encounters were considered data deficient and were not included in any statistical model due to time gaps >4 hr in whale locations occurring in the before, during, or after segments. Most encounters involved a single ship; however, six encounters contained two ships and one encounter involved three ships (Table 2). Of the 18 ships involved in these encounters, the Canadian Coast Guard research vessel *Sir Wilfrid Laurier* had the most encounters ($n = 5$; Table 3). There were no ships considered to be heavy icebreakers or seismic survey vessels; therefore, we did not examine whether the ships were operating in ice or if seismic ships might have been active. For the encounters within 50 km, CPAs between whales and ships were highly variable and ranged from 6.8 to 46.7 km (Table 2).

## 3.2 | Statistical effects

Results of the statistical models should be interpreted with caution since some variables were modeled and without experimental validation from additional controlled studies. A negative correlation was identified in the modeled variables where beluga swim speed increased with decreasing distance to ships in the encounter (i.e., impact) time series (slope $= -0.704 \pm 0.139$ m/s/$\log_{10}$ ship distance, $t_{966} = -5.059$, $p < .001$) and was different from the control time series ($t_{966} = -2.316$, $p = .021$; Figure 4a, Table 5), but remained relatively constant through time within the control time series ($t_{963} < 1.493$, $p > .136$). A perceived nonlinear change in the correlation between beluga swim speed with distance to ships was identified (GAMM: edf $= 3.208$, $F = 22.81$, $p < .001$). An inflection point occurred around a distance of $\log_{10}4.9$ m (Figure 4b), which equates to a distance of ~79 km. The average swim speed was 1.92 m/s ± 0.34 *SD*) at ~13 km ($\log_{10}4.1$ m) distance to ships compared to 1.07 m/s ± 0.70 *SD*) at ~79 km distance to ships (Figure 4b). The second set of models examining beluga swim speed by encounter segment showed evidence that swim speed increased in the during segment ($t_{965} = 2.051$, $p = .041$, $M \pm SD = 1.26 \pm 0.59$ m/s), but did not differ from the control ($M \pm SD = 1.07 \pm 0.51$ m/s) in the before segment ($t_{965} = -0.844$, $p = .399$, $M \pm SD = 0.99 \pm 0.58$ m/s) and after segment ($t_{965} = -0.191$, $p = .849$, $M \pm SD = 0.99 \pm 0.58$ m/s; Figure 5; Table 5).

There was evidence that change in beluga bearing increased in encounters visually assigned as "potential avoidance response" compared to the control time series ($t_{965} = 2.800$, $p = .005$). There was no evidence of a difference in beluga delta bearing in encounters visually assigned as "no lateral response" compared to the control time series ($t_{965} = -0.212$, $p = .833$; Table 5). There was no evidence of a correlation between beluga swim speed and the visually assigned behavior type categories. There was some indication of temporal autocorrelation when analyzing residuals, and the lowest AICc values were obtained by including the continuous time autoregressive process; hence, all final models included the random effect for temporal autocorrelation.

## 3.3 | Encounters with a potential avoidance behavioral response

Of the eight encounters between belugas and ships where a potential avoidance behavioral response was observed, four encounters involved a single ship and four encounters included two or three ships (Table 2). The CPAs between the whales and ships ranged from 12.6 to 43.1 km and at CPA the estimated RLs of ship noise near the whale were 98–133 dB re 1 μPa (Table 2). A brief summary of each encounter is provided in the following paragraphs. All times are reported in UTC. In these eight cases, there were indications of two broad types of dive disturbance response: (1) shallow diving/swimming behavior from 0 to 20 m depth, and (2) anomalous spike-shaped dives, where maximum depth was reached and the beluga either immediately started to ascend or had a much shorter bottom phase than was typical for the given dive type based on measured dive parameters in Storrie et al. (2022; Table 4, Figures S1–S8).

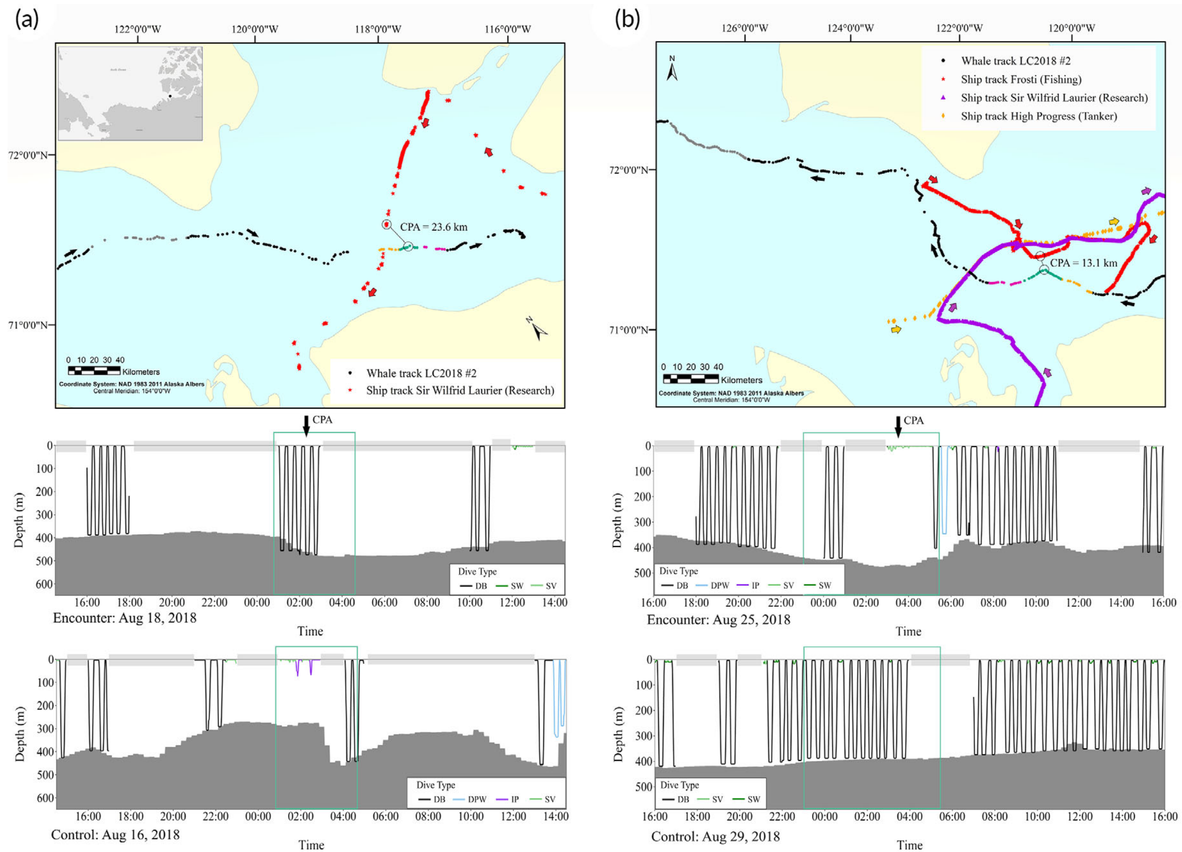



**FIGURE 3** (a) Beluga encounter with a ship where no lateral behavioral response was observed. (b) Beluga encounter with three ships with evidence of a potential whale avoidance behavioral response. For each encounter, the top panel is a bird's eye view of ship AIS and whale tracks; the closest points of approach (CPA) identified with black circles. Whale locations estimated from the CRW model are shown as color coded dots pertaining to the encounter segments and control segments. Color coded whale locations: gray ("control" segment), orange ("before" segment), green ("during" segment), pink ("after" segment), and black (all other locations). The inset map in gray scale shows the location of the encounters as a black dot in the Pacific Arctic. The bottom two panels show the whale's dive profile with sea floor depth during the encounter and the control period. Light gray bars are placed along the top of the dive profiles for time periods when dive data were missing. A green box is placed over the "during" period which includes the CPA.

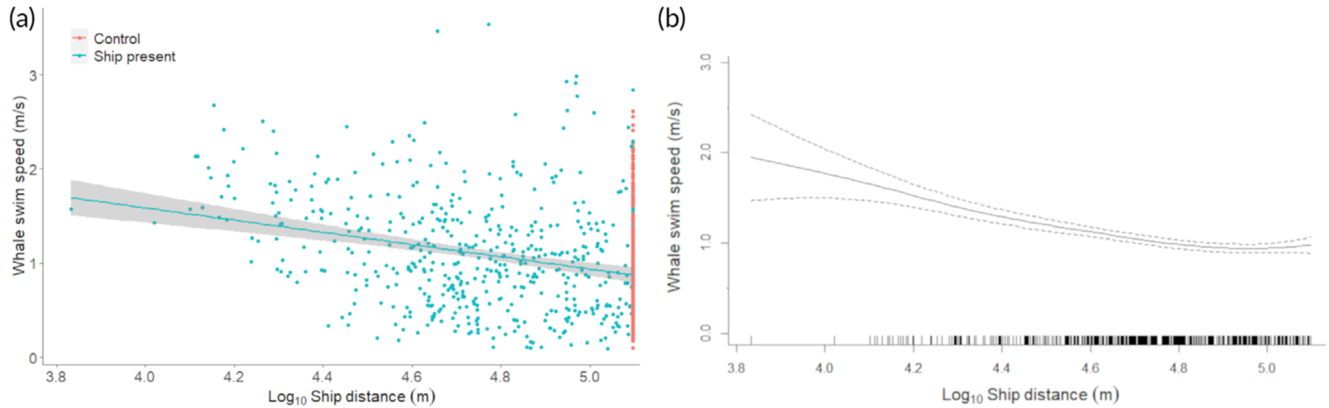



**FIGURE 4** (a) Scatterplot of beluga swim speed by distance to ships. A negative correlation was identified in the modelled variables indicating an increase in beluga swim speed with increasing proximity to ships in the encounter (i.e., impact) time series and was different from the control time series. (b) Generalized additive mixed model result used to identify a nonlinear change in the relationship between beluga swim speed with distance to ships. An inflection point occurred around a ship distance of $\log_{10}$ 4.9 m, which equates to a distance of ~79 km.

**TABLE 5** Linear mixed effect model results for the comparison of tagged beluga swim speed and change in bearing between the control (ship absent) and distance to ships ($df = 966$), encounter time segment ($df = 965$), and behavioral response type ($df = 965$). Eighteen encounters between tagged belugas and ships consisting of 986 whale locations were included in these models. Effect sizes are reported with 95% confidence intervals (CI) and values based on $p < .05$ are shown in bold.

| Swim speed by distance to ships | | | | Swim speed by encounter segment | | | | Delta bearing by response type | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Predictors** | **Estimates** | **CI** | ***p*** | **Predictors** | **Estimates** | **CI** | ***p*** | **Predictors** | **Estimates** | **CI** | ***p*** |
| (Intercept) [Control] | 4.6 | 3.21, 5.98 | **<.001** | (Intercept) [Control] | 1.03 | 0.85, 1.21 | **<0.001** | (Intercept) [Control] | 16.52 | 10.33, 22.71 | **<.001** |
| Ship present | −0.15 | −0.28, −0.02 | **0.021** | Segment: Before | −0.06 | −0.19, 0.08 | 0.399 | Behavior: Avoidance | 6.75 | 2.02, 11.48 | **0.005** |
| $log_{10}$distance | −0.7 | −0.98, −0.43 | **<.001** | During | 0.15 | 0.01, 0.30 | **0.041** | No lateral response | −1.04 | −10.68, 8.60 | 0.833 |
| | | | | After | −0.02 | −0.17, 0.14 | 0.849 | Undetermined | 6.07 | −0.07, 12.20 | 0.053 |

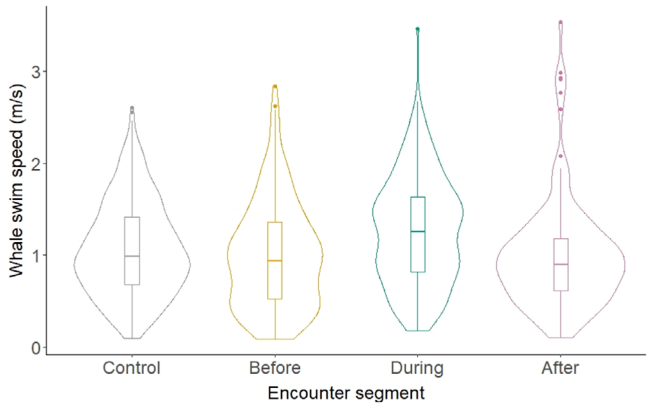



**FIGURE 5** Beluga changes in swim speed (meters/second) estimated at the times of the CRW-modeled locations during each of the encounter segments "before," "during," and "after" based on when one or more ships were within 50 km of a tagged whale, as well as during control segments when no ships were present within a 125 km radius. Violin plots are used to show the probability density of the data at different values. Boxes inside each violin plot represent the interquartile range, the line within the boxes is the median, whiskers are the minima and maxima, and dots are outliers.

### 3.3.1 | Potential avoidance response 1

On August 7, 2018, whale #2 was in the Amundsen Gulf and traveling in a westward direction (heading ~260°) toward shore (Figure S1). This was the first known encounter between whale #2 and a vessel at ≤50 km distance during the study period. Two ships, a fishing/government research vessel, *Frosti*, and a coast guard/government research vessel, *Sir Wilfrid Laurier* (Tables 2 and 3), were traveling in a southeasterly direction in tandem (see Animation S1). The CPA between the whale and the two ships occurred at 22:27 UTC at a distance of 19.1 km (based on *Frosti's* position) with an estimated combined ship noise broadband RL near the whale of 98 dB re 1 μPa (Table 2). A U-shaped diversion in lateral movement in the during segment added a distance of 12 km to the whale's westward transit to shore. During the hour prior to the CPA, the beluga made three anomalous spike-shaped dives with short bottom durations (Figure S1).

### 3.3.2 | Potential avoidance response 2

On August 20, 2018, whale #2 was located in the Amundsen Gulf when it encountered the tugboat *Kelly Ovayuak* (Tables 2 and 3). The CPA between the whale and the ship occurred at 14:58 UTC at a distance of 12.6 km, and the estimated received level from the ship near the whale was 127 dB re 1 μPa (Table 2). There were no dive data from 14:00 to 19:00 UTC, including during the CPA. Prior to the CPA, the dive profile indicated foraging behavior with alternating DB and SV dives. The whale appeared to be foraging, and then exhibited a directed lateral movement north and away from the ship track in the during segment (see Animation S2, Figure S2).

### 3.3.3 | Potential avoidance response 3

On August 25, 2018, whale #2 was traveling in a northwesterly direction (heading ~320°) in the Amundsen Gulf (Figure 3b). Three ships, *Frosti* (fishing/government research vessel), *High Progress* (tanker ship), and *Sir Wilfrid Laurier* (coast guard/government research vessel) (Tables 2 and 3), were traveling in an easterly direction overall; however, the *Frosti* changed heading several times likely due to fishing activity (see Animation S3). The CPA between the whale and the three ships occurred at 03:48 UTC at a distance of 13.1 km (based on *Frosti's* position) with an estimated combined ship noise broadband RL of 119 dB re 1 μPa (Table 2). During the hour prior to the CPA, the beluga made seven consecutive SV dives to 6.5–20.5 m depth. At 04:02 the animal returned to the surface and did not descend below 3 m depth for the next full hour (Figure 3b). These shallow dives/subsurface swimming coincided with a distinct westward change in lateral movement (heading changed from ~320° to 280°) in the during segment (Figure 3b).

### 3.3.4 | Potential avoidance response 4

On November 8, 2018, whale #4 was located in the Chukchi Sea near the east coast of Russia in shallow water (~50 m depth; Figure S4). A cargo ship, the *Arkadiy Chernyshev* (Tables 2 and 3), was traveling southeast parallel to the coast (see Animation S4). The CPA between the whale and the ship occurred at 07:27 UTC at a distance of 40.8 km, and the estimated broadband RL from the ship was 105 dB re 1 μPa near the whale (Table 2). Half an hour prior to the CPA, the whale made two shallow dives (SW and SV) followed by an anomalous spike-shaped IB dive to 42 m depth immediately prior to the CPA at 07:17 UTC, which lasted for 8.5 min but had no bottom duration (i.e., zero time spent at the dive's maximum depth). These dives coincided with an eastward change in the whale's lateral movement (heading ~50°), toward open water and away from the ship's track in the during segment (Figure. S4).

### 3.3.5 | Potential avoidance response 5

On August 12, 2018, whale #6 was located in the Amundsen Gulf moving southwest in ~350 m deep water (Figure S5). This was the first known encounter between whale #6 and a vessel at ≤50 km distance during the study period. A coast guard/government research vessel, *Sir Wilfrid Laurier*, was heading in an eastward direction in tandem behind the track of a tugboat, *Fathom Wave*, trailing by approximately 400 m (Tables 2 and 3; see Animation S5). The CPA (based on *Fathom Wave's* position) occurred at 06:32 UTC at a distance of 43.1 km. The estimated combined RL near the whale from both ships during the CPA was 99 dB re 1 μPa (Table 2). In the during segment, the whale did not alter its dive behavior and performed a series of DB and DPV dives to 400–500 m depth (Figure S5). There was a distinct change in lateral movement where the whale appears to have moved in a northeastward direction in the before segment, followed by a southwestward directed movement in the during segment, creating a circular shaped movement path.

### 3.3.6 | Potential avoidance response 6

This encounter occurred on August 29, 2018. Whale #6 was westbound in the Beaufort Sea when it encountered the Canadian coast guard/government research vessel *David Thompson* (Tables 2 and 3). The CPA between the whale and the ship occurred at 09:15 UTC at a distance of 20.9 km, and the estimated received level from the ship near the whale was 100 dB re 1 μPa (Table 2). There were no dive data from 05:00 to 09:00 or from 10:00 to 19:00 UTC, with only 1 hr of dive data during the CPA (09:00 to 10:00). The whale made one DB dive until 9:15 UTC and then remained at the surface with no additional dives for the next 45 min (Figure S6). In the during segment, the whale appeared to backtrack along its previous route and then moved in a southward direction away from the ship track (see Animation S6). In the after segment the whale returned to its previous westbound trajectory. The changes in lateral movement in the during and after segments created a circular shape in the whale's movement path (Figure S6).

### 3.3.7 | Potential avoidance response 7

On September 12, 2018, whale #6 was located in deep water (~700 m depth) in the western Alaskan-Beaufort Sea moving in a northward direction. A research vessel, *Sikuliaq* was traveling in a southeasterly direction and a tanker ship, *High Progress* (Tables 2 and 3), was headed in a southwesterly direction. The CPA between the whale and the closest ship (*Sikuliaq*) occurred at 08:44 UTC at a distance of 14.3 km, and the combined estimated RL from the ships, for a location near the whale, was 112 dB re 1 μPa (Table 2). Between 01:00 and 07:00 UTC, whale #6 was traveling in a northward direction. At 07:30, the whale made two anomalous 'spike' shaped dives which included a DPWS dive to 163 m depth with no bottom duration directly followed by a DB dive to 1,010 m depth with a short bottom duration of 3.75 min. The whale then remained at the surface and did not descend below 4 m depth from 07:53 to 08:08 which coincided with the start of a distinct westward change in the animal's heading (from ~320° to 280°) away from the ship (Figure S7). The whale remained at the surface from 08:17 to 08:53 and did not descend below 4 m depth during this time. These shallow dives/subsurface swimming coincided with the westward change in lateral movement in the during segment (see Animation S7).

### 3.3.8 | Potential avoidance response 8

On November 19, 2018, a tanker ship, *Georgiy Brusilov* (Tables 2 and 3), was moving northwest parallel to the Russian coastline approximately 40 km offshore in the Chukchi Sea. The CPA occurred at 06:16 UTC at a distance of 13.4 km from whale #6 (Table 2). During the CPA, the estimated RL from the ship near the whale was 133 dB re 1 μPa. There are gaps in the dive data from 05:00 to 06:00 and from 07:00 to 12:00 UTC; however, all dives identified over 24 hr centered around the CPA were IB dives to the seafloor (~48 m depth) indicating foraging behavior (Figure S8). There was a distinct change in lateral movement in the before segment where the whale began swimming in the opposite direction (see Animation S8). There was another distinct change in lateral movement in the during segment where the whale moved in a northeastward direction away from the ship track. The changes in lateral movement in the before and during segments created a circular shape in the whale's movement path (Figure S8).

## 3.4 | Encounters with no lateral response (NLR)

There were three encounters between belugas and ships when we identified no apparent lateral behavioral responses (NLR), defined as no clear change in lateral movement. All three of these encounters involved a single ship (Table 2). The CPAs between the whales and ships ranged from 23.6 to 46.7 km and estimated RLs near the whale ranged from 104 to 113 dB re 1 μPa (Table 2). Foraging dive types (DB, IB) were recorded in the encounter segments; however, there are nonnegligible gaps in the dive data. A summary of each encounter is provided in the following paragraphs.

### 3.4.1 | No lateral response 1

On August 18, 2018, whale #2 was located in Amundsen Gulf headed in a southeasterly direction (heading ~120°; Figure 3a). A research vessel, *Sir Wilfrid Laurier* (Tables 2 and 3), was headed in a southwesterly direction. The AIS ship locations were intermittent around the time of the CPA which occurred at 02:34 UTC at a distance of 23.6 km (Table 2). The estimated RL from the ship near the whale during the CPA was 113 dB re 1 μPa. The whale appeared to be foraging and the dive profile did not change prior to, or during, a period of two hr around the CPA (Figure 3a). Dives were long (~17.5 min) DB dives to the seafloor (~475 m depth) including dives at 02:13 and 02:37 UTC. There was no apparent change in the lateral movement path of the whale during the ship encounter (see Animation S9).

### 3.4.2 | No lateral response 2

This encounter occurred on November 8, 2018. Whale #2 was located in the Chukchi Sea moving southeast in parallel with the cargo ship *Arkadiy Chernyshev* (Tables 2 and 3). The whale was located between the ship and land (Figure S10). The CPA between the whale and the ship occurred at 04:56 UTC at a distance of 46.7 km, and the estimated received level from the ship near the whale was 104 dB re 1 μPa (Table 2). Post ship encounter, the whale turned to an easterly direction toward the ship track and open water (see Animation S10). In the during segment of this encounter, there was only 1 hr of dive data (05:00–06:00) which contained four IB dives and one SW dive (Figure S10).

### 3.4.3 | No lateral response 3

This encounter occurred on August 24, 2018. Whale #6 was located in the Beaufort Sea when it encountered the tanker ship *High Progress* (Tables 2 and 3; Figure S11). The CPA between the whale and the ship occurred at 04:33 UTC at a distance of 39.3 km, and the estimated received level from the ship near the whale was 112 dB re 1 μPa (Table 2). There were no dive data from 02:00 to 03:00 and 04:00 to 06:00 UTC, including during the CPA. When dive data were available, other time periods indicated foraging with only DB and SV recorded dives. Throughout the encounter, the whale was moving in a southwesterly direction away from the ship track with no directional change in lateral movement (see Animation S11).

## 3.5 | Encounters with undetermined behavior (UND)

There were seven encounters between belugas and ships in which the behavioral responses were considered to be undetermined due to unclear whale lateral movements through time. For an encounter to be categorized as undetermined, whale locations were in close proximity to shore or whale points were sparse outside of the control and impact segments to a degree where a change in lateral behavior could not be visually assessed with confidence (see Animations S12–S18, Figures S12–S18). Whales #2 and #4 were involved in undetermined encounters (Table 2). Four encounters involved a single ship and three encounters included two ships. The CPAs between the whales and ships ranged from 6.8 to 39.4 km and estimated RLs near the whales ranged from 108 to 159 dB re 1 μPa (Table 2).

## 3.6 | Encounters determined to be data deficient (DD)

There were five encounters between belugas and ships that were considered to be data deficient due to significant gaps (>4 hr) in whale location data during the encounter segments. Four whales (#1, 2, 6, and 8) were involved in data deficient encounters (Table 2). The encounters each involved a single ship. The CPAs between the whales and ships ranged from 25.2 to 45.8 km and estimated RLs at a location near the whales ranged from 97 to 126 dB re 1 μPa (Table 2).

# 4 | DISCUSSION

This study summarizes the number of instances ($n = 177$) ships were encountered by tagged belugas and their behavioral responses during the period July–December 2018 in the Pacific Arctic (Table 1). We provide correlational evidence that belugas showed behavioral responses to vessels in the Pacific Arctic based on an increase in swim speed and change in bearing when in variable range of one or more ships. Results of the linear mixed effects models on modeled variables provide evidence that beluga swim speed was faster in the during segment of encounters (i.e., when ships ≤50 km from the whale) compared to the control, before, and after segments (Table 5, Figure 5). A correlation between an increase in beluga swim speed in the presence of ships was estimated to occur up to ~79 km distance (Figure 4). Additional model results provide evidence that change in beluga bearing increased in encounters visually assigned as "potential avoidance response" ($n = 8$ encounters) compared to the control time series. Furthermore, there was no evidence of a difference in beluga delta bearing in encounters visually assigned as "no lateral response" ($n = 3$ encounters) compared to the control time series.

A flee or avoidance response in belugas has been documented repeatedly at distances >10 km from ships (Finley et al., 1990; Miller et al., 2005; this study), suggesting that the response was to noise given that these distances are beyond the whales' visual and echolocation detection ranges. Finley et al. (1990) reported that belugas altered their acoustic behavior and began producing alarm calls when a transiting icebreaker vessel was approaching at 80 km distance. The whales further responded by fleeing when the icebreakers were at distances of 35–50 km with broadband RLs ranging from 94 to 105 dB re 1 μPa (Finley et al., 1990). Erbe and Farmer (2000) modeled the zones of acoustic impact around icebreaker ships affecting Arctic belugas and found that zones of disturbance were only slightly smaller than predicted zones of audibility (35–78 km distance, depending on location), which supports earlier conclusions by Cosens and Dueck (1993) and Richardson et al. (1995). Further, based on a propagation model Schack and Haapaniemi (2017) estimated that belugas could potentially detect ship noise from container and icebreaker vessels up to distances of 48 km and 57 km, respectively, during the ice-covered season and up to 75 km and 79 km, respectively, in open water. Results of the statistical analysis between beluga swim speed and ship distance corroborate these findings, with a negative correlation between increasing swim speed with decreasing ship distance up to approximately 79 km (Figure 4).

In this study, potential avoidance responses were observed in eight encounters at varying distances (12.6–43.1 km) with estimated maximum RLs of 98–133 dB re 1 μPa from a variety of ship types and sizes (Tables 2 and 3). This again raises the question as to whether received level, signal to noise ratio, signal type, or a combination of these elicit a flee response in belugas in the Arctic (e.g., Richardson et al., 1995). The wide range of estimated maximum received levels also calls into question the applicability of a single noise threshold, such as the 120 dB re 1 μPa disturbance threshold established by the National Oceanic and Atmospheric Administration (NOAA; National Marine Fisheries Service, 2018), since the tagged belugas in this study likely reacted at much lower received levels in agreement with the findings of previous studies. However, it should be noted that the received level estimates in this study include a degree of error, given that the source levels used were modeled based on different ships measured in other areas (i.e., the Port of Vancouver's ECHO program) and the propagation loss calculations were relatively simplistic and did not include water depth or bottom conditions along the acoustic propagation path, or the location of the beluga in the water column. It is important to note; however, that the relative differences in received levels is still useful for comparisons between different distances and vessel types, but caution should be used when examining the absolute values.

Two belugas (whale #2 and #6) were involved in seven of the eight encounters exhibiting potential avoidance behavior (Table 2). Comparatively, these two whales were present in the three encounters where no lateral behavioral response was found (Table 2). Both whale #2 and #6 were consequently represented frequently in case studies due to their higher number of encounters with ships during the study period (Table 1). Currently, it is unknown if there is an individual or group-related noise threshold where some belugas exhibit an avoidance response whereas others might have no reaction.

It is possible that whales became more tolerant to ship noise as the season progressed, or that costs associated with disrupted foraging outweigh the costs of avoiding a perceived threat in certain encounters. There is potential for some level of habituation or desensitization to ships for whales with repeated encounters; however, this is difficult to assess in the current study due to possible confounding factors, low sample sizes, and because tag spatial resolution declined toward the end of the study period. Moreover, it is important to consider that all tagged individuals were adult male belugas. These individuals likely encountered ships in previous years in the region, and the potential level of seasonal or permanent habituation to ship noise is unknown.

Additional observations support that belugas are more tolerant of stationary, constant noise sources compared to dynamic noise sources such as an approaching vessel (Fraker, 1977, 1978; McCarty, 1981; Stewart et al., 1982, 1983). Fraker (1978) and Stewart et al. (1983) also report instances where feeding belugas did not react to approaching ships or underwater playbacks of drilling sounds, respectively. The encounters where no lateral behavioral response was observed were chronologically intermixed with encounters from the same individuals where a potential avoidance response was observed (Table 2). CPA distance between the whales and ships and the estimated RLs in nonresponsive encounters were similar to encounters where potential avoidance responses were identified (Table 2). In three encounters with a potential avoidance response, the whales exhibited diving behavior characteristic of foraging prior to ship approach, which appeared to be disrupted towards the CPA (Figures 3b, S4, S7). Our findings corroborate previous studies which report disrupted foraging behavior in the presence of ships or ship noise for additional cetacean species (e.g., New et al., 2020; Pirotta et al., 2015; Steckenreuter et al., 2011; Wisniewska et al., 2018). However, exhibiting different reactions to similar noise levels suggests context-dependent responses in this species. Gomez et al. (2016), Richardson et al. (1995), and Southall et al. (2007) found that noise level failed to reliably predict identifiable behavioral responses in some marine mammals, as responses were affected by the context of the exposure and by the animal's experience with acoustic disturbances and motivation.

In six out of eight encounters that indicated a potential avoidance response, belugas demonstrated some degree of shallow diving behavior (SV, SW, and some IP type dives) or subsurface swimming, representative of transiting behavior in the during segment (Storrie et al., 2022). When paired with the lateral movement responses, this may strengthen the evidence of a flee response from ships, as observed in previous studies (Finley et al., 1990; Miller et al., 2005).

A second possible indicator of a dive disturbance response were the anomalous spike-shaped dives which occurred in the during segment in three of the potential avoidance encounters (Figures S1, S4, S7). Maximum depths between 20 and 1,010 m were reached, and the beluga either immediately started to ascend or had a much shorter bottom phase than expected for the given dive type (Table 4; Storrie et al., 2022). Belugas in the Arctic and sub-Arctic previously have been observed to perform long duration dives as an avoidance response to ships (Blevins, 2015; Finley et al., 1990; Krasnova et al., 2009); however, the present study provides the first evidence of a potential deep dive response down to 1,010 m depth (Figure S7). Similarly, northern bottlenose whales (*Hyperoodon ampullatus*) were reported to undertake nonforaging dives (evidenced by lack of foraging echolocation clicks) to 2,339 m depth in response to naval sonar (Miller et al., 2015). Such deep dives could represent an initial cryptic escape response thought to have evolved to reduce detection by predatory killer whales (*Orcinus orca*, Miller et al., 2015). Killer whales are not commonly found in the eastern Beaufort Sea and Amundsen Gulf where belugas were during July–September of this study, and are not considered to have elicited this dive response, at least in the earlier encounters of this study (Higdon et al., 2013; Stafford, 2019). Alternatively, the relatively short bottom phases of the deep spike dives could represent abandoned foraging behavior similar to that exhibited in beaked whales exposed to naval sonar and recordings of killer whale vocalizations (Tyack et al., 2011). Diving to several hundred meters as an escape response and disruption of likely foraging activity may be energetically costly to belugas, but only over relatively short periods with unknown long-term consequences.

The dive types characterized and classified by their time- and depth-structures in Storrie et al. (2022) exhibit within-group variability, and occur through the annual cycle often in regions which currently experience little to no anthropogenic activity. Hence, it is likely that certain dive types observed during ship encounters represent several behaviors rather than solely a response to vessels. Future studies will require the incorporation of ancillary data on animal acoustics, orientation, and/or acceleration to enable identification of foraging behavior within dives (e.g., Miller et al., 2015; Tyack et al., 2011) to confirm whether these deep dives represent a cryptic escape response, disrupted foraging behavior, a natural part of beluga behavior, or some combination.

Changes in a cetacean's lateral and vertical movements can be caused by other factors including social cues from conspecifics. Another social odontocete, the sperm whale (*Physeter macrocephalus*), has been observed making sudden turns during directed movements, which Whitehead (2016) suggests could be in response to receiving information on foraging success from another member of the group. The possibility that belugas exhibit the same behavior cannot be discarded; however, the timing of the movements described herein relative to ships and the consistency of beluga foraging behavior within a season (Storrie et al., 2022) indicates that avoidance is a more parsimonious explanation. Furthermore, EBS belugas are harvested by Inuvialuit in estuaries and nearshore areas during July and August (Harwood et al., 2014a). The seasonal whaling camps clustered on the coast of the Mackenzie River delta and Paulatuk when a change in lateral movement was observed were >100 km away, so responses in August 2018 were more likely due to the larger vessels analyzed herein than Inuvialuit harvesters.

Repeated anthropogenic disturbance likely has led to changes in local distributions of beluga populations (see Blevins, 2015 for a review). Therefore, increased shipping activity in key regions also may result in shifted distributions, at least in some areas. During migration along the coast of Alaska, belugas have shown a greater degree of displacement where there is extensive active subsistence hunting by local Indigenous communities (Burns & Seaman, 1986; Huntington, 2000; Stanek, 1996), which suggests avoidance behavior associated with experience. However, this may not be the case in other areas such as the Mackenzie River estuary, where thousands of belugas migrate each summer (Harwood et al., 2014b) despite local subsistence hunting each year (Fisheries Joint Management Committee, 2013). Consequences of anthropogenic disturbance that do not cause physical harm, such as belugas avoiding an area, may seem inconsequential; however, displacement from important habitats including feeding or calving grounds could be harmful to the sustainability of this species (Hobbs et al., 2006). For encounters where an avoidance behavioral response was detected, three encounters (A3, A4, A7; Figures S3, S4, S7) indicate that the whales' perceived foraging behavior ceased for a period of one to two hours during or when approaching the CPA. This could represent a 4.2%–8.3% reduction in available time spent foraging on a given day if the animal reacted to the ship stimuli. Such values are an estimate but provide insight to an amount of lost foraging effort elicited by single disturbance events in this study and provide context for future increases in ship traffic and expected encounter rates.

There are certain caveats associated with this study that need to be considered. These include (1) the inherent spatial accuracy in some whale location data derived from the Argos satellite system and time between original time stamped data points. While the crawl model accounts to some degree for issues associated with spatial accuracy, variable times between spatially corrected original time stamped data points could bias estimates of actual swim speed and turning angle. Five encounters between belugas and ships were classified as data deficient and could not be investigated further primarily due to insufficient tag data (Table 2). (2) The received level estimates were also approximations and include a degree of inaccuracy due to data not being available on the source level of each ship during the encounter, the simplistic propagation modeling used, and variable depths of the tagged whales in the water column. Future work would benefit from additional focused recordings of underwater ship noise unique to each vessel, including measurements of source levels. To accurately assess the received level for each individual whale would require the use of acoustic tags or an extensive array of acoustic recorders, which would not be feasible with currently available technology for the long-term tagging period of this study and the wide geographic scope of the encounters with ships. With developments in tag technology, future incorporation of 3-dimensional movement and acoustic data streams would provide the opportunity to examine changes in the acoustic behavior of belugas, identify the acoustic signature, received level and exact time when ship noise is received at the whale, and ultimately allow a more in-depth examination of belugas' behavioral response to the type and received level of ship noise and other sounds. (3) It is possible that there were ships present which did not carry AIS transponders. For example, Halliday et al. (2018) found that only 32% of pleasure craft (i.e., private yachts, sailboats) and 70% of passenger ships traveling in the Inuvialuit Settlement Region (western Canadian Arctic) during 2012–2015 were broadcasting AIS signals. Most small local boats and many tugs operating in this region similarly do not carry AIS transponders (Halliday et al., 2020b). We may therefore have underestimated the total number of beluga encounters with ships within the 125 km radius, and as such our counts represent minimum estimates. Individual encounters could also include additional ships that were not accounted for in the AIS data set.

Finley et al. (1990) reported that responses to ship noise by both belugas and narwhals (*Monodon monoceros*) at long ranges up to 80 km may be explained in part by the fact that no similar field studies previously were conducted in pristine marine environments with industrially naive populations of marine mammals. We provide evidence that belugas in the Pacific Arctic are still reacting to ship noise at long ranges and low received levels despite a doubling or tripling of ship traffic over the past three decades (Dawson et al., 2018) and high levels of oil and gas activity in the Beaufort and Chukchi Seas during the same period (Reeves et al., 2012). Our findings corroborate previous studies showing that belugas in the Arctic often react to ships far beyond the whales' visual range, implying that the whales are reacting to the ships' underwater sound stimuli. Richardson et al. (1990) hypothesized that reaction distances of belugas will be larger when anthropogenic noise contains higher frequency (>1 kHz) components due to their sensitive high-frequency hearing. Cosens and Dueck (1993) confirmed the presence of higher frequency (5 kHz band) components in the noise signal from the icebreaker ship studied by Finley et al. (1990), and Erbe and Farmer (2000) and Schack and Haapaniemi (2017) provided further evidence that belugas should be able to detect such sounds at large distances (35–78 km and 43–79 km, respectively).

## ACKNOWLEDGMENTS

Satellite AIS data were provided by the Marine Environmental Observation Prediction and Response (MEOPAR) network and the Meridian project through partnerships with exactEarth Ltd. (2019). The Eastern Beaufort Sea beluga tagging program acknowledges our partners the Inuvialuit Game Council and Fisheries Joint Management Committee for their work in supporting program design, along with members of the Tagging Advisory Group. Special thanks to members of the 2018 field crew for their work in data collection, advice on project delivery, and discussions on beluga ecology: John Noksana Sr., Joseph Felix Jr., James Pokiak and Mikkel Panaktalok (Tuktoyaktuk), Lawrence Kaglik and Linley Day (Inuvik), Dennis Arey and Dwayne Benoit (Aklavik), Patrick Akhiatak (Ulukhaktok), Émilie Couture and Benjamin Lamglait (Granby Zoo/Canadian Wildlife Health Cooperative), Greg Elias (Aurora Research Institute), and Jeremy Hansen (Fisheries and Oceans Canada, Inuvik). Thank you to Laura Murray (Fisheries and Oceans Canada), Emily Way-Nee (Joint Secretariat), Jimmy Kalinek (Only Way Outfitting) and Charles Pokiak for key logistical support. Finally, we thank the reviewers of this manuscript for their insight and useful feedback. The following approvals were required for whale capture and handling procedures: DFO License to Fish for Scientific Purposes (S-18/19-3020-YK), Freshwater Institute Animal Care Committee permit (FWI-ACC-2018-24), and Letters of Support from Inuvialuit Hunters and Trappers Committees and the Inuvialuit Game Council.

## AUTHOR CONTRIBUTIONS

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## FUNDING

This work was supported by The Weston Family Foundation, Fisheries and Oceans Canada through the Canada Nature Fund for Aquatic Species at Risk, and Mitacs through the Mitacs Accelerate program. Funding for the Eastern

Beaufort Sea beluga tagging program was provided by Crown-Indigenous Relations and Northern Affairs Canada (Beaufort Regional Strategic Environmental Assessment), Fisheries and Oceans Canada (Intergovernmental Strategy, Strategic Program for Ecosystem-based Research and Advice, National Conservation Plan), the Fisheries Joint Management Committee (Tarium Niryutait Marine Protected Area Funds, Anguniaqvia niqiqyuam Marine Protected Area Funds, FJMC Core Funds), and Natural Resources Canada (Polar Continental Shelf Program).

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Martin, M. J., Halliday, W. D., Storrie, L., Citta, J. J., Dawson, J., Hussey, N. E., Juanes, F., Loseto, L. L., MacPhee, S. A., Moore, L., Nicoll, A., O'Corry-Crowe, G., & Insley, S. J. (2023). Exposure and behavioral responses of tagged beluga whales (*Delphinapterus leucas*) to ships in the Pacific Arctic. *Marine Mammal Science*, *39*(2), 387–421. https://doi.org/10.1111/mms.12978

# Chapter 6
# Underwater noise from shipping – a special case for the Arctic

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## Abstract

Until recently, the Arctic Ocean has supported limited shipping and it remains one of the only oceans on the planet to be relatively unpolluted by anthropogenic underwater noise. Climate change is transforming the Arctic Ocean and opening it to unprecedented levels of industrial development, including shipping expansion. Concurrently, Arctic marine biodiversity – relied upon by many coastal Indigenous communities – is under pressure to adapt to rapid environmental changes. In this chapter we discuss why the Arctic is a special case for underwater noise from shipping and how management tools could be applied to safeguard its unique biodiversity and ecosystems. The Arctic Ocean's underwater acoustic properties differ from non-polar waters, being primarily affected by sea ice, which is a source, shield and diffuser of underwater sound. Cold water and changing salinity gradients also affect sound propagation underwater. Long-range sound propagation occurs at shallow depths within the swimming and diving ranges of many marine animals, which are likely to be highly sensitive to noise. Finally, Arctic shipping itself has distinctive characteristics, including icebreaking and a high propensity for spatial overlap with biodiversity hotspots due to ice cover. With trans-Arctic shipping routes predicted to become navigable by mid to late century, we suggest a proactive approach by Arctic coastal states that addresses key knowledge gaps about noise-sensitive species, systematically monitors underwater soundscapes and holds noise at safe levels for biodiversity. Climate change-induced effects on underwater soundscapes, ecosystem processes and the distribution of biodiversity in time and space must also be accounted for.



**KEYWORDS**
Acoustic, Arctic, Arctic Council, IMO, marine mammal, shipping, soundscape, underwater noise.

## 1. Addressing underwater noise – from monitoring to management

Effective measures to regulate underwater noise in the Arctic should include monitoring, mitigation and management. Monitoring underwater noise, implementing mitigation measures and establishing legal tools to guide management regimes can be costly, and countries may need to be incentivised or obliged to invest in proper frameworks and programs. Currently there is no such requirement for Arctic states to do this.

Recognition of underwater noise as a pollutant is one way to enforce its regulation. The European Union (EU), for instance, has expressly defined underwater noise as a form of pollution in its 2008 Marine Strategy Framework Directive (MSFD), where it outlines the need for the introduction of energy, including underwater noise, to be at levels that do not adversely affect the marine environment in order to achieve Good Environmental Status (Directive 2008/56/EC 2008). European Member States are required to develop strategies for their marine waters to achieve such status. This has encouraged new research in the field, stimulated the market of underwater sound equipment, engineering and advice, and instigated technical working groups to define indicators, targets and guidelines for measuring and monitoring underwater noise from impulsive and continuous sources.

## 6.1 Monitoring the Arctic Ocean soundscape and underwater noise

Regional underwater noise baselines are necessary because they define the receiving environment for marine species and enable changes in noise to be measured over time. Although there is no purpose-built acoustic observing system in place across the Arctic, ambient soundscapes of the Arctic Ocean have been explored since the 1960s across various regions (PAME 2019). While these studies could provide valuable baselines to compare how anthropogenic noise has changed over time, there are still large geographic areas without available information on ambient sound levels. Most of these gaps exist in regions where shipping is increasing, including in the Russian Arctic (East Siberian Sea, Kara Sea and Laptev Sea) and much of the Canadian Arctic Archipelago (PAME 2019). In Russia this increase is due to the use of the Northern Sea Route, mostly for the export of Liquified Natural Gas (LNG), and in Canada, the export of iron ore by bulk carriers from one of the Arctic's largest mines.

Strategic, systematic acoustic monitoring of the Arctic Ocean is needed for effective management of underwater noise. Coverage should encompass locations within and beyond the Exclusive Economic Zones (EEZ) of Arctic coastal states. A comprehensive acoustic network would include locations where other sources of anthropogenic underwater noise are occurring or likely to increase, as well as areas that are currently quiet. Implementing such a system could be staged, since it would require significant financial and logistical investments due to of the sheer size of the region and because the use of underwater acoustic equipment can be seriously challenged by ice conditions. Priority could be given to areas ranked as having high combined biological, ecological and cultural importance (regardless of their current overlap with underwater noise-producing activities), and to locations where shipping is increasing or predicted to increase, including along future trans-Arctic shipping routes. Arctic coastal states may also choose to prioritise habitats used by commercially valuable species that are sensitive to noise.

In combination with collecting actual measurements, modelling to create noise maps would be of benefit and is a focus of a current Arctic Council PAME project. In the EU, the combined use of measurements and models is considered the best way for Member States to ascertain levels of and trends in ambient noise (Dekeling et al. 2014). If sufficiently ground-truthed with acoustic data to calibrate noise propagation, models can provide an overview of noise levels and their distribution across time and space, and further, can help to inform positions for acoustic monitoring (Dekeling et al. 2014). Accurate data on source levels of noise from ships operating in Arctic waters would be needed, so efforts to understand the levels of underwater radiated noise emitted by different vessel classes, propulsion systems and vessel components during operation, including transiting through ice, could inform not only noise models, but also adaptive approaches to mitigating noise through redesign or retrofit.

If Arctic coastal states were to commit to a goal to ensure that underwater noise is managed at levels safe for Arctic marine biodiversity, it would be essential that they obtain high-quality information not just about underwater noise, but also biodiversity. There are still many gaps in our knowledge about noise-sensitive species in the Arctic, including their important habitats, their use of sound and thresholds for behavioural and hearing effects of underwater noise. Filling these gaps could be a priority for the Arctic Council through supporting scientific research and Indigenous knowledge studies. Further, climate change effects on the Arctic marine environment mean that important areas for biodiversity are unlikely to be static over time. Loss of sea ice and shifts in distributions of predators and their prey mean that high-quality habitats and important processes (e.g., spawning, migration) are likely to continue to change spatially and temporally in the future. Monitoring and predicting these shifts, where possible, will be necessary for proactive management of underwater noise.

## 6.2 Mitigating impacts of underwater noise from shipping

Unlike other forms of pollution, underwater noise does not linger in the environment. Changing the amount of noise emitted will therefore have a virtually immediate effect. There are numerous tools and solutions to mitigate effects of underwater noise from shipping that can be categorised broadly into technology and operations. We will discuss them briefly here in relation to their applicability for the Arctic.

Technological solutions focus on redesigning, retrofitting, or maintaining ships to reduce noise at the source. Retrofits and modifications to propellers have significant potential to reduce underwater noise generated by ships. This has been demonstrated by Maersk's Radical Retrofit program in 2015 and 2016, where 11 Class G container ships were retrofitted to improve fuel economy. Modification of the bulbous bow to reduce drag, a new propeller with four fins, and propeller boss cap fins to reduce cavitation resulted in a six decibel reduction of underwater noise in the 8 – 100 Hz frequency band and an eight decibel noise reduction in the 100 – 1000 Hz frequency band, together with a 10% improvement in fuel economy (Gassmann et al. 2017). Modifying the design of new vessels to be quieter is another option to reduce underwater noise. Ship classification societies have a quiet notation for ships and new builds that incorporates quiet ship design and technology to ensure certain standards of noise emissions are met. This latter option – to modify the design of new ships – is certainly an opportunity Arctic coastal states could take. Recent media articles have stated that Canada has commissioned six ships to be constructed for Arctic operations in 2020[1] and Russia has plans to build a new fleet of 14 icebreakers[2].

Operational solutions most commonly comprise reducing vessel speed or implementing routeing measures. Source levels of underwater noise increase with ship speed and size (McKenna et al. 2013). Slow steaming has resulted in an estimated reduction in underwater noise by as much as 50 percent in the eastern Mediterranean Sea (Leaper et al. 2014) and by 29 percent in Haro Strait,

[1] https://www.ctvnews.ca/canada/delivery-of-the-navy-s-first-arctic-and-offshore-patrol-ship-delayed-until-2020-1.4682002

[2] https://thebarentsobserver.com/ru/node/164

Canada (MacGillivray et al. 2019). Routeing measures entail physically separating ships from important areas for marine wildlife such as breeding, feeding, spawning, nursery and mating areas and migration pathways by changing the location of shipping routes or creating dedicated shipping corridors. The creation of Marine Protected Areas (MPA) or other special management areas with restrictions on shipping traffic is an additional spatial measure to reduce impacts of underwater noise.

In the Arctic, all abovementioned operational solutions are feasible, but once again the characteristics of the Arctic marine environment affect which measures can be used where. In the presence of sea ice cover, ships are likely to take routes through open water for safer and faster passage. Leads and cracks are used by Arctic marine mammals in ice-covered waters and polynyas – highly productive features of the Arctic Ocean because they are ice-free in winter – are hotspots for marine mammals, seabirds and their prey (fish and invertebrates). Similarly, the Bering Strait is a ‘choke point’ for the Northern Sea Route and all future trans-Arctic shipping routes and is also a seasonal migratory corridor and permanent hotspot for millions of animals. Here, physical separation of ships from wildlife may not be possible, but slow steaming could be. In other parts of the Arctic, physical separation is possible. Area-based protection of important habitats and rerouting of ships far enough to ensure that underwater noise does not permeate into these habitats could be a viable option. With only 4.7% of Arctic waters currently under protection at the most recent inventory (CAFF and PAME 2017), there is plenty of scope to expand marine protection to include quiet MPAs (concept suggested by Williams et al. 2015b).



### 6.3 Policy to guide management of underwater noise

Stronger regulation of underwater noise from shipping at the global scale would benefit the Arctic. The International Maritime Organization (IMO), the global standard-setting authority for the safety, security and environmental performance of international shipping, established voluntary guidelines in 2014 for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life (MEPC.1/Circ.833). Recent analysis suggests that the guidelines have not been effective in reducing underwater noise or compelling the marine sector to invest in quiet ships (MEPC 75/14). A mandatory instrument, either through existing measures like the EEDI (Energy Efficiency Design Index), or regulated targets for ship design, retrofits and performance, could prompt stronger action.

Because the existing IMO guidelines are not specific to polar environments, in themselves they may be insufficient for protecting Arctic marine biodiversity (Czarski 2017). An additional policy instrument specific to the Arctic and Antarctic is the IMO International Code for Ships Operating in Polar Waters (Polar Code), which came into force in 2017. While the Polar Code does not include underwater noise in its definition of vessel pollution, it calls upon mariners to take into account, when considering a route through polar waters, known areas with densities of marine mammals, including seasonal migration areas (Paragraphs 11.3.6, 11.3.7). While not sufficient to avoid impacts on other groups of noise-sensitive marine species, this provision could be a starting point by which to mandate stronger measures for underwater noise impact mitigation.

Additional voluntary or mandatory measures at the international or regional scale that could contribute significantly to managing impacts of underwater noise are underwater noise management plans (UNMP) and habitat-based noise budgets. UNMP generally include public and transparent commitments to reduce underwater noise and operational and maintenance guidance to achieve those reductions. For example, British Columbia Ferries on Canada's west coast has made a commitment in its UNMP to reduce underwater noise levels by 50 percent and developed a plan to achieve those targets. Having habitat-based noise budgets in place can also help define the operating environment for shipping, encourage innovation, and be specific enough to include unique features and account for sensitive and threatened species.

## 2. Conclusion

The Arctic is a region under rapid transformation as a result of climate change. The Arctic Ocean is home to many wildlife species that use sound to survive and, until recently, have been naïve to anthropogenic activities. This situation is changing as sea ice retreats and new industrial development opportunities become a reality. Healthy populations of marine mammals, fish and invertebrates are critical for ecosystem function, the livelihoods and cultures of Indigenous coastal communities and in some cases, commerce. Already experiencing stress brought on by climate change effects, marine species are highly threatened by the adverse effects of anthropogenic underwater noise introduced to their environment by multiple sources. The increase in Arctic shipping in the past decade and the predicted extension of the shipping season and expansion to new areas requires commitment by Arctic states to understand and manage underwater noise pollution. Their leadership to strengthen policy in the shipping sector through the IMO Polar Code and other instruments, together with protection of high-quality habitats for noise-sensitive wildlife within their waters are measures that can be taken immediately. The Arctic Ocean is one of the last on the planet to remain relatively unpolluted by underwater noise. While the rest of the world adopts noise reduction targets and shoulders the hefty economic costs of mitigation and rehabilitation, in the Arctic there is an opportunity for a proactive, more cost-effective approach to management of underwater noise pollution that will safeguard Arctic species, ecosystems and the people who depend on them.