



Quantifying the effect of ship noise on the acoustic environment of the Bering Strait

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ABSTRACT

The narrow Bering Strait provides the only gateway between the Pacific Ocean and the Arctic, bringing migrating marine mammals in close proximity to ships transiting the strait. We characterized ship activity in the Bering Strait during the open-water season (July–November) for 2013–2015 and quantified the impact of ship noise on third-octave sound levels (TOLs) for bands used by baleen whales (25–1000 Hz). Peak ship activity occurred in July–September with the greatest overlap in ship noise and whale vocalizations observed in October. Ships elevated sound levels by ~4 dB on average for all TOL bands combined, and 250-Hz TOLs exceeding 100 dB re 1 μ Pa were recorded from two large vessels over 11 km away from the hydrophones. Our results show that ship noise has the potential to impact baleen whales in the Bering Strait and serve as a baseline for measuring future changes in ship activity in the region.

1. Introduction

Declining sea ice is opening the Arctic to increased ship activity (Eguíluz et al., 2016), potentially impacting the acoustic habitat of Arctic and subarctic marine mammals (Moore et al., 2012; Halliday et al., 2017, 2021a; Hauser et al., 2018). Known impacts of ship noise on marine mammals include masking of important biological signals (Clark et al., 2009; Pine et al., 2018), elevating stress hormone levels (Rolland et al., 2012; Lemos et al., 2022), and provoking avoidance behavior (Finley et al., 1990; Nowacek et al., 2007; Southall et al., 2007; Martin et al., 2022). The two major Arctic shipping routes—the Northwest Passage through the Canadian Arctic Archipelago, and the Northern Sea Route along the northern coast of Eurasia—are expected to see a sharp increase in trans-Arctic ship transits by 2050 (Stephenson et al., 2011, 2013; Smith and Stephenson, 2013). Both sea routes pass through the Bering Strait, making it an important region for studying the effects of ship noise on the marine soundscape.

The Bering Strait connects the Bering Sea to the south with the Chukchi Sea to the north (Fig. 1). The region is shallow (30–60 m), and narrow, spanning only ~80 km at its narrowest point. The marine ecosystem of the Chukchi Sea is one of the richest in the world, home to

dense aggregations of benthic invertebrates and swarms of lipid-rich zooplankton that attract marine mammals to the region (Grebmeier et al., 2006; Eisner et al., 2013; Ershova et al., 2015). Marine mammals endemic to the Arctic and commonly observed in the Chukchi Sea include bowhead whales (*Balaena mysticetus*), belugas (*Delphinapterus leucas*), walrus (*Odobenus rosmarus*), bearded seals (*Erignathus barbatus*), and ringed seals (*Pusa hispida*), all of which are important subsistence species for the Chukchi, Inupiaq, St. Lawrence Island Yupik, Siberian Yupik, and Yup'ik Peoples of the coastal Pacific Arctic (Huntington et al., 2015).

The seasonal migrations of species through the Bering Strait region are driven by the melting of sea ice in spring (~ May), and the formation of sea ice in late fall and early winter (November–December; Frey et al., 2015; Serreze et al., 2016; Grebmeier et al., 2006, 2018). When the sea ice disappears in the summer, subarctic baleen whales, namely gray whales (*Eschrichtius robustus*), humpback whales (*Megaptera novaeangliae*), fin whales (*Balaenoptera physalus*), and minke whales (*B. acutorostrata*), migrate northward into the Chukchi Sea to feed on seasonally-abundant prey (Clarke et al., 2013; Woodgate et al., 2015; Brower et al., 2018; Escajeda et al., 2020). Marine mammals rely on sound as their primary sense (Richardson et al., 1995); consequently, the

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intrusion of ships into the Pacific Arctic presents a potential threat to the acoustic habitat of these animals.

Despite the potential for increased ship noise, little work has been done to quantify the impact of ships on sound levels in the Bering Strait region. Southall et al. (2020) examined sound levels produced by three vessels that passed within 10 km of two recorders, one in the Bering Strait and the other at a site north of St. Lawrence Island, and found that the ships produced sound levels below or higher than monthly average conditions depending on the proximity of the ship. A follow-up study by McKenna et al. (2021) examined the impact of ship noise on annual median sound levels measured for third-octave frequency bands at a site west of St. Lawrence Island in the northern Bering Sea. They found that radiated sounds measured from ships traveling at speeds >5 knots within 10 km of their hydrophone had negligible impact on year-round sound levels (< 1 dB difference between median sound levels with ships present and annual median sound levels for third-octave frequency bands between 100 and 1000 Hz). Instead, wind and sea ice were the most significant contributors to annual sound levels (except for the 1000-Hz third-octave band; McKenna et al., 2021). Most vessels are only able to transit the Pacific Arctic when its waters are ice-free (June–November), necessitating an examination of how ships affect ambient sound levels of the region specifically during the open-water season.

In this study, we characterized the acoustic effects of ship activity in the Bering Strait during the open-water season (June through November) for 2013–2015 using three moored hydrophones within the Bering Strait. Specifically, we quantified the contribution of ship noise above ambient sound levels, with a focus on frequency bands used by baleen whales (25–1000 Hz; Southall et al., 2007; Moore et al., 2012). Our results reveal how ship noise is affecting the acoustic environment of the Bering Strait, and serve as a baseline for measuring future changes in ship activity for the region.

2. Methods

2.1. Acoustic data collection

We collected acoustic recordings from AURAL-M2 hydrophones (Autonomous Underwater Recorder for Acoustic Listening-Model 2; Multi-Électronique, Inc.) attached to three moorings positioned within the Bering Strait. Site A2 was in the center of the eastern channel and Site A4 on the east side of the eastern channel. Site A3 was located ~35 km north of the strait in the southern Chukchi Sea (Fig. 1). The mooring sites were originally established in 1990 for measuring the physical properties of the oceanic throughflow through the strait (Woodgate et al., 2015; Woodgate, 2018). Hydrophone sensitivity was -155 dB re 1 V/ μ Pa with a gain of 16 dB and the recordings were made using a 16-bit resolution. Each hydrophone was positioned 4–8 m above the sea-floor and sampled at 8192 Hz, with a 20-min (2013 and 2014) or 22-min (2015) duty cycle, and varying deployment periods (Table 1). All recordings were timed to start at the top of the hour.

We focused our analyses on recordings from June through November of each year since the Bering Strait is typically ice-free during this period (Serreze et al., 2016; Grebmeier et al., 2018). We also noted the presence of ships in May and December; however, we did not analyze recordings for either month due to the abundance of vocalizing bearded seals and sea ice, which would make isolating ship sounds difficult. Note that acoustic data were unavailable for June 2013 at Sites A2 and A3, therefore we began our analysis in July for 2013. Recordings were visualized in the *Ishmael* software program (2014 version; Mellinger, 2002) using a fast Fourier transform (FFT) size of 4096 samples with a Hamming window and spectrogram equalization enabled (time constant of 30 s). Recordings with ship sounds, as well as biotic sounds (e.g., whale calls) and line strumming created by water rushing past the mooring were identified by manually analyzing spectrograms in *Ishmael*. We quantified the number of recordings that matched three scenarios: 1) recordings with only ship noise present, 2) recordings with ship noise together with baleen whale vocalizations, and 3) recordings with baleen whale vocalizations only.

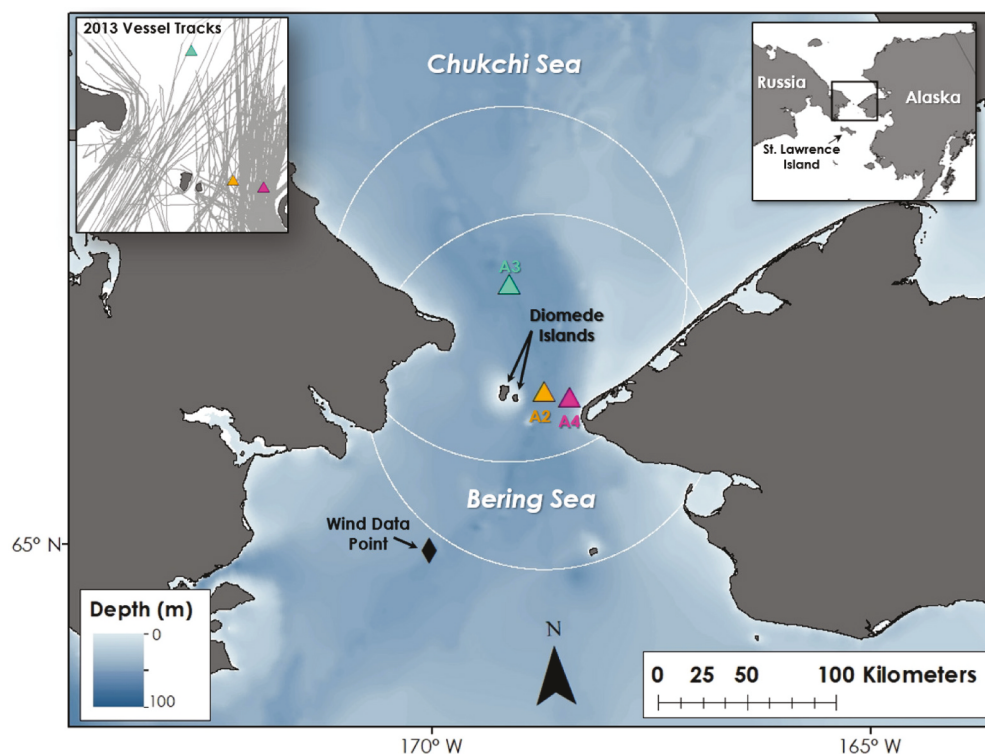


Fig. 1. Map of the study area with the three mooring locations: Sites A2 and A4 in the eastern channel of the strait, and Site A3 north of the strait. The nearest NCEP–NARR wind data point is located southwest of the strait (65°N , 170°W ; Mesinger et al., 2006). The two white circles represent 100-km buffers around Sites A2 and A3, respectively, and were used for identifying ships within the Bering Strait region. Depth data were taken from the International Bathymetric Chart of the Arctic Ocean version 3.0 (500-m resolution; Jakobsson et al., 2012). The top left inset shows the tracklines for all AIS-transmitting vessels that transited the Bering Strait between June–November 2013.

Table 1

Hydrophone deployment data, including latitude and longitude (in decimal degrees), and recording settings. Dates are in the format 'yyyy-mm-dd.' Mooring names are from the Bering Strait mooring program (Woodgate et al., 2015). See Fig. 1 for the mooring locations.

Mooring	Deployment Year	Latitude N	LatitudeW	Record Start Date	Record End Date	Hydrophone Depth (m)	Water Depth (m)	Sampling Rate (Hz)	Hourly Duty Cycle
A2	2013	65.78°	168.57°	2013-07-15	2014-07-01	48	54	8192	20 min
	2014	65.78°	168.57°	2014-07-10	2015-07-04	49	53	8192	20 min
	2015	65.78°	168.57°	2015-07-05	2016-07-08	49	54	8192	22 min
A3	2013	66.33°	168.97°	2013-07-15	2014-07-02	52	56	8192	20 min
	2014	66.33°	168.97°	2014-07-10	2015-07-02	50	56	8192	20 min
	2015	66.33°	168.97°	2015-07-05	2016-07-08	48	56	8192	22 min
A4	2013	65.75°	168.26°	2013-07-15	2014-07-02	42	47	8192	20 min
	2014	65.75°	168.25°	2014-07-10	2015-07-02	42	47	8192	20 min
	2015	65.75°	168.25°	2015-07-05	2016-07-08	41	47	8192	22 min

Marine mammals are sensitive to changes in frequency among third octaves, therefore summarizing sound amplitude using third-octave bands is useful for approximating sound levels for a range of frequencies (Richardson et al., 1995). Third-octave bands have a lower frequency limit, an upper frequency limit that is equivalent to $2^{1/3}$ of the lower frequency, and a central frequency roughly equivalent to the square-root of the product of the lower and upper frequencies. Third-octave bands are referred to by their central frequencies; for example, the 250-Hz third-octave band has a central frequency of 250 Hz and covers the frequency band from 223 to 281 Hz. We calculated the root-mean-square (RMS) sound pressure levels integrated over the 17 standard third-octave frequency bands between 25 and 1000 Hz for each recording using *PAMGuide* software in *MATLAB* (FFT with a 1-s long Hann window and 50% overlap; Merchant et al., 2015). We hereafter refer to third-octave sound levels as TOLs.

2.2. Effects of wind and water speed on sound levels

We examined the impact of wind and water speed on TOLs commonly used to quantify radiated sound from ships, specifically TOLs with center frequencies of 63 Hz, 125 Hz, and 250 Hz (Van der Graaf et al., 2012; Dekeling et al., 2014; Merchant et al., 2014), to understand how wind and water speed may affect sounds recorded by our hydrophones. Wind is an important contributor to ambient sound levels during the open-water season (Wenz, 1962; Hildebrand, 2009; Roth et al., 2012; Insley et al., 2017; Stafford et al., 2018; Halliday et al., 2021b; McKenna et al., 2021), and thus, should be taken into consideration when quantifying the impact of ship noise. The Bering Strait has high water speeds, with hourly mean northward water speeds occasionally exceeding 130 cm/s (Woodgate, 2018), which can lead to flow noise and/or mooring line strumming (McKenna et al., 2021). Consequently, it was also important to consider how water speeds contribute to sound levels recorded by the hydrophones in the three third-octave frequency bands. Both flow noise and line strumming result from water flowing past the mooring, and therefore are not considered features of the broader acoustic environment (Robinson et al., 2014).

We analyzed ambient sound recordings—recordings without ship noise, line strumming, or biotic sounds—to isolate the effect of wind and water speeds on third-octave sound levels recorded by the hydrophones. We computed TOLs for the three third-octave bands (63 Hz, 125 Hz, and 250 Hz) over 1-s time windows and then time-averaged the sound levels over the full duration of the recording (~ 20 min in 2013 and 2014: 1199 s; ~ 22 min in 2015: 1399 s). We assumed that sound levels recorded when the hydrophones were on (i.e., during the first 20–22 min

of the hour) were representative of the entire hour. We then calculated the daily median for each TOL band. Surface wind speed and direction were taken from the National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis 2 (NARR) wind data product (grid size of ~32 km; Mesinger et al., 2006) calculated for the closest grid point to the strait, ~110 km southwest of the moorings (65°N, 170°W; Fig. 1). We calculated daily mean water speeds using hourly water velocity data measured at 30-m depth by Acoustic Doppler Current Profilers (ADCP) attached to each mooring (Woodgate, 2018).

Given that the daily median TOLs for a given day could be correlated to the daily median TOLs from the previous day, we used generalized least squares (GLS) regression to examine the influence of daily mean wind and water speeds on daily median TOLs for the three bands. GLS regression accounts for correlation between the model residuals, making the method a good choice when temporal correlation in the response variable is a concern (Aitken, 1936). We built individual models for each third-octave band using data from each mooring site with all three years combined (e.g., we created a separate model for the 63 Hz TOLs recorded at Site A2 in 2013–2015, etc.) using the *nlme* package in *R* (v. 4.1.0; R Core Team, 2021; Pinheiro et al., 2022). We included a first-order autoregressive correlation structure in each model using a continuous time variable (day number) and the Pearson correlation coefficient taken from correlation tests between daily median TOLs as inputs (Table 2). We defined a day as a 24-h period starting at 00:00 UTC and assumed that daily means for wind and water speeds were independent. We used a significance threshold of 0.05 for all statistical tests.

2.3. Characterizing ship activity

We used Automatic Identification System (AIS) vessel tracking data to characterize the presence of ships throughout the open-water season

Table 2

Correlation coefficients and *p*-values from Pearson correlation tests between daily median third-octave sound levels measured for the 63-Hz, 125-Hz, and 250-Hz bands. The correlation coefficients were used in the autoregressive correlation factors for the generalized least squares regression models (See Section 2.2).

	A2			A4		
	63 Hz	125 Hz	250 Hz	63 Hz	125 Hz	250 Hz
Correlation Coefficient	0.51	0.5	0.54	0.53	0.53	0.5
<i>p</i> -value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

(June–November) in the Bering Strait region, which we defined as within 100 km of the A2 and A3 moorings (see Fig. 1 for boundaries). Note that the 100-km buffer around A4 covered the same region as the 100-km buffer around A2, therefore we used the merged buffer for A2 and A3 to filter the AIS data. AIS data were obtained from the Nationwide Automatic Identification System (NAIS) dataset managed by the United States Coast Guard (<https://marinecadastre.gov/ais/>). The NAIS dataset is collected by land-based receivers every minute and includes vessel name (2015 only), status (2015 only), length, width, draft, a unique Maritime Mobile Service Identity (MMSI) number, vessel type, latitude and longitude, speed over ground (in knots), course over ground, and heading. The vessel types identified in the NAIS dataset are based on the U.S. Coast Guard's Authoritative Vessel Identification Service (AVIS) database (<https://marinecadastre.gov/ais/>; Lee et al., 2019). The International Maritime Organization (IMO) only requires large vessels (> 300 gross tonnage), passenger vessels (vessels ≥ 100 gross tons and carrying a minimum of 12 passengers; U.S Code of Federal Regulations, Title 46), and large fishing vessels to carry AIS transponders (IMO International Convention for the Safety of Life at Sea, 1974). Consequently, AIS is not a reliable tool for tracking the presence of small vessels (Hermannsen et al., 2019).

We filtered the AIS data to include only transmissions from vessels observed within a 100-km buffer around moorings A2 and A3. We identified unique vessels using their MMSI number and removed any transmissions that were missing a MMSI number from the dataset as we could not verify the source of these data (whether the transmissions were from unique ships). We then summed the number of unique ships by vessel type (provided by the AIS data) and by year. Finally, we calculated the average speed for each vessel using the reported speed over ground (SOG). See Fig. 2 for a flowchart of our approach for filtering the AIS data.

2.4. Comparison between vessel noise and ambient sound levels

Recordings with identified ship noise were paired with AIS transmissions from a single moving vessel (reported SOG > 5 knots) that passed within 10 km of the recorder ($n = 156$ recordings), following McKenna et al. (2021). Any ship recordings that did not match with AIS data or that had other sound sources present (e.g., whale calls) were excluded from the analysis. We refer to a ship recording that matched with the closest pass of a single unique vessel by the mooring as a “ship event” (unique vessels were identified using their MMSI number). AIS

transmissions for each ship event were visualized in ArcMap (v. 10.8; Environmental Systems Research Institute, ESRI, 2020) to ensure that the vessel was in a reasonable position relative to the mooring (i.e., not behind a landmass), and that the vessel was moving during the recording window.

We quantified ambient and ship noise levels as the TOLs for third-octave bands with standard center frequencies between 25 and 1000 Hz averaged over the full duration of the recording. Both wind speeds and water flowing past the mooring are known to affect received sound levels (McDonald et al., 2006; Insley et al., 2017; Halliday et al., 2021b; McKenna et al., 2021), therefore we separated the ship and ambient recordings into categories based on the mean wind speed from the NCEP-NARR dataset for the day of the recording and the hourly mean water speed from the ADCP instrument on the mooring (see Fig. 3 for a flowchart of our procedure). Recordings on days with mean wind speeds <10 knots (~ 5 m/s) were labeled as “Low Wind” recordings since the effect of wind speed on ambient sound levels was found to decrease when winds were below this level (McDonald et al., 2006). Recordings with water speeds <40 cm/s were labeled as “Low Water” since strumming noise was reduced below this level. We then compared median ambient third-octave SPLs to the median third-octave SPLs for the ship recordings for all sites and years combined by wind-water speed category: “Low Water/Low Wind,” “Low Water/High Wind,” “High Water/Low Wind,” “High Water/High Wind” (Fig. 3).

2.5. Ship received levels vs. range

We investigated the spatial impact of ship noise on the Bering Strait using received levels (RLs) for ship events where one vessel was present. Using the dataset of ship events from the ship noise vs. ambient analysis (see Section 2.4), we examined the AIS transmissions for each vessel and eliminated any ship events with fewer than three AIS transmissions during the 20/22-min recording window. We then eliminated duplicate ship events where the same vessel was detected at two mooring sites by selecting the recording from the closest hydrophone to the ship's track. In the case of repeat recordings of the same ship by the same hydrophone, we kept the recording from the closest pass of the vessel (total $n = 73$ ship events; Fig. 2).

We quantified the RLs for each ship event as the root-mean-square pressure for the 250-Hz TOL band time-averaged over 60-s intervals to match the same time resolution as the AIS transmissions. The 250-Hz band was chosen since it is less likely to be contaminated with flow

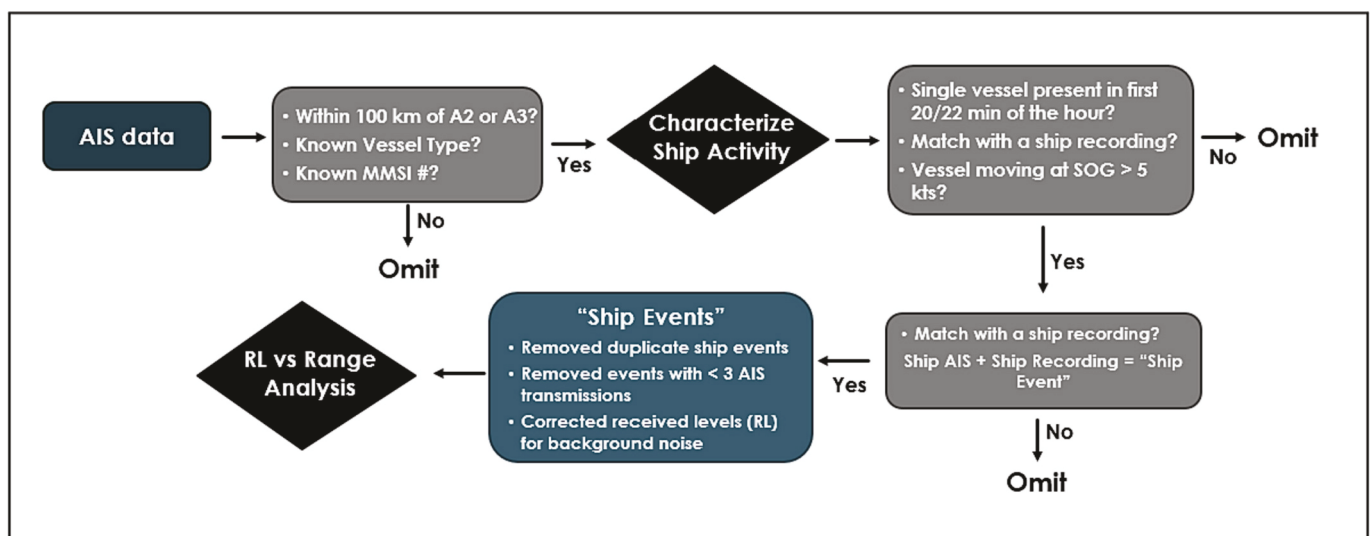


Fig. 2. Summary of our approach for selecting the ship transmissions from the AIS data for characterizing ship activity in the Bering Strait and for the received level (RL) vs. range to receiver analysis. SOG = speed over ground in knots; MMSI = Maritime Mobile Service Identity number.

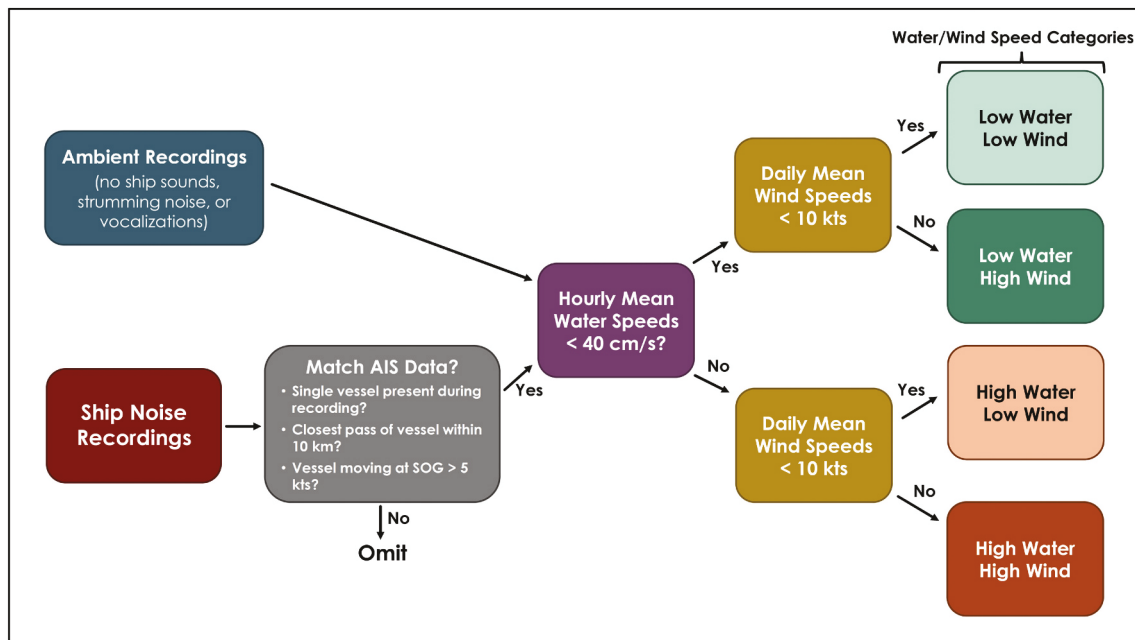


Fig. 3. Summary of our approach to dividing the ambient and ship acoustic files into wind and water speed categories for the ship vs. ambient sound level analysis.

noise than lower frequency TOL bands (Merchant et al., 2014). We then calculated the slant range between the recorder and each point from the ship's AIS transmissions using the hydrophone depth and straight-line distance between the ship and the recorder. Given that background noise levels could have contributed to the RLs, we corrected for background noise using the following equation (ANSI, 2009):

$$L_S = 10 \log_{10} \left[10^{\left(\frac{L_T}{10} \right)} - 10^{\left(\frac{L_B}{10} \right)} \right]$$

where L_S is the RL attributed to the ship (in dB), L_T is the total sound level in dB which consists of the ship and background noise, and L_B is background noise. Background TOLs were calculated from recordings that did not have any detectable sound sources present and that were recorded on the same day as the corresponding ship event (or as close to the day as possible).

We examined plots of background noise-corrected RLs for the 250-Hz band as a function of slant range for all the ship events. We then partitioned the ships by vessel type and examined the ship event with the maximum TOLs for the 250-Hz band for each vessel type.

3. Results

We analyzed 41,866 recordings combined across the three sites and years. There were 2992 recordings with ship noise in total, with 1031 recordings at Site A2, 1000 recordings at Site A3, and 961 recordings at Site A4. Out of the recordings with ship noise, 4% (A2), 17% (A3), and 3% (A4) also had baleen whale vocalizations present (Table 3). October had the highest number of recordings with both whale vocalizations and

Table 3

Total numbers of recordings with ship noise, baleen whale vocalizations, or a combination of both for each mooring. Note that there were ship recordings with other marine mammal species present, we focus on whales only here.

	A2	A3	A4
Total number of recordings with ship noise	1031	1000	961
Number of recordings with ship noise ONLY	936	757	911
Number of recordings with ship noise AND whale calls	39	165	33
Number of recordings with whale calls ONLY	1672	5444	1306

ship noise detected (44% of recordings from October had both ship noise and whale sounds present), followed by September (20%) and August (13%). In total, there were 93 days with ship noise present in 2013, 103 days in 2014, and 131 days in 2015. Most of the ships detected at Site A3 were also detected at Sites A2 and A4, and the AIS transmissions were closer to A2 and A4. Consequently, we focused our analyses only on Sites A2 and A4 (see Fig. 1 for map of mooring sites).

3.1. Effects of wind and water speed on sound levels

All models indicated that both wind and water speeds influence sound levels for all three TOL bands (63 Hz, 125 Hz, and 250 Hz) at Sites A2 and A4 (Table 4). The relationship between sound levels for the three third-octave bands, and wind and water speeds were all significant (all $p < 0.05$) and positive (Table 4), indicating that daily median sound levels in the three TOL bands increased with increasing daily mean wind and water speeds at Sites A2 and A4 (Table 4). The water speed coefficients were higher for 63-Hz TOL band at both sites (A2: increase of 0.56 dB per cm/s increase in water speed, A4: increase of 0.44 dB per cm/s) and the coefficients were barely higher than zero for the 250-Hz TOL band (A2: 0.02 dB per cm/s, A4: 0.04 dB per cm/s), indicating very little change in sound levels measured at this band in response to changes in wind and water speed. Conversely, the highest coefficients for wind speed were at the 250-Hz band (A2: increase of 0.86 dB per m/s increase in wind speed, A4: increase of 0.86 dB per m/s) and lowest at the 63-Hz band (A2: 0.47 dB per m/s, A4: 0.48 dB per m/s), suggesting that wind speeds have a greater effect on the 250-Hz TOL band while water speeds have a greater effect on the 63-Hz and 125-Hz TOL bands.

3.2. Ship activity in the Bering Strait

A total of 412 unique AIS-transmitting vessels entered the Bering Strait region from May to November 2013–2015. The highest number of unique vessel passages occurred in 2013 with 153 vessels, compared to 123 vessels in 2014, and 136 vessels in 2015 (Table 5). Peak ship activity occurred in the months of July through September (Fig. 4), with the earliest AIS transmissions occurring in early May and the latest in mid-December. We did not analyze ship recordings from May or December due to the increased acoustic presence of marine mammals and sea ice. Two cargo ships and a military vessel traveled north of Site A3 on 4–6

Table 4

Coefficients (“Coef.”) and *p*-values from the generalized least squares (GLS) regression models examining the relationship between daily mean wind (m/s) and water speeds (cm/s), and daily median sound levels recorded for the 63-Hz, 125-Hz, and 250-Hz third-octave bands at Sites A2 and A4 (2013–2015 combined). All *p*-values were significant (significance threshold = 0.05).

	A2						A4					
	63 Hz		125 Hz		250 Hz		63 Hz		125 Hz		250 Hz	
	Coef.	<i>p</i>	Coef.	<i>p</i>	Coef.	<i>p</i>	Coef.	<i>p</i>	Coef.	<i>p</i>	Coef.	<i>p</i>
Intercept	66.2	<0.001	68.1	<0.001	76.2	<0.001	68.8	<0.001	69.3	<0.001	75.1	<0.001
Water Speed	0.56	<0.001	0.29	<0.001	0.02	0.02	0.44	<0.001	0.25	<0.001	0.04	<0.001
Wind Speed	0.47	<0.001	0.73	<0.001	0.86	<0.001	0.48	<0.001	0.71	<0.001	0.86	<0.001

Table 5

Total counts of vessels by type observed in the Bering Strait region (i.e., within 100-km of Sites A2 and A3) during May–November for the years 2013–2015 according to the U.S. Coast Guard’s Nationwide Automatic Identification System (NAIS) data. The vessel types were defined by the NAIS dataset and are based on the U.S. Coast Guard’s Authoritative Vessel Identification Service (AVIS) database. Note that only large vessels (> 300 gross tonnage), passenger vessels (≥ 100 gross tons and carrying a minimum of 12 passengers), and large fishing vessels are required to carry AIS transponders by the International Maritime Organization (IMO). Sailing and smaller vessels are not required to carry AIS transponders, and consequently, their numbers may be underrepresented in the totals presented here.

Vessel type	2013	2014	2015	Totals
Cargo	51	43	45	139
Tug	27	23	35	85
Other	23	22	1	46
Tanker	21	11	10	42
NA	14	12	8	34
Passenger	7	5	6	18
Research Vessel	0	0	9	9
Offshore Supply Vessel	0	0	9	9
Fishing	4	1	2	7
Public Vessel	0	0	7	7
Pleasure Craft/Sailing	2	2	2	6
Military	3	1	0	4
Search and Rescue	1	2	0	3
Offshore Drilling Unit	0	0	2	2
Law Enforcement	0	1	0	1
Totals	153	123	136	412

May 2015, and the latest passage in the open-water season was made by a Russian icebreaker which transited northward through the western channel on 17 December 2015. A summary of the vessel types observed in the Bering Strait region can be found in Table 5. Cargo ships were the most common vessel type (139 unique vessels, 34%), followed by tug-boats ($n = 85$ vessels, 21%), and vessels labeled as “other” in the NAIS dataset ($n = 46$ vessels, 11%). A total of 33 vessels had an unknown vessel type (i.e., vessel type was not listed in the NAIS dataset). Average speed over ground (SOG) for all vessel types ranged from 5 knots (tug-boat) to 13.1 knots (law enforcement vessel), with an average of 9.1 knots (SD: ± 2.1 knots; Table 6).

3.3. Comparison between vessel noise and ambient sound levels

Median sound levels when a ship was present were higher than ambient sound levels for the majority of the third-octave frequency bands, regardless of water and wind speeds (mean difference for all wind/water speed categories and TOL frequency bands combined = ~ 4 dB ± 3 dB SD; range: -3 to 15 dB; Fig. 5). Ambient and ship median sound levels recorded on days with low water and low wind speeds had the greatest differences with ships elevating sound levels by 2–15 dB above ambient with an average difference of ~ 7 dB (Fig. 5A). The smallest differences between ship and ambient median TOLs were observed in recordings with high wind speeds (high wind and low/high water speed) with an average difference of 3 dB ± 2 dB SD (range: -3 to 5 dB; Fig. 5). The highest median received levels were observed in the recordings with high water speeds (Fig. 5B), reflecting the influence of flow noise on sound levels recorded by the hydrophones (Section 3.1; Table 4).

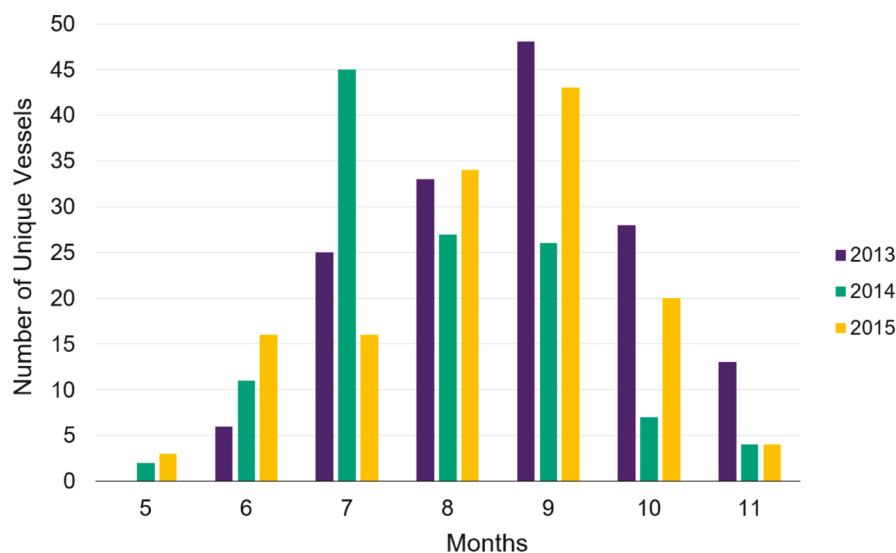


Fig. 4. Total counts of unique vessels that transited within 100 km of the Bering Strait region ($n = 412$ vessels), defined as merged 100-km buffers around Sites A2 and A3 (see Fig. 1). Note that the totals are likely underestimates since not all vessels are required to carry AIS transponders.

Table 6

Number of unique vessels by type (total $n = 378$) along with the average speed over ground (SOG, knots) and the standard deviation in parentheses. The average SOG was calculated using all unique vessels combined for each vessel type. Note that there were 34 ships with unknown vessel type that were not included in the table below.

Vessel type	<i>n</i>	Mean SOG (knots)
Cargo	139	11.2 (± 2.5)
Tug	85	7.4 (± 2.2)
Other	46	9.2 (± 2.9)
Tanker	42	11.4 (± 2.6)
Passenger	18	8.7 (± 2.6)
Research Vessel	9	9.1 (± 2)
Offshore Supply Vessel	9	7 (± 2.4)
Fishing	7	8.3 (± 2.1)
Public Vessel	7	11 (± 5.2)
Pleasure Craft/Sailing	6	9.2 (± 3.4)
Military	4	8 (± 3.6)
Search and Rescue	3	8.8 (± 1.4)
Offshore Drilling Unit	2	5 (± 0.3)
Law Enforcement	1	13.1

3.4. Ship received levels vs. range

Received levels (RL) measured at the 250-Hz TOL band for the select ship events ($n = 73$) show a general declining trend with higher RLs closer to the recorder, and lower RLs as the ships move away from the recorder (Fig. 6). The loudest vessel was a 102-m long ship in the “other” category. The ship was traveling at an average of 13 knots during the recording and produced RLs > 110 dB re 1 μ Pa at ~ 4.5 km from the recorder, and RLs > 100 dB re 1 μ Pa over 11 km away from the recorder (Fig. 6). The second loudest ship, a 122-m long military vessel, produced RLs > 100 dB re 1 μ Pa from ~ 5.5 km to ~ 11 km away from the recorder. Other loud vessels included three “other” ships of various lengths (Fig. 6), a cargo ship (225 m), a tugboat (32 m), and an offshore supply vessel (82 m). Speed over ground (SOG) ranged from 6 knots (“other” ship) to 14 knots (cargo ship).

4. Discussion

Our goal was to quantify how ship noise affects the soundscape of the Bering Strait during the open-water season. We found that ships elevated ambient sound levels by ~ 7 dB on average for calm days with low water/low wind speeds (range: 2 to 15 dB; Fig. 5A). On days with high water and high wind speeds, the mean increase over background levels was smaller (mean: 2 dB, range: -3 to 5 dB), however recordings with ship noise still had higher median TOLs (Fig. 5B). We also observed an increase in the number of days with ship noise over our study period, which could be a reflection of increasing ship activity in the Bering Strait. Wind and water speeds were found to affect sound levels in third-octave bands commonly used to quantify ship noise with increases of 0.02–0.73 dB per unit change in wind/water speeds, emphasizing the importance of correcting for background noise and choosing a band that is less influenced by water speed when flow noise is a concern.

McKenna et al. (2021) conducted a similar study using a single hydrophone west of St. Lawrence Island and found that median third-octave sound levels (100–1000 Hz) produced by ships traveling at speeds > 5 knots within 10 km of their recorder were < 1 dB higher than annual median ambient sound levels. Given that ships are only able to transit the strait during the open-water season, we felt it was necessary to examine how ship noise affected median sound levels during this specific period. We observed sound levels 2–12 dB (mean: ~ 6 dB) above ambient for third-octave frequency bands between 100 and 1000 Hz on days with low wind and low water speeds during the open-water season in the Bering Strait (Fig. 5A). Note that the values given here are slightly different from the mean and range stated in the previous paragraph as the frequency range is different. While they may contribute a negligible

amount of sound in comparison to annual median sound levels, ships are a major contributor of anthropogenic noise during the open-water season.

Our analysis of ship received levels as a function of range represents a preliminary approximation of the spatial impact of ship noise in the Bering Strait. The two loudest ships, a 102-m long “other” ship and a 122-m long military vessel, produced received levels that exceeded 100 dB re 1 μ Pa out to 11.1 km and ~ 10.9 km away from the recorder, respectively (Fig. 6). These distances indicate that ships could affect marine mammals well beyond the immediate vicinity of the traveling ships. Previous studies have demonstrated the long-range impacts of ship noise on marine mammals in the Arctic. For example, Martin et al. (2022) observed that tagged belugas increased their swimming speeds and their lateral and vertical movements when ships were within 13–43 km. Other flee behaviors such as diving and swimming close to sea ice were observed by Finley et al. (1990) when ships were > 10 km away, suggesting that belugas are likely disturbed by ship noise rather than the ships themselves. We quantified the impact of ship noise with only one vessel present within 10 km of the recorders. Noise from multiple ships would certainly exacerbate any negative effects and should be the focus of a future study.

Most of the ships detected in the Bering Strait during our study period were cargo ships and tugboats, reflecting an increasing trend in commercial shipping in the Arctic. The Bering Strait has served as a corridor for large vessels transiting to the Arctic from the Pacific since the late 1800s when commercial whaling vessels first sailed its waters (Bockstoe, 1986). In the 20th century, the majority of vessels in this region were small cargo ships, tugboats, tankers, and barges en route to support coastal Arctic communities in the Chukchi and Beaufort seas (AMSA, 2009). With increased industrial activity and resource extraction in the western Arctic, the number of cargo ships and tankers observed in the region increased between 2008 and 2013 (AMSA, 2009; Huntington et al., 2015). Along with cargo transport, ship-based tourism in the Arctic is expected to increase in the 21st century (AMSA, 2009). Only 6% of the vessels observed in the Bering Strait region from 2013 to 2015 were identified as passenger vessels or pleasure crafts in the NAIS dataset (Table 5), however we anticipate that these numbers will grow in the future. It is also important to note that pleasure crafts and smaller passenger vessels (< 100 gross tons) are not required to carry AIS transponders by the IMO, and consequently, are underrepresented by the AIS data.

Most of the ship transits through the strait occurred in the summer and early fall months (July–September; Fig. 6), similar to Eguíluz et al. (2016) and Halliday et al. (2021a) who noted the highest numbers of Arctic transits in July–October. The peak in ship activity overlaps with the migrations of subarctic baleen whales through the strait (Clarke et al., 2013; Woodgate et al., 2015; Escajeda et al., 2020), increasing the probability of interactions between ships and whales. We observed the greatest overlap in ship noise and whale vocalizations in October, followed by September and August. Therefore, ships transiting through the Bering Strait during the month of October should be aware of migrating whales in the region and slow down when whales are observed.

Another key finding was how much both wind and water speeds affect sound levels in the third-octave bands used for quantifying ship noise. The European Union (E.U.) currently recommends using the 63-Hz and 125-Hz third-octave band for measuring ship noise (Van der Graaf et al., 2012; Dekeling et al., 2014). However, both bands exhibited significant, positive relationships to wind and water speed (Table 4), suggesting that sound levels for the 63-Hz and 125-Hz bands recorded by the hydrophone on days with strong currents may be artificially high (change of 0.25–0.56 dB per cm/s increase in water speed). Additionally, we found that median ambient sound levels for the 63-Hz band exceeded 100 dB re 1 μ Pa, the threshold for ambient noise set by the E.U. (Tasker et al., 2010), on days with high wind and water speeds (Fig. 5B). This result indicates that sound levels in the 63-Hz band may be higher on days with high wind and water speeds, regardless of ship activity. The

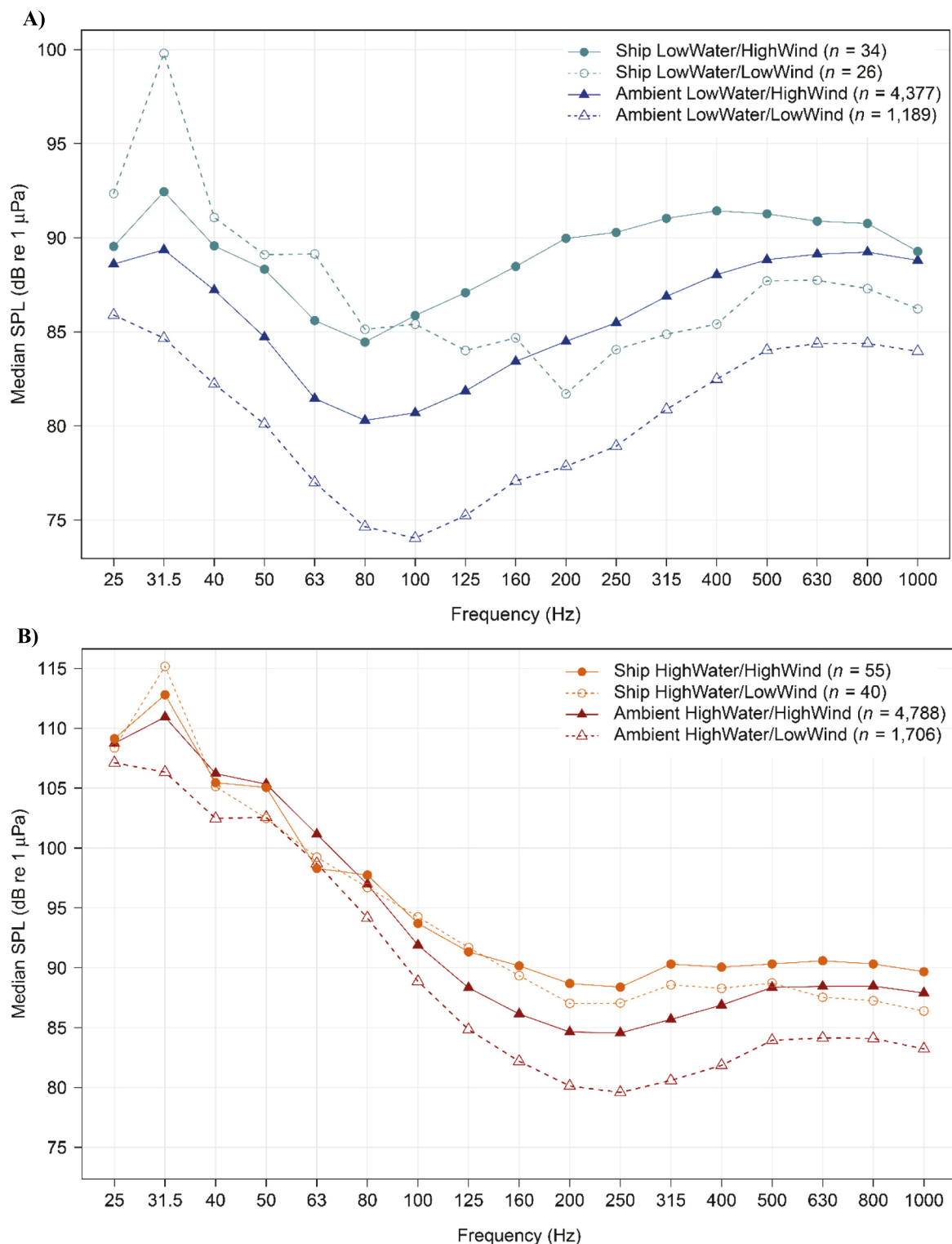


Fig. 5. (Color online) Median sound pressure levels (SPL) measured across third-octave frequency bands (Hz) for recordings with ship noise (circles) plotted against ambient SPLs (triangles) for (A) days with low water speeds (≤ 40 cm/s), and (B) days with high water speeds (> 40 cm/s) visualized by whether the recording occurred on a day with high wind speeds (> 10 knots; solid lines and points), or low wind speeds (≤ 10 knots; dotted lines and hollow points). Total sample sizes for the ship recordings are as follows: low water/high wind = 34 recordings; low water/low wind = 26 recordings; high water/high wind = 55 recordings; and high water/low wind = 40 recordings. Ambient sample sizes are as follows: low water/high wind = 4377 recordings; low water/low wind = 1189 recordings; high water/high wind = 4788 recordings; and high water/low wind = 1706 recordings. Note that the x-axis is log-scaled.

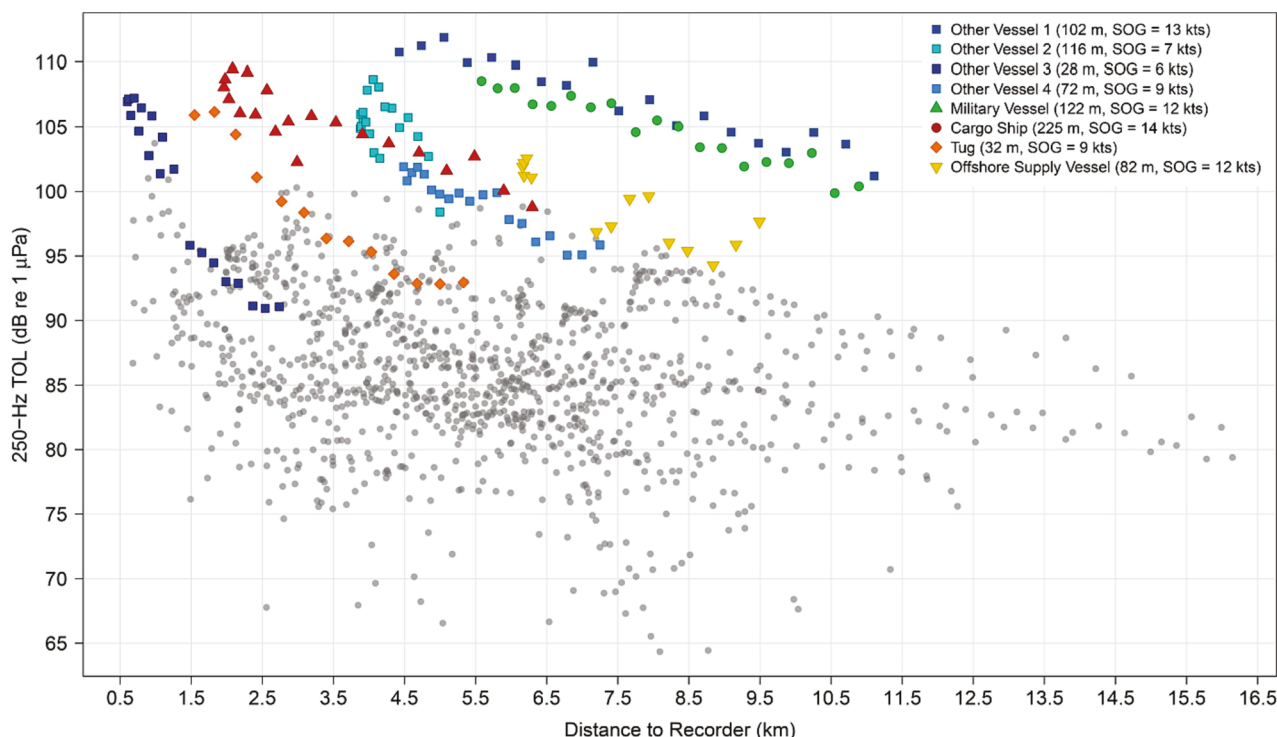


Fig. 6. (Color online) Received levels (RL) for the 250-Hz third-octave frequency band (TOL) vs. slant range to the recorder (km) for the loudest vessels from the select dataset of unique ship events ($n = 8$; color points) plotted against the RLs for all select ship events (total $n = 73$; gray points). A ‘ship event’ is a ship recording matched with the AIS tracks of a single vessel that was traveling at speeds >5 knots and passed within 10 km of the mooring (see Section 2.5). Vessel type is listed for each of the loudest vessels along with the ship’s length and mean speed over ground (SOG) in knots (kts). Each point represents the RL measured over each minute of the ship event recording and corresponds to an AIS transmission.

difference for the 250-Hz band, on the other hand, was negligible (change of 0.02–0.04 dB per cm/s increase in water speed), suggesting that the 250-Hz band may be a better choice for quantifying ship noise when flow noise is a concern.

As the presence of ships continues to increase in the Bering Strait region, ship noise will become a greater threat for marine species that rely on sound for critical life functions (Erbe and Farmer, 2000; Halliday et al., 2017, 2020). Even relatively small changes in background sound levels could impact communication among Arctic and subarctic baleen whales given their documented sensitivity to changes in the soundscape. In Glacier Bay National Park, Alaska, humpback whales raised the source levels of their vocalizations by 0.81 dB and were 9% less likely to call for every 1 dB increase in ambient sound levels (Fournet et al., 2018). Gray whales similarly increased the source level of their calls along with their vocalization rate when exposed to increased vessel noise in their breeding grounds (Dahlheim and Castellote, 2016). As for fin whales, the features of their 20-Hz song notes, including note duration and peak frequency, changed when exposed to increased background noise (Castellote et al., 2012). Our findings that ship noise elevated sound levels as much as 15 dB in the frequency bands used by baleen whales indicates that increased noise levels due to ships could interrupt baleen whale communication during the open-water season in the Bering Strait.

Recommendations for mitigating the negative impacts of ships include limiting the travel of commercial ships to a specific route through the strait as well as encouraging vessel speed limits (Halliday et al., 2017, 2020). In late 2018, the IMO approved a joint proposal from the U.S. Coast Guard and the Russian Federation for a two-way route for large ships in the western and eastern channels of the Bering Strait (Fletcher et al., 2020). The routing measures also include multiple ‘Areas to be Avoided,’ including the coastal region surrounding St. Lawrence Island, south of the Bering Strait. The routes are voluntary for vessels of 400 gross-tons and above, however a 2019 study by the Nuka

Research and Planning Group found that compliance was high among large commercial vessels, including bulk carriers, tankers, and cargo ships (Fletcher et al., 2020).

Shipping routes through the Bering Strait region are a good first step to managing vessel traffic in this sensitive area, however they do not address the issue of ship noise. Previous studies suggest that the reducing the speed of ships could reduce noise levels (MacGillivray et al., 2019; ZoBell et al., 2021). We found that large vessels transiting the Bering Strait are already traveling at speeds around or below the 13-knot speed limit currently enforced in Glacier Bay National Park (ships in this study had a mean speed through water = $9.1 \text{ knots} \pm 2.1 \text{ knots SD}$; Code of Federal Regulations [CFR] 36 CFR 13.65, 2001; Frankel and Gabriele, 2017). Installing a voluntary speed limit through the strait is therefore likely to have high compliance among ship operators since ships are already transiting at relatively slow speeds and are already largely compliant with current Bering Strait routing measures (Fletcher et al., 2020). Additionally, decreasing the speed of vessels traveling the strait would have the added benefits of reducing the risk and lethality of vessel strikes for whales (Vanderlaan and Taggart, 2007) and lowering carbon emissions (Leaper, 2019). Moreover, voluntary speed limits are already in place in other regions of the Arctic. The Inuvialuit Settlement Region in the western Canadian Arctic established a voluntary speed limit of 10 knots with the goal of reducing the risk of vessel strikes and underwater noise (Fisheries and Oceans Canada, 2022). Therefore, a similar speed limit could be pursued for the Bering Strait region.

Coordinated efforts among multiple governments and agencies are required to reduce the potential harm to marine organisms from the expansion of economic activity in the Arctic. It is also important to realize that noise pollution is just one impact of increased shipping in the Arctic. Ship strikes, oil spills (leaks or major accidents), introduction of invasive species, and disruption of marine mammal behavior such as feeding and migration (AMSA, 2009) will negatively affect sensitive species that are already being pushed to their limits by changing habitat

conditions brought on by climate change (Laidre et al., 2008; Hauser et al., 2018; Halliday et al., 2020). The results presented here can serve as a baseline for measuring future impacts of shipping on the acoustic environment of the Bering Strait. More research is needed, however, to understand, anticipate, and mitigate the impacts of ships on the marine environment of the Pacific Arctic.

CRedit authorship contribution statement

Erica D. Escajeda: Conceptualization, Methodology, Software, Formal analysis, Investigation, Visualization, Data Curation, Writing - Original draft preparation, Writing - Editing. **Kate M. Stafford:** Validation, Supervision, Resources, Data Curation, Project administration, Funding acquisition, Writing - Review & Editing. **Rebecca A. Woodgate:** Data Curation, Validation, Resources, Project administration, Funding acquisition, Writing - Review & Editing. **Kristin L. Laidre:** Supervision, Resources, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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