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William D. Halliday
Wildlife Conservation Society Canada

David Barclay
Dalhousie University

Amanda N. Barkley
University of Windsor

Emmanuelle Cook
Dalhousie University

Jackie Dawson
University of Ottawa

See next page for additional authors

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Authors

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Underwater sound levels in the Canadian Arctic, 2014–2019

William D. Halliday [a,b,c,*], David Barclay [d], Amanda N. Barkley [e], Emmanuelle Cook [d], Jackie Dawson [f], R. Casey Hilliard [g], Nigel E. Hussey [e], Joshua M. Jones [h], Francis Juanes [c], Marianne Marcoux [i], Andrea Niemi [i], Shannon Nudds [j], Matthew K. Pine [a,c], Clark Richards [j], Kevin Scharffenberg [i], Kristin Westdal [k], Stephen J. Insley [a,c]

[a] Wildlife Conservation Society Canada, Whitehorse, Yukon, Canada
[b] School of Earth and Ocean Sciences, University of Victoria, Victoria, British Columbia, Canada
[c] Department of Biology, University of Victoria, Victoria, British Columbia, Canada
[d] Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada
[e] Department of Integrative Biology, University of Windsor, Windsor, Ontario, Canada
[f] Department of Geography, Environment and Geomatics, University of Ottawa, Ottawa, Ontario, Canada
[g] Institute for Big Data Analytics, Dalhousie University, Halifax, Nova Scotia, Canada
[h] Scripps Institution of Oceanography, University of California San Diego, La Jolla, CA, USA
[i] Freshwater Institute, Fisheries and Oceans Canada, Winnipeg, Manitoba, Canada
[j] Bedford Institute of Oceanography, Fisheries and Oceans Canada, Dartmouth, Nova Scotia, Canada
[k] Oceans North, Vancouver, British Columbia, Canada

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ABSTRACT

The Arctic has been a refuge from anthropogenic underwater noise; however, climate change has caused summer sea ice to diminish, allowing for unprecedented access and the potential for increased underwater noise. Baseline underwater sound levels must be quantified to monitor future changes and manage underwater noise in the Arctic. We analyzed 39 passive acoustic datasets collected throughout the Canadian Arctic from 2014 to 2019 using statistical models to examine spatial and temporal trends in daily mean sound pressure levels (SPL) and quantify environmental and anthropogenic drivers of SPL. SPL (50–1000 Hz) ranged from 70 to 127 dB re 1 μPa (median = 91 dB). SPL increased as wind speed increased, but decreased as both ice concentration and air temperature increased, and SPL increased as the number of ships per day increased. This study provides a baseline for underwater sound levels in the Canadian Arctic and fills many geographic gaps on published underwater sound levels.

1. Introduction

Underwater noise in the ocean and its impact on marine animals is an important global conservation issue (Duarte et al., 2021). Underwater noise has a variety of effects on marine life, including acoustic masking (Clark et al., 2009; Erbe et al., 2016), behavioural disturbance (Gomez et al., 2016; Nowacek et al., 2007; Southall et al., 2007), increased stress hormone levels (Rolland et al., 2012), hearing loss (Finneran, 2016; Southall et al., 2019), and even death (McCauley et al., 2017). The impacts of underwater noise have been studied most in marine mammals (Gomez et al., 2016; Southall et al., 2007, 2019), and have also been studied in fish (Cox et al., 2018; de Jong et al., 2020; Slabbekoorn et al., 2010) and invertebrates (McCauley et al., 2017; Murchy et al., 2020).

Ambient sound levels have been increasing in the ocean as the global fleet of ships has grown, along with other noisy anthropogenic activities (Andrew et al., 2002, 2011; Chapman and Price, 2011; McDonald et al., 2006; Miksis-Olds and Nichols, 2016). Given the increasing underwater noise levels and a more comprehensive understanding of the impacts of underwater noise on marine life, national and international policy makers have begun to pay attention to these concerns (Colbert, 2020; Lewandowski and Staaterman, 2020), resulting in calls for wide-ranging monitoring of underwater sound levels and setting targets or caps on anthropogenic underwater noise (Lewandowski and Staaterman, 2020). Global efforts on measuring and managing anthropogenic noise include efforts to standardize the different acoustic metrics being used (Martin et al., 2019; Merchant et al., 2015; PAME, 2019; Tyack et al., 2021).

* Corresponding author.
E-mail address: whalliday@wcs.org (W.D. Halliday).

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The Arctic generally has some of the lowest underwater sound levels on the planet, comparable only to the Antarctic (Halliday et al., 2020a). The presence of sea ice generally limits anthropogenic activities, which reduces anthropogenic noise. Sea ice also limits noise associated with surface winds (Halliday et al., 2020b; Insley et al., 2017; Roth et al., 2012) and scatters underwater sound to a degree dependent upon characteristics of the ice and the frequency of the sound (Diachok, 1976; Yang and Votaw, 1981). As a result, ambient sound levels in the Arctic can be below the noise floor of many acoustic recorders (Insley et al., 2017; Kinda et al., 2013; Roth et al., 2012). Sea ice is also a major source of underwater sounds, particularly when ice is forming and breaking (Kinda et al., 2015). However, Arctic sea ice is melting earlier in the spring, freezing later in the autumn, and has a much lower extent now than it did in the past (Maslowski et al., 2012; Meredith et al., 2019; Stroeve et al., 2007; Wang and Overland, 2009), leading to increased access to ship traffic in the Arctic (Dawson et al., 2017; Pizzolato et al., 2016; Stephenson et al., 2011). Both the loss of sea ice and increased anthropogenic activity will likely lead to increased underwater sound levels (Halliday et al., 2020a). Arctic animals have historically been exposed to lower levels of ship traffic and underwater noise than animals occupying more temperate waters (Halliday et al., 2020a). Moreover, a few Arctic species (e.g., narwhal (*Monodon monoceros*), beluga whales (*Delphinapterus leucas*)) have been shown to react to relatively low levels of underwater noise from ships (i.e. just above ambient levels; Finley et al., 1990; Halliday et al., 2019), indicating that Arctic species may be more at risk from the threats of underwater noise than their temperate counterparts.

The underwater soundscape in the Arctic is naturally more complex than in non-polar waters: while it is dominated by sounds generated by wind (both wind stress on water and on ice), it is also controlled by seasonal sea ice that can dampen the impacts of wind, and add its own complex signals to the soundscape (Insley et al., 2017; Kinda et al., 2013, 2015; Roth et al., 2012; Southall et al., 2020), especially in colder or rapidly changing temperatures (Ganton and Milne, 1965; Milne and Ganton, 1964). Biological sounds can also add significant energy to the soundscape, particularly during the breeding season or in areas where vocal species congregate (Frouin-Mouy et al., 2016; Halliday et al., 2018a, 2020c; Heimrich et al., 2021; Tervo et al., 2012). Anthropogenic noise from ship traffic, seismic airgun surveys, and even drilling operations, have been recorded in the Arctic (Blackwell et al., 2004; Halliday et al., 2020b; Keen et al., 2018; Roth et al., 2012; Thode et al., 2010). These sources of noise are often localized around industrial activity. Oil and gas exploration and extraction activities, for example, can be quite prevalent in some years, but entirely absent in others (PAME, 2019). Underwater noise from ships has likely been increasing in the Arctic along with levels of ship traffic (Halliday et al., 2020a), however, long-term monitoring is required to assess how much underwater sound levels have increased as a result of growth in ship traffic. Given the remote nature of the Arctic, maintaining long-term underwater observatories or passive acoustic monitoring stations can be logistically difficult. Many gaps, both spatial and temporal, currently exist in the Arctic for underwater noise monitoring (PAME, 2019). For example, within the last decade, only seven studies have published quantitative assessments of underwater sound levels in the Canadian Arctic (Halliday et al., 2020b, 2020c; Heard et al., 2013; Insley et al., 2017; Kinda et al., 2013, 2015; Martin et al., 2019), and five of these studies were located within the very western portion of the Canadian Arctic. This effort, however, is not reflective of the total amount of acoustic data that has been collected within the Canadian Arctic over the past decade or longer. A number of datasets exist that were collected for a different purpose, such as monitoring marine mammals (e.g., Marcoux et al., 2017) and carrying out long range tomographic experiments (e.g. Badiey et al., 2019). A number of older studies also collected underwater sound measurements in the Canadian Arctic, but over much shorter deployments and often with less precise measurements (e.g., Ganton and Milne, 1965; Milne and Ganton, 1964). Some attempts have been made to combine these older datasets with newer data (e.g., Cook et al., 2020), but these short-term datasets do not fully capture the variability in the Arctic soundscape.

In this study, we examine trends in underwater sound levels from 39 acoustic datasets collected across the Canadian Arctic from 2014 to 2019. We assess the influence of wind, ice concentration, and air temperature on sound levels to document variations in sound levels caused by environmental processes. We then assess how ship traffic is affecting sound levels, and how these trends vary spatially, to determine current levels of anthropogenic noise across the Canadian Arctic. This study is the first large-scale analysis of long-term trends in underwater sound levels in the Canadian Arctic and provides a useful baseline for future monitoring as the Arctic soundscape continues to change.

2. Methods

2.1. Datasets

We gathered long-term passive acoustic datasets from 39 deployments at 15 sites throughout the Canadian Arctic deployed between 2014 and 2019 by five different research groups (Fig. 1, Table 1). All sites are effectively located within the Canadian Arctic Archipelago, with the majority within a few km of a coastline. Acoustic recorders were deployed using a variety of techniques, including anchored directly to the ocean floor, attached to short mooring lines with sub-surface floats, or attached to mooring lines with surface floats. Deployment time ranged from 23 days (during the ice-free summer) to a full year. Deployments took place at 15 different sites, from Baffin Island in the east to Banks Island in the west. Seven different models of recorders were used, including Song Meter SM2M and SM3M ($n = 16$ and $n = 7$, respectively; Wildlife Acoustics, Maynard, Massachusetts, USA), HARPs ($n = 6$; Scripps Institution of Oceanography, La Jolla, California), iCListen ($n = 2$; Ocean Sonics, Truro Heights, Nova Scotia), Aural M2 (n = 1; Multi Electronique Inc., Rimouski, Quebec, Canada), and SoundTrap ST300 and ST500 (n = 1 and $n = 4$, respectively; Ocean Instruments, Auckland, New Zealand) (Table 1). Recorders were set with sampling rates between 1.6 and 384 kHz and with duty cycles ranging from continuous recording to 1 min of sound recorded every 2 h. Recorders were deployed at depths between 24 and 670 m. All of these recorders have relatively flat sensitivity curves between 50 Hz (or lower for many recorders) and 1000 Hz.

2.2. Analyses

Root mean squared sound pressure levels (SPL) were calculated for each acoustic dataset from each deployment in three bandwidths: 50–1000 Hz and the 1/3-octave bands centred on 63 Hz and 250 Hz. The 50–1000 Hz band represents the widest bandwidth possible, based on the lower bound of the flat portion of the sensitivity curve of Wildlife Acoustics recorders (SM2M and SM3M, the most common recorders in the dataset; Insley et al., 2017) and based on the maximum acoustic sampling frequency of one deployment (deployment ID 24); one dataset (deployment ID 23) had a maximum frequency of 800 Hz, and was not included in analyses of the 50–1000 Hz bandwidth. The 63 Hz and 250 Hz 1/3-octave bands were selected for comparability with other studies of underwater sound levels, which selected these bands because they may be important indicators of anthropogenic noise (e.g., Aulanier et al., 2017; McDonald et al., 2006; Roth et al., 2012). SPLs were calculated in each of the three bandwidths described above using one of three methods. The first method was used for all acoustic data collected by Wildlife Conservation Society Canada (IDs 1–11 in Table 1), Fisheries and Oceans Canada and the University of Windsor (IDs 12–22 in Table 1), and by Oceans North (IDs 25–31 in Table 1). In this first method, wav files were processed using the PAMGuide package (Merchant et al., 2015) in Matlab (version 2017a; Mathworks, Natick, Massachusetts, USA) to calculate SPL in each bandwidth in one-second bins

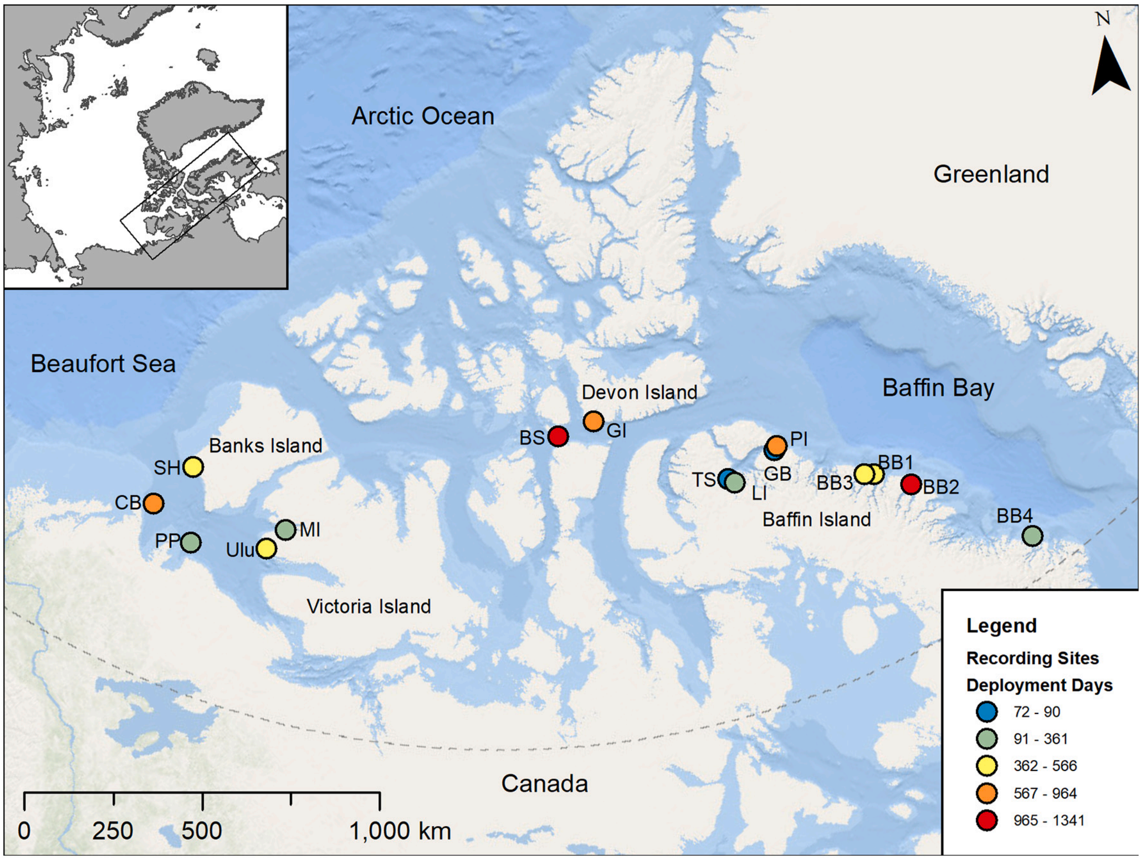

Fig. 1. Map of the locations of passive acoustic recording sites that collected data used in this study. Recording sites are colour-coded based on the number of days of recording included in this study from each site, which typically includes data from multiple deployments. BB1 – BB4 are four recording sites in Baffin Bay, BS = Barrow Strait (Resolute), CB = Cape Bathurst (Amundsen Gulf), GB = Guys Bight (Eclipse Sound), GI = Gascoyne Inlet, LI = Low Island (Milne Inlet, Eclipse Sound), MI = Minto Inlet (Amundsen Gulf), PI = Pond Inlet, PP = Pearce Point (Amundsen Gulf), SH = Sachs Harbour, TS = Tremblay Sound (southwest of Eclipse Sound), and Ulu = Ulukhaktok.

with 50% overlap using a Hanning window. Five-minute averages were then calculated by the PAMGuide package, which typically matched the length of the audio file. Note that this 5-minute SPL is used later in a test of the effect of temporal averaging on trends in SPL, which is fully described at the end of the Methods section. The second method was used for all data collected by Scripps Institution of Oceanography, including data collected in partnership with Oceans North (IDs 32–39 in Table 1). For this second method, acoustic data were processed using custom Matlab code, where acoustic data were divided into one-second bins, and this time series was processed with a fast Fourier transform with length = 200,000 samples (i.e. the sample rate of these recordings, one-second bins), no overlap, and using a Hanning window within the target bandwidth. Hourly averages were then calculated from the time series. The third method of SPL calculation was used for the two datasets collected by Dalhousie University and Fisheries and Oceans Canada (IDs 23 and 24 in Table 1). These datasets are unique compared to all other datasets used in this study, as they are collected from a cabled observatory (all others are from autonomous recorders), and this observatory automatically calculated a spectrogram with SPL calculated in 15.62 Hz bins for each second of the full 1 min file using a Hanning window with 50% overlap. These one-minute spectrograms were then remotely transmitted back for researchers to use, rather than relying on raw audio data as in all other datasets. The underlying SPL data from the spectrogram was converted to pressure:

$$P_{f,t} = 10^{\left(\frac{SPL_{f,t}}{10}\right)} \tag{1}$$

where $P_{f,t}$ is the sound pressure for each frequency (f) by time (t) bin of the spectrogram and $SPL_{f,t}$ is the SPL in each frequency by time bin. Pressure levels of the spectrum were decimated using linear regression and integrated over the bandwidths used for this study using the trapezoidal rule ($P_{bandwidth}$), and then converted back to decibels:

$$SPL_{bandwidth} = 10log_{10}P_{bandwidth} \tag{2}$$

The SPL data from all recorders were then collected by the lead author and standardized across recorders by computing the linear daily average (based on the UTC time zone) for each day of each deployment by first converting SPL within a file to pressure (P_{file}):

$$P_{file} = 10^{\left(\frac{SPL_{file}}{10}\right)} \tag{3}$$

then calculating the mean P_{file} within a day and converting back to SPL:

$$SPL_{day} = 10log_{10}P_{day} \tag{4}$$

This daily mean SPL removes much of the variation from the datasets, particularly for short (e.g., a few seconds), low amplitude, and transient signals. However, it captures high amplitude signals, events of any amplitude that are on time scales of multiple hours or greater, such as storms, and short signals that are repetitive. Moreover, daily SPL provides a consistent way to compare across datasets with varying duty cycles, as in this study, although datasets with more extreme duty cycles have a higher likelihood of SPL being biased by high amplitude transient events. Since every dataset has multiple measurements uniformly distributed over the day, the daily SPL will capture the varying SPL with

Table 1
Acoustic deployment metadata. Data owners include Wildlife Conservation Society Canada (WCSC), Fisheries and Oceans Canada (DFO), University of Windsor (UW), Dalhousie University (Dal), Oceans North (ON), and Scripps Institution of Oceanography (Scripps). Model refers to the type of acoustic recorder; see Methods for a list of the manufacturers of the different models. * indicates that no precise depth measurement was taken. BB1 – BB4 are four recording sites in Baffin Bay, BS = Barrow Strait (Resolute), CB = Cape Bathurst (Amundsen Gulf), GB = Guys Bight (Eclipse Sound), GI = Gascoyne Inlet, LI = Low Island (Milne Inlet, Eclipse Sound), MI = Minto Inlet (Amundsen Gulf), PI = Pond Inlet, PP = Pearce Point (Amundsen Gulf), SH = Sachs Harbour, TS = Tremblay Sound (southwest of Eclipse Sound), and Ulu = Ulukhaktok.

ID	Data owner	Site	Latitude	Longitude	Model	Start date	Duration (days)	Water depth (m)	Sample rate (kHz)	Duty cycle (min on/off)
1	WCSC	SH	71.97	−125.29	SM3M	2014-07-05	31	26	24	60/60
2	WCSC	SH	71.94	−125.91	SM3M	2015-05-18	92	27	32	60/60
3	WCSC	SH	71.94	−126.14	SM3M	2015-07-03	47	49	32	10/20
4	WCSC	SH	71.93	−125.39	SM3M	2015-08-20	323	30	48	5/35
5	WCSC	SH	71.95	−125.41	ST300	2017-07-28	28	21.3	48	60/60
6	WCSC	Ulu	70.72	−117.80	SM3M	2017-07-25	241	24.4	48	5/30
7	WCSC	Ulu	70.72	−117.80	SM3M	2018-07-31	267	24.4	48	5/60
8	WCSC	CB	70.57	−127.66	ST500	2018-10-07	355	50	48	5/60
9	WCSC	CB	70.68	−126.87	ST500	2018-09-30	362	295	48	5/60
10	WCSC	PP	70.20	−123.16	ST500	2018-10-02	361	351	48	5/60
11	WCSC	MI	71.30	−116.84	ST500	2019-02-07	213	319	48	5/60
12	DFO/UW	BB1	71.13	−70.97	Aural M2	2014-09-26	127	255	384	4/60
13	DFO/UW	BB1	71.13	−70.98	SM2M	2015-09-28	303	255	96	4/60
14	DFO/UW	BB1	71.13	−70.98	SM2M	2016-09-14	165	205	96	4/60
15	DFO/UW	BB2	70.32	−68.34	SM2M	2014-09-25	352	408	48/96	7/60
16	DFO/UW	BB2	70.32	−68.34	SM2M	2015-10-07	345	425	96	5/60
17	DFO/UW	BB2	70.32	−68.34	SM2M	2016-09-25	295	412	96	4/60
18	DFO/UW	BB2	70.33	−68.34	SM2M	2017-09-29	183	414	192	5/60
19	DFO/UW	BB3	71.02	−70.29	SM3M	2015-09-30	342	507	96	7/60
20	DFO/UW	BB3	71.02	−70.32	SM2M	2016-09-13	202	161	96	4/60
21	DFO/UW	BB4	67.61	−63.45	SM2M	2016-09-05	209	150	96	3/60
22	DFO/UW	BB4	67.61	−63.45	SM2M	2017-09-26	112	329	192	5/60
23	DFO/Dal	GI	74.61	−91.25	iCListen	2017-08-17	375	157	1.6	1/120
24	DFO/Dal	GI	74.61	−91.25	iCListen	2018-08-29	351	162	12.8	1/120
25	ON	LI	72.26	−80.58	SM2M	2014-06-30	59	100*	192	5/60
26	ON	LI	72.26	−80.58	SM2M	2015-08-05	57	100*	192	5/60
27	ON	LI	72.26	−80.58	SM2M	2016-05-28	57	100*	192	5/60
28	ON	LI	72.26	−80.58	SM2M	2017-08-01	58	100*	96	45/60
29	ON	GB	72.65	−76.56	SM2M	2015-07-01	91	100*	192	5/60
30	ON	TS	72.41	−80.99	SM2M	2015-08-04	47	100*	192	5/60
31	ON	TS	72.41	−80.99	SM2M	2016-08-28	23	100*	192	5/60
32	Scripps	BS	74.34	−94.54	HARP	2013-09-14	310	200	200	45/60
33	Scripps	BS	74.35	−94.70	HARP	2014-09-09	357	190	200	40/60
34	Scripps	BS	74.35	−94.67	HARP	2015-09-12	306	189	200	60/60
35	Scripps	BS	74.42	−94.71	HARP	2017-09-03	368	160	200	45/60
36	Scripps/ON	PI	72.72	−76.23	HARP	2016-05-28	131	657	200	60/60
37	Scripps/ON	PI	72.72	−76.23	HARP	2016-10-05	304	670	200	60/60
38	Scripps/ON	PI	72.72	−76.23	HARP	2017-08-15	169	670	200	60/60
39	Scripps/ON	PI	72.73	−76.23	HARP	2018-09-27	360	670	200	60/60

respect to the environmental factors considered. However, to examine variation in daily measurements and impact of various duty cycling schemes across the ensemble of recorders, we also calculated the standard error (SE) around the daily mean SPL measurements.

We paired each acoustic dataset with three environmental variables (wind speed, air temperature, and ice concentration) and with a variable representing ship traffic. Wind speed and ice concentration have frequently been identified as important environmental predictors of underwater sound levels in the Arctic (Halliday et al., 2020b; Insley et al., 2017; Kinda et al., 2013; Roth et al., 2012; Southall et al., 2020), which is why we focused on these two variables specifically. Air temperature has also been identified as an important driver of underwater sound levels in the Arctic, particularly due to the role that it places in generating physical changes in ice (Ganton and Milne, 1965; Milne and Ganton, 1964). Wind speed and air temperature data were downloaded from Environment and Climate Change Canada's Historic Climate Database (Environment and Climate Change Canada, 2018) for the nearest weather station to the deployment site, which is typically the nearest community airport. Wind speed and air temperature data were available every hour, so the average for each day (in UTC time) was calculated for each variable. Daily sea ice concentration (percent area covered by ice within a pixel) data from the AMSR2 satellite were downloaded from the Institute of Environmental Physics at the University of Bremen (Spreen et al., 2008) at a 6.25 km width cell resolution. Values for the pixel directly over each deployment location were extracted from this dataset. Satellite Automatic Identification System (AIS) data, which is a dataset that tracks the locations of ships based on ships transmitting information with an AIS transceiver, were obtained from exactEarth (Cambridge, Ontario, Canada). This dataset includes all large commercial ships and passenger ships, but does not include many smaller recreational boats, including small boats used for subsistence activities. The number of AIS ships (based on the number of unique MMSI numbers) within 10 km of each deployment location was calculated for each day of each deployment. 10 km was chosen because it has been used in a previous study to estimate ship noise around an acoustic recorder in the Arctic (Halliday et al., 2020b), but we acknowledge that propagation of ship noise will vary greatly between different recorders due to localized effects on sound propagation.

Daily SPL in each frequency band were examined statistically using mixed effects generalized additive models (also known as hierarchical generalized additive models; package: gamm4; Wood and Scheipl, 2020) and linear mixed effects models (package: lme4; Bates et al., 2015) in R version 3.6.1 (R Core Team, 2019). Mixed effects general additive models are a robust approach for statistically analyzing complex datasets with implicit random effect structures while also examining curvilinear relationships in the fixed effects (Pedersen et al., 2019). We included deployment ID (Table 1) as a random effect in all models. We ran three different sets of models for each frequency band

(50–1000 Hz and 1/3-octaves centred on 63 Hz and 250 Hz). For the first model, we used mixed effects general additive models to examine the influence of wind speed, ice concentration, air temperature, water depth, and recording location (site) on SPL in each band, including curvilinear effects of all continuous main effects and two-way interactions between wind speed, ice concentration, and air temperature. The combination of wind speed, ice concentration, and air temperature allowed us to account for natural variance in underwater sound levels, which in the Arctic, is mainly driven by these three variables (Ganton and Milne, 1965; Halliday et al., 2020b; Insley et al., 2017; Kinda et al., 2013; Milne and Ganton, 1964; Roth et al., 2012). By controlling for these main environmental effects, we were able to examine differences between sites that were not caused by wind, ice, or temperature, such as long-range transmission of sounds, which would be especially important in deeper sites and in sites that are near shipping lanes. For the second model, we used linear mixed effects models to examine the influence of the number of ships on SPL, and included the number of ships within 10 km of a recorder within a day as the main fixed effect of interest, but also included wind speed and site as fixed effects to control for the large effects of these variables on SPL. These models only used data from the summer open water period (July through September) when ships are present in the Canadian Arctic. We did not include ice concentration or air temperature in this second model because this model only focuses on data from the summer, ice-free season. For the final model, we used linear mixed effects models to examine seasonal patterns in SPL across sites, including either month or season (winter = January–March; spring = April–June; summer = July–September; autumn = October–December) as fixed effects. For all models, we systematically removed fixed effects that were not statistically significant, and compared models with Akaike's Information Criterion (AIC; R package: stats) to determine the optimal model.

We were unable to account for biological sounds in these analyses due to the large amount of effort required to consistently conduct bioacoustic analyses in all of these datasets. However, we recognize that biological sounds can account for very large amounts of variance in underwater sound levels. For example beluga whales in the Mackenzie River estuary can add an average of 14 dB to the soundscape in the 10–48 kHz bandwidth when they are present (Halliday et al., 2020c), and bearded seals (*Erignathus barbatus*) calls can add substantial pressure to the 50–1000 Hz bandwidth (Heimrich et al., 2021). Yet, in sites where marine mammals are not vocalizing close to the acoustic recorder, their vocalizations have minimal impacts on SPL (Halliday et al., 2020b).

We collated different metrics of underwater noise for each deployment during the summer shipping season (July through September). These metrics include the number of days where daily SPL exceeded 100, 110, or 120 dB re 1 μ Pa (henceforth referred to as dB) in each of the bandwidths, as well as the total number of ships within 10 km of the recorder during the deployment and average number of ships per day. The goal of using these metrics was to maximize comparability with future studies. For example, the European Union's Marine Strategy Framework Directive originally suggested keeping underwater noise levels in the 63 Hz 1/3-octave band below 100 dB (Erbe, 2013). However, it has previously been shown with data from the western Canadian Arctic (deployments 2 and 4 in Table 1) that wind speed alone can cause SPL in the 50–1000 Hz band to vary from 90 dB when wind speed is 0 km/h to 110 dB when wind speed is 50 km/h (Halliday et al., 2017; Insley et al., 2017). We therefore use 100 dB as our lower threshold, but also examine how often SPL surpasses 110 and 120 dB, given that 110 dB may be an upper threshold to natural ambient sound levels in the absence of anthropogenic noise in the 50–1000 Hz band. 120 dB is the threshold for behavioural disturbance to marine mammals by continuous noise sources used by the US National Oceanic and Atmospheric Administration (National Marine Fisheries Service, 2016; Southall et al., 2007).

We examined uncertainty in our daily estimates of average SPL by calculating the daily standard error (SE) in SPL. We then used an identical mixed effects general additive model to our first analysis, except with daily SE as the dependent variable. We also tested the impact of daily averaging of the SPL data by comparing the influence of wind speed and ice concentration on SPL in the 50–1000 Hz band for one of the datasets (Deployment ID 4 in Table 1). We compared the effect size and R^2 of the relationship using linear regression in R (package: mgcv; function: gam; R Core Team, 2019; Wood, 2011), with one model using the daily SPL and the other model using 5-minute SPL (i.e. mean SPL within a 5-minute file) as the dependent variable.

In all of these statistical tests, we used various test statistics and metrics to assess statistical significance and goodness-of-fit. These include: the F-test statistic ($F_{pdf,rdf}$), which is always denoted with the degrees of freedom for the parameter being tested (p_{df}) and for the residuals (r_{df}); the *t*-test statistic (t_{rdf}), which includes the degrees of freedom for the residuals; *p*-value (p), which is compared to an α value of 0.05; the coefficient of determination (R^2); and the standard error of the mean (SE).

3. Results

Wind speed, ice concentration, and air temperature were important variables explaining daily SPL in all frequency bands. In the 50–1000 Hz band, SPL increased in a nearly linear fashion as wind speed increased ($F_{3.2,7790} = 50.31$, $p < 0.0001$; Fig. 2), with an estimated equivalent linear slope of 0.14 dB/km/h. SPL in the 50–1000 Hz band decreased in a curvilinear fashion as ice concentration increased ($F_{6.7,7790} = 157.41$, $p < 0.0001$), where SPL stayed relatively stable and high at ice concentrations between 0 and 10%, but then SPL decreased in a roughly linear fashion when ice concentration increased from 10 to 100% (Fig. 2). SPL in the 50–1000 Hz band had a more complex curvilinear relationship with air temperature ($F_{6.9,7790} = 21.71$, $p < 0.0001$), where SPL generally decreased as air temperature increased, but SPL stayed relatively stable between air temperatures of −20 and −5 °C (Fig. 2). The interaction between wind speed and ice concentration was negative (slope ± SE = $-7.8 \times 10^{-4} \pm 1.9 \times 10^{-4}$ dB / (% × km/h); $t_{7790} = 4.17$, $p < 0.0001$), such that under increased ice concentration, wind speed had a smaller influence on SPL. The interaction between ice concentration and air temperature was also negative (slope ± SE = $-1.4 \times 10^{-3} \pm 3.1 \times 10^{-4}$ dB / (% × °C); $t_{7790} = 4.66$, $p < 0.0001$), such that under increased ice concentration, an increase in temperature had a smaller effect. The interaction between wind speed and temperature was not significant ($p > 0.05$).

The 63 Hz 1/3-octave band had similar relationships to the 50–1000 Hz band, with wind speed having a nearly linear positive relationship with SPL ($F_{3.9,7790} = 8.18$, $p < 0.0001$), ice concentration having a negative curvilinear relationship with SPL ($F_{6.9,7790} = 74.63$, $p < 0.0001$), and air temperature having a negative curvilinear relationship with SPL ($F_{6,37790} = 14.49$, $p < 0.0001$) (Fig. 2). All three interaction terms for the 63 Hz band were significant: the wind by ice concentration interaction was positive (slope ± SE = $7.8 \times 10^{-4} \pm 2.8 \times 10^{-4}$ dB/(% × km/h); $t_{7790} = 2.78$, $p < 0.01$), the ice concentration by temperature interaction was negative (slope ± SE = $-1.1 \times 10^{-3} \pm 3.7 \times 10^{-4}$ dB/(% × °C); $t_{7790} = 3.06$, $p < 0.01$), and the wind by temperature interaction was positive and only weakly significant (slope ± SE = $1.9 \times 10^{-3} \pm 9.1 \times 10^{-4}$ dB / (°C × km/h); $t_{7790} = 2.05$, $p = 0.04$).

The 250 Hz 1/3-octave band also had a positive and slightly curvilinear relationship with wind speed ($F_{4.0,7790} = 59.36$, $p < 0.0001$), negative curvilinear relationship with ice concentration ($F_{7.0,7790} = 172.19$, $p < 0.0001$), and a negative curvilinear relationship with air temperature ($F_{7.3,7790} = 13.95$, $p < 0.0001$) (Fig. 2). The interaction terms for the 250 Hz 1/3-octave model were nearly identical to those for the 50–1000 Hz model, with negative interactions with both wind speed and ice concentration (slope ± SE = $-9.9 \times 10^{-4} \pm 1.8 \times 10^{-4}$ dB/(% × km/h); $t_{7790} = 5.38$, $p < 0.0001$) and with ice concentration and air temperature (slope ± SE = $-2.1 \times 10^{-3} \pm 3.1 \times 10^{-4}$ dB/(% × °C); $t_{7790} = 6.93$, $p < 0.0001$), but a non-significant relationship with wind speed

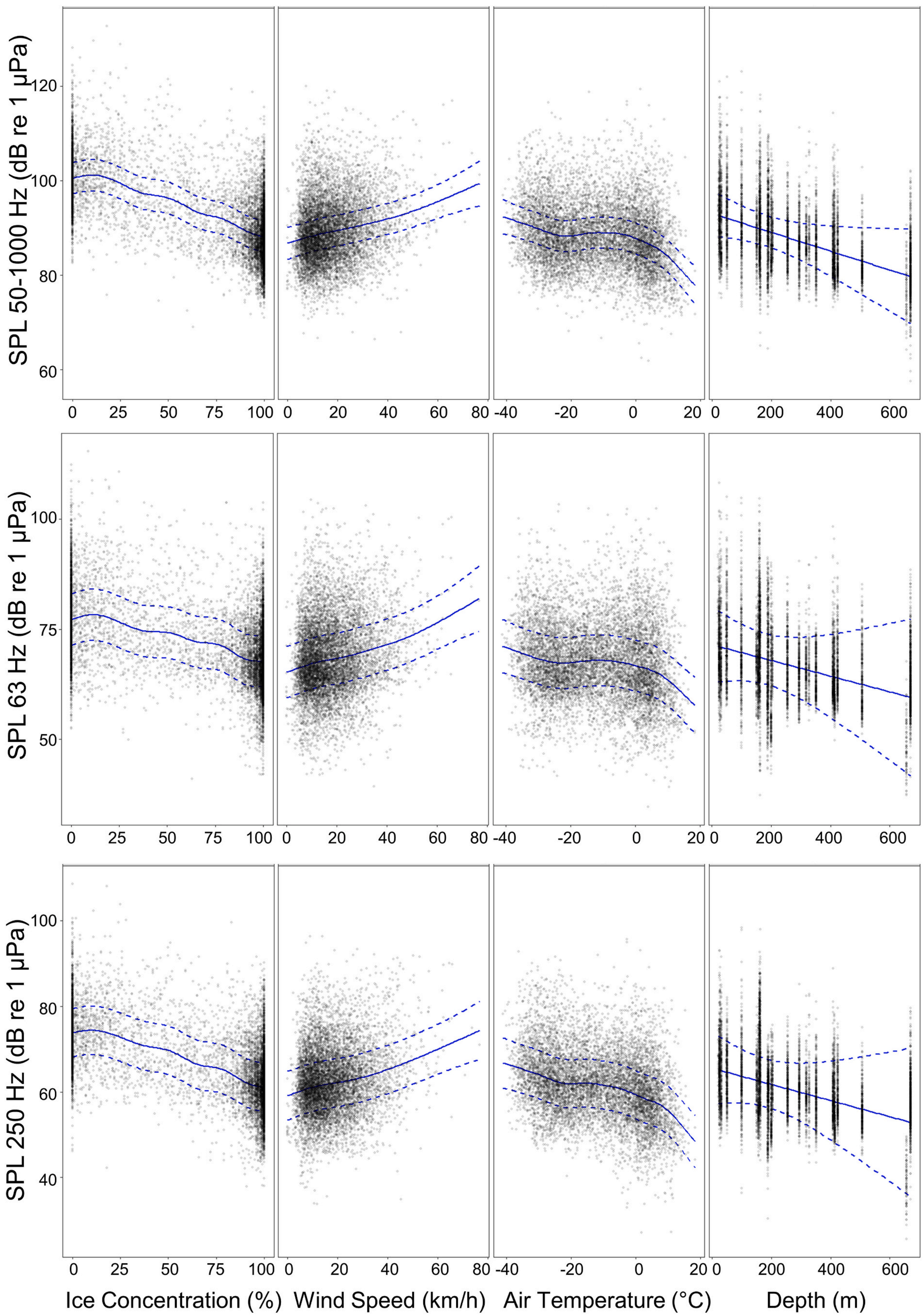

Fig. 2. Sound pressure level (SPL) in the 50–1000 Hz band (top), 63 Hz 1/3-octave band (middle) and 250 Hz 1/3-octave band (bottom) by ice concentration, wind speed, air temperature, and water depth at the recording site. The solid line is the curvilinear fit by the generalized additive model, and the dashed lines represent 2 × standard error.

and air temperature ($p > 0.05$).

Water depth had a weak, linear negative relationship with SPL in the 50–1000 Hz band ($F_{1,7790} = 4.00$, $p = 0.046$), with an estimated slope of −0.02 dB/m, but non-significant relationships in the 63 and 250 Hz 1/3-octave bands (Fig. 2).

Sites generally varied greatly in daily SPL (Fig. 3). Across all recordings, the average daily SPL at a site (i.e. the average of daily SPL across all data from a site) in the 50–1000 Hz band ranged from 87.2 to 99.7 dB, from 62.9 to 88.0 dB in the 63 Hz 1/3-octave band, and from 66.6 to 87.9 dB in the 250 Hz 1/3-octave band (Table 2). The three bandwidths that we examined were all significantly correlated to each other ($p < 0.0001$), although the 50–1000 Hz band was slightly more closely correlated with both the 63 Hz ($r = 0.80$) and 250 Hz 1/3-octave bands ($r = 0.80$) than either of the 1/3-octave bands were correlated with each other ($r = 0.78$). Although there was quite a bit of variation in water depth between these sites, we accounted for this variation in the model by including water depth as a fixed effect.

The three sites with the highest mean daily SPL in the 50–1000 Hz band, in order of highest to lowest, were Baffin Bay 4 (99.7 dB), Gascoyne Inlet (99.6 dB), and Cape Bathurst (96 dB). The three sites with the lowest mean daily SPL in the 50–1000 Hz band, from lowest to highest, were Minto Inlet (87.2 dB), Ulukhaktok (88.1 dB), and Baffin Bay 3 (88.4 dB). Many of the trends in the 50–1000 Hz band were comparable in the 1/3-octave bands, such as Baffin Bay 4 having the highest mean daily SPL in all bands. Gascoyne Inlet and Cape Bathurst also had one of the highest mean daily SPLs in all bands, although their ranking among the sites changed slightly in the 1/3-octave bands. The three sites with the lowest mean daily SPL in the 63 Hz 1/3-octave were Ulukhaktok, Sachs Harbour, and Baffin Bay 2, and the three sites with the lowest mean daily SPL in the 250 Hz 1/3-octave band were Barrow Strait, Minto Inlet, and Ulukhaktok.

We also examined patterns between sites during the summer shipping season (July–September). The per-site average daily SPL in the 50–1000 Hz band in the summer ranged from 91.7 to 108.1 dB, from 68.8 to 97.0 dB in the 63 Hz 1/3-octave band, and from 76.3 to 96.8 dB in the 250 Hz 1/3-octave band (Table 2). Baffin Bay 4 (southeast end of Baffin Island) had the highest SPL in all bands, on average, even after other sources of sound (wind speed and ice) were accounted for, whereas other shallow or sheltered sites, such as Sachs Harbour and Tremblay Sound, tended to have lower SPLs in all bands. Trends in the 50–1000 Hz band across sites did not always match up with trends in the 1/3-octave bands, although it often matched better with the 250 Hz 1/3-octave band than the 63 Hz 1/3-octave band. For example, Minto Inlet had the lowest mean SPL in the 50–1000 Hz band and in the 250 Hz 1/3-octave band, but the 8th lowest mean SPL in the 63 Hz 1/3-octave band. Conversely, Ulukhaktok had the lowest mean SPL in the 63 Hz 1/3-octave band, but the 6th highest in the 50–1000 Hz band and the 4th highest in the 250 Hz 1/3-octave band. Much of this variation during the summer was driven by patterns in ship traffic.

The number of ships with AIS transceivers within 10 km of the acoustic recorder within a day (which ranged between 0 and 8 ships/day) had a positive effect on the daily SPL in the 50–1000 Hz band (slope ± SE = 3.21 ± 0.20 dB/ship, $t_{1904} = 16.38$, $p < 0.0001$; Fig. 4), the 63 Hz 1/3-octave band (3.52 ± 0.23 dB/ship), and the 250 Hz 1/3-octave band (3.26 ± 0.20 dB/ship).

Daily SPL varied widely between months (Fig. 4). March (86.9 ± 7.3 dB) and April (87.8 ± 7.3 dB) had the lowest SPL in the 50–1000 Hz band, on average, whereas August (97.6 ± 6.7 dB), September (100.4 ± 7.3 dB), and October (99.8 ± 8.2 dB) had the highest SPLs in this band. This pattern of highest SPL in August–October was consistent in both the 63 Hz and 250 Hz 1/3-octave bands. SPL in the 63 Hz band was lowest in March–May, and in the 250 Hz band was lowest in March–June.

3.1. Acoustic indicators of underwater noise

Acoustic indicators of underwater noise levels may be an important management tool in the future as more national and international policies are developed. We therefore collated some useful indicator variables for each deployment site, including the percentage of days with mean SPL > 100 dB, 110 dB, and 120 dB in all three bands, as well as the average number of ships within 10 km of the acoustic recorder per day over the summer season (July through September) (Table 3). All sites had at least some days with mean SPL > 100 dB in the 50–1000 Hz band, although this varied between 6% (Minto Inlet and Tremblay Sound) and 100% (Baffin Bay 4), and the mean across all sites was 30%. One site did not have daily SPL > 110 dB (Guys Bight), but all other sites ranged between 1% (Minto Inlet, Pearce Point, and Tremblay Sound) and 24% (Baffin Bay 4), with a mean across these 14 sites of 5%. Only seven sites had daily SPL > 120 dB, ranging between 0% of summer days (1/261 days at Pond Inlet) and 2% (Gascoyne Inlet), with a mean across these seven sites of 0%. The site with the highest mean daily SPL on average, Baffin Bay 4, had no days with SPL > 120 dB. Focusing on the 63 Hz 1/3-octave band, sites had between 0% (Guys Bight, Minto Inlet, Pearce Point, and Sachs Harbour) and 21% (Baffin Bay 4) of days with daily SPL > 100 dB, with a mean across all sites of 3%. Only five sites had any days with mean daily SPL in the 63 Hz 1/3-octave band >110 dB, with a max of 1% of days (Baffin Bay 2, Cape Bathurst, Gascoyne Inlet, and Low Island). In the 250 Hz 1/3-octave band, sites had between 0% (Guys Bight, Minto Inlet, Pearce Point, and Sachs Harbour) and 17% (Baffin Bay 4) of their mean daily SPL > 100 dB, with a mean across all sites of 3%. Only four sites (Baffin Bay 2, Gascoyne Inlet, Low Island, and Tremblay Sound) had mean daily SPL > 110 dB in the 250 Hz 1/3-octave band. No sites in either the 63 Hz or 250 Hz 1/3-octave bands had daily SPL > 120 dB. The average number of ships per day within 10 km of acoustic recorders during the summer ranged from 0.01 (Guys Bight and Tremblay Sound) to 1.94 (Pond Inlet), with a mean across all sites of 0.44 ships/day.

3.2. Impact of daily averaging on results

Daily SE decreased linearly as ice concentration increased (slope = $2.61 \times 10^{-3} \pm 3.41 \times 10^{-4}$ dB/%; $t_{7823} = 7.64$, $p < 0.0001$). Daily SE also decreased in a curvilinear fashion as wind speed increased, with the largest rate of decrease at higher wind speeds ($F_{1.97,7823} = 5.72$, $p < 0.01$). Conversely, as the number of ships increased, daily SE increased linearly (slope = $0.17 \pm 1.2 \times 10^{-2}$ dB/ship; $t_{7823} = 13.63$, $p < 0.0001$). The effect size of these different drivers of variability in SPL appears to be related to the temporal scale of these factors, as well as their general impact on SPL. For example, underwater noise from ship traffic is a relatively short event, so days with ship traffic see high variability due to the short-term increase in SPL caused by a passing ship. Ice concentration and wind speed tend to vary on longer time scales, where wind speed can stay consistent over a number of hours and ice concentration may stay consistent over multiple months. When ice concentration is high, SPL tends to be relatively stable because ice limits the propagation of sounds and also limits the ability of wind speed and ship traffic to impact SPL. SPL is also relatively stable when wind speed is high because wind becomes the dominant driver of SPL.

Standard error around the daily SPL measurements varied by site ($F_{14,7823} = 28.92$, $p < 0.0001$), with the Gascoyne Inlet site having the highest daily SE, and to a lesser extent, the Pond Inlet, Barrow Strait, and Cape Bathurst sites having the next highest daily SE values ($p < 0.05$, Fig. 5). This site-specific variability is likely related to a number of factors. Gascoyne Inlet, for example, had the most extreme duty cycle of any of the recording sites, with only 1 min of data recorded every 2 h. This extreme duty cycle could lead to high variability in the SPL measurements within a day simply because short, transient events that were captured in the one-minute recordings would have a larger influence on daily SPL than at other sites with less extreme duty cycles. Other sites with high SE also had increased ship noise, such as the Pond Inlet site that had the highest levels of ship traffic for the entire study. These repeated signals with high SPL would lead to a larger daily SE at this site.

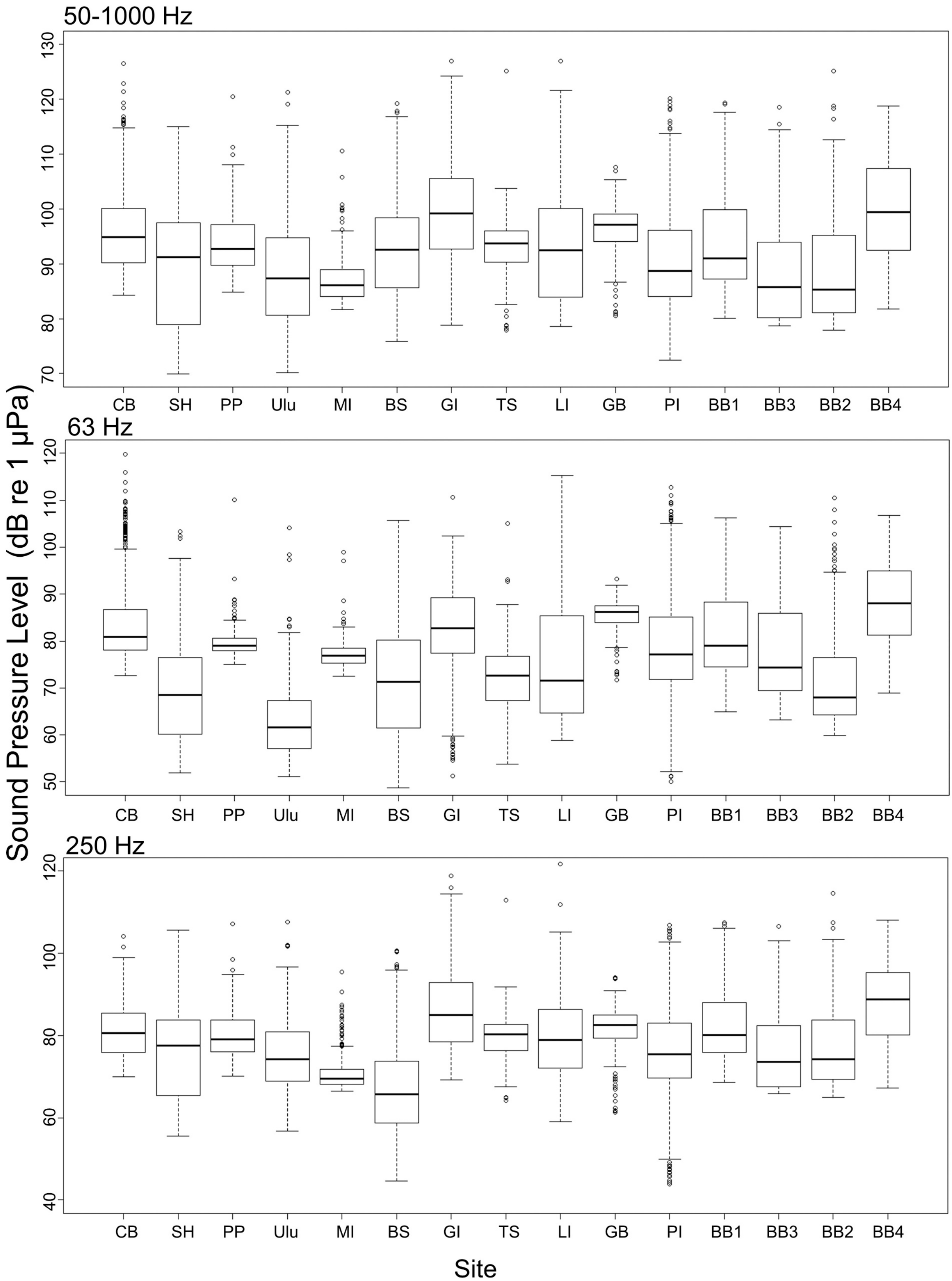

Fig. 3. Sound pressure level (SPL) in the 50–1000 Hz band (top), 63 Hz 1/3-octave band (middle), and 250 Hz 1/3-octave band (bottom) by recording site over the entire recording period. Sites are ordered by longitude, from west to east. BB1–BB4 are four recording sites in Baffin Bay, BS = Barrow Strait (Resolute), CB = Cape Bathurst (Amundsen Gulf), GB = Guys Bight (Eclipse Sound), GI = Gascoyne Inlet, LI = Low Island (Milne Inlet, Eclipse Sound), MI = Minto Inlet (Amundsen Gulf), PI = Pond Inlet, PP = Pearce Point (Amundsen Gulf), SH = Sachs Harbour, TS = Tremblay Sound (southwest of Eclipse Sound), and Ulu = Ulukhaktok.

Table 2
Mean ± S.E. sound pressure level for three bandwidths (50–1000 Hz and the 63 Hz and 250 Hz 1/3-octave bands) at each site based on data from the full year or just during the summer (July–September). BB1–BB4 are four recording sites in Baffin Bay, BS = Barrow Strait (Resolute), CB = Cape Bathurst (Amundsen Gulf), GB = Guys Bight (Eclipse Sound), GI = Gascoyne Inlet, LI = Low Island (Milne Inlet, Eclipse Sound), MI = Minto Inlet (Amundsen Gulf), PI = Pond Inlet, PP = Pearce Point (Amundsen Gulf), SH = Sachs Harbour, TS = Tremblay Sound (southwest of Eclipse Sound), and Ulu = Ulukhaktok.

Site	Full year			Summer		
	50–1000 Hz	63 Hz	250 Hz	50–1000 Hz	63 Hz	250 Hz
BB1	93.4 ± 0.36	81.2 ± 0.38	82.1 ± 0.36	98.4 ± 1.23	88.5 ± 0.92	85.1 ± 1.49
BB2	88.5 ± 0.26	71.0 ± 0.25	77.1 ± 0.27	93.2 ± 0.79	77.2 ± 0.81	81.6 ± 0.83
BB3	88.4 ± 0.40	77.6 ± 0.43	76.1 ± 0.40	93.1 ± 1.04	85.1 ± 0.98	81.2 ± 1.05
BB4	99.7 ± 0.47	88.0 ± 0.47	87.9 ± 0.49	108.1 ± 0.58	97.0 ± 0.69	96.8 ± 0.60
BS	92.7 ± 0.23	71.5 ± 0.34	66.6 ± 0.32	100.0 ± 0.37	78.3 ± 0.74	76.7 ± 0.64
CB	96.1 ± 0.29	83.7 ± 0.32	81.1 ± 0.24	97.0 ± 0.43	83.1 ± 0.50	82.6 ± 0.37
GB	95.8 ± 0.60	84.8 ± 0.45	80.8 ± 0.79	95.8 ± 0.60	84.8 ± 0.45	80.8 ± 0.79
GI	99.6 ± 0.35	83.0 ± 0.31	86.4 ± 0.35	104.5 ± 0.71	82.6 ± 0.54	91.7 ± 0.66
LI	92.5 ± 0.66	75.6 ± 0.82	79.7 ± 0.67	94.3 ± 0.69	77.4 ± 0.89	81.3 ± 0.72
MI	87.2 ± 0.31	77.1 ± 0.23	71.3 ± 0.34	91.7 ± 0.60	79.4 ± 0.48	76.3 ± 0.70
PI	90.9 ± 0.30	79.1 ± 0.34	76.5 ± 0.33	99.3 ± 0.54	86.5 ± 0.74	82.1 ± 0.71
PP	93.6 ± 0.27	79.5 ± 0.15	79.9 ± 0.29	95.6 ± 0.43	78.7 ± 0.14	81.4 ± 0.41
SH	89.5 ± 0.50	69.4 ± 0.46	75.5 ± 0.48	93.80 ± 0.40	72.1 ± 0.60	79.5 ± 0.44
TS	92.7 ± 0.81	72.1 ± 1.05	79.0 ± 0.81	92.7 ± 0.81	72.1 ± 1.05	79.0 ± 0.81
Ulu	88.1 ± 0.41	62.9 ± 0.35	75.2 ± 0.38	97.4 ± 0.57	68.8 ± 0.76	83.3 ± 0.60

For one deployment (Deployment ID 4 in Table 1), we compared a model using the daily SPL data to a model using 5-minute SPL, and examined the influence of wind speed, ice concentration, and their interaction on SPL. Both models explained >50% of variation in SPL (daily SPL $R^2_{adj} = 0.59$; 5-minute SPL $R^2_{adj} = 0.56$). With both metrics of SPL, SPL increased as wind speed increased, and decreased as ice concentration increased (Table 4). We detected a significant interaction between wind speed and ice concentration for the 5-minute SPL, but not for the daily SPL. The non-significant interaction in the daily SPL model may simply be because this model has 1/24th the sample size of the 5-minute SPL model and thus lower power, especially since the interaction between wind speed and ice concentration has a relatively small effect size in both models.

4. Discussion

In this study, we provide evidence that underwater sound levels in the Canadian Arctic are strongly linked to wind activity, sea ice, air temperature, and ship traffic, where an increase in the number of ships present drove large increases in underwater sound levels. While none of these trends are particularly novel, the context of using 39 unique datasets spread across the Canadian Arctic over a 6 year period fills important gaps in our knowledge, and provides a valuable regional baseline for future studies aimed at understanding the impact of underwater noise from various ecological and anthropogenic factors. This is particularly important in light of climate change, through both the loss of multiyear and summer sea ice and increasing air temperature and volume of ship traffic. Below, we discuss the trends from our study in more detail, and relate them to other relevant studies.

4.1. Environmental drivers

Wind speed had a relatively strong, positive effect on SPL, whereas both ice concentration and air temperature had curvilinear negative effects on SPL. There were also relatively weak negative interactions between ice concentration and wind speed and between ice concentration and air temperature, suggesting that increased ice concentration causes a decrease in the relationship between wind speed and SPL, and that the relationship between ice concentration and SPL varies depending on air temperature given that air temperature drives changes to ice, both by causing ice to melt and freeze, but also by changing the physical structure of ice. Air temperature on its own likely does not directly cause changes in SPL, but rather it indirectly impacts SPL by causing ice to make different sounds, which then influence SPL. These trends and effect sizes are consistent with previous, localized analyses of underwater sound levels at other sites in the western Arctic (Halliday

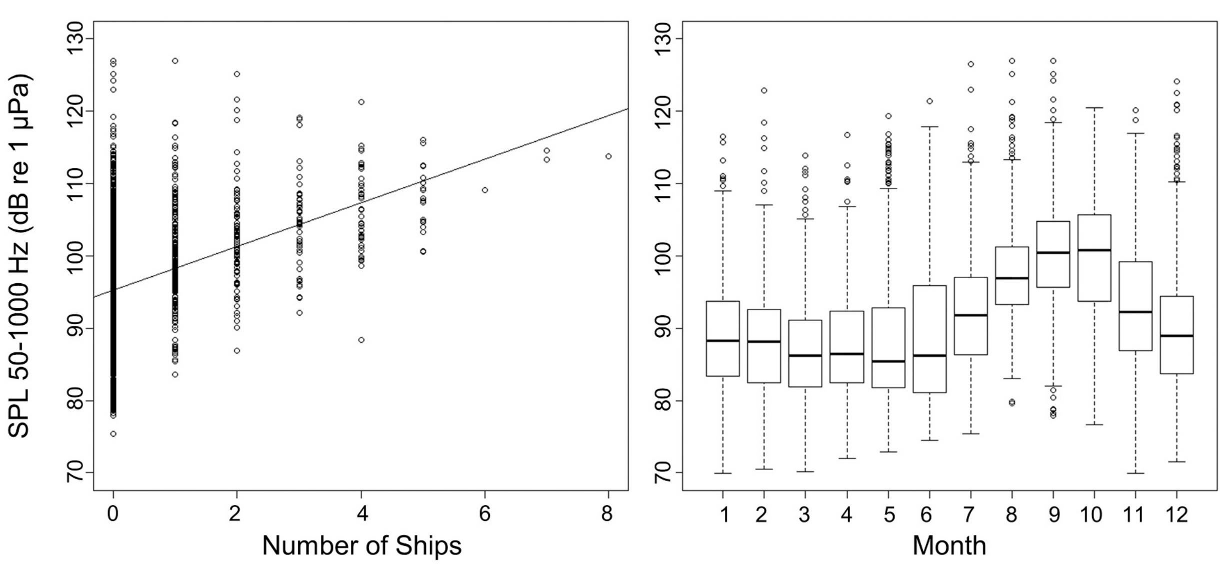

Fig. 4. Sound pressure level (SPL) in the 50–1000 Hz band by the number of ships within 10 km of the recorder (left) and month (right). The SPL by ship comparison (left) is based on data collected in the summer (July to September).

Table 3
Percent of days during the summer at each recording site where the daily sound pressure level in the 50–1000 Hz band and in the 63 Hz and 250 Hz 1/3-octave bands was ≥100, 110, or 120 dB re 1 μPa at each site during the summer (July to September). The sample size (N Days) of the number of days recorded, number of ships (N Ships), and mean N Ships/Day are also presented.

Site	50–1000 Hz			63 Hz		250 Hz		N Days	N ships	N ships/day
	100 dB	110 dB	120 dB	100 dB	110 dB	100 dB	110 dB			
Baffin Bay 1	45	10	0	2	0	6	0	51	7	0.14
Baffin Bay 2	30	4	1	2	1	3	1	182	32	0.18
Baffin Bay 3	25	2	0	2	0	1	0	87	14	0.16
Baffin Bay 4	100	24	0	21	0	17	0	29	7	0.24
Barrow Strait	48	5	0	3	0	1	0	253	13	0.05
Cape Bathurst	19	4	1	2	1	1	0	180	48	0.27
Gascoyne Inlet	26	11	2	0	0	0	0	176	37	0.21
Guys Bight	20	0	0	1	1	16	2	90	1	0.01
Low Island	30	5	1	4	1	3	1	199	186	0.93
Minto Inlet	6	1	0	0	0	0	0	70	2	0.03
Pond Inlet	46	7	0	9	0	4	0	261	507	1.94
Pearce Point	11	1	0	0	0	0	0	90	18	0.2
Sachs Harbour	12	0	0	0	0	0	0	203	12	0.06
Tremblay Sound	6	1	1	1	0	1	1	72	1	0.01
Ulukhaktok	36	4	1	1	0	3	0	130	37	0.28

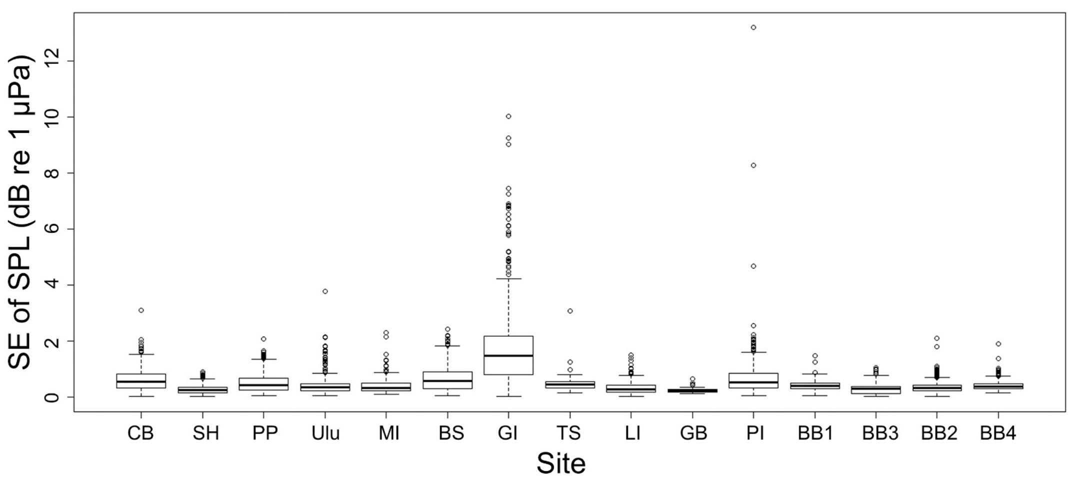

Fig. 5. Daily standard error (SE) around SPL in the 50–1000 Hz (dB re 1 μPa) band by recording site over the entire recording period. Sites are ordered by longitude, from west to east. Daily SE was calculated based on the SPL measurements used to calculate mean daily SPL. BB1–BB4 are four recording sites in Baffin Bay, BS = Barrow Strait (Resolute), CB = Cape Bathurst (Amundsen Gulf), GB = Guys Bight (Eclipse Sound), GI = Gascoyne Inlet, LI = Low Island (Milne Inlet, Eclipse Sound), MI = Minto Inlet (Amundsen Gulf), PI = Pond Inlet, PP = Pearce Point (Amundsen Gulf), SH = Sachs Harbour, TS = Tremblay Sound (southwest of Eclipse Sound), and Ulu = Ulukhaktok.

Table 4
Comparison of models using daily sound pressure level (SPL) (upper; $df = 318$) and 5-minute SPL (lower; $df = 7739$), with both examining the influence of wind speed, ice concentration, and their interaction on SPL.

Parameter	Estimate	S.E.	*t*	*p*
Daily mean SPL				
Intercept (dB)	89.77	2.15	41.76	<0.0001
Wind speed (dB/(km/h))	0.37	0.10	3.85	<0.001
Ice concentration (dB/%)	−0.16	0.02	6.48	<0.0001
Wind speed × ice concentration	0.0007	0.001	0.62	0.54
5-minute mean SPL				
Intercept (dB)	85.61	0.35	245.86	<0.0001
Wind speed (dB/(km/h))	0.44	0.01	29.84	<0.0001
Ice concentration (dB/%)	−0.12	0.004	28.26	<0.0001
Wind speed × ice concentration	−0.002	0.0002	13.15	<0.0001

et al., 2020b; Insley et al., 2017; Milne and Ganton, 1964; Roth et al., 2012). Wind speed is also an important driver of underwater sound levels across the entire world (Hildebrand, 2009; Wenz, 1962).

Our analyses focused on coarse, daily changes in SPL, as did the environmental variables that we used. Ice concentration alone, for example, does not account for many of the sounds made by ice (Kinda et al., 2015). Ice creates many different signals, in both low and high frequencies, and these are generated as ice forms and breaks up, and also when the ice is under stress during high wind (Kinda et al., 2015). Some of these sounds might have been captured by the interaction terms between ice concentration and wind speed and between ice concentration and air temperature. Previous studies have also demonstrated increased underwater sound levels in the marginal ice zone or at the edge of pack ice compared with under solid ice or in open water (Diachok and Winokur, 1974; Johannessen et al., 2003), thus showing that sounds created by ice can cause large increases in underwater sound levels. Another important source of environmental noise that we did not account for is flow noise, which may be associated with strong currents or tides (Haxel et al., 2013). Tide-driven flow noise, in particular, may vary greatly among the sites where we collected data. For example, in the western Canadian Arctic, tides are typically <1 m (Halliday et al., 2020c), whereas tides can be 8 m or more around southern Baffin Island (Environment and Climate Change Canada, 2017).

4.2. Ship traffic

There was a wide range in ship traffic across geographic sites, ranging from one ship in a season to more than one ship a day throughout the summer season. Most sites (13/15) had fewer than 0.3 ships/day (<3 ships every 10 days), which equates to fewer than 30 ships over the summer shipping season, and more than half of the sites (8/15) had fewer than 0.2 ships/day. These trends are consistent with other analyses of ship traffic across the Canadian Arctic (Dawson et al., 2017; Halliday et al., 2018b, 2021), where the majority of sites have relatively low traffic. Only a few exceptions occur within the Canadian Arctic, specifically in areas around a few industrial sites like the Mary River Iron Ore Mine, which is driving increased ship traffic through Eclipse Sound (e.g., Deployment IDs 36–39 in Table 1) and Baffin Bay. Indeed, the site from our analysis with the greatest ship traffic was near Pond Inlet where currently all of the traffic from the mine transits and where a higher proportion of cruise ships are present (Dawson et al., 2017).

In this analysis, we examined trends at the daily temporal scale, yet ships passing an acoustic recorder likely only cause large increases in underwater sound levels over tens of minutes. Much of the noise from ship traffic would therefore be averaged out with the daily SPL values that we used in this analysis. Indeed, this large variation in SPL across a day, caused by increased ship traffic, was detected in our analysis of standard error around daily SPL. Similarly, higher variability in daily mean SPL was observed when 0–2 ships came within 10 km of a recorder on a given day, compared to much lower variability when higher numbers of ships were present. Much of the variation when lower numbers of ships were present is related to natural variability in underwater sounds levels driven by changes in wind speed, combined with the likelihood that the brief noise input from a single ship is averaged out in our calculation of daily mean SPL. Conversely, for higher numbers of ships (i.e. 3–8), which were rare across our dataset, there is a higher probability that noise generated from those ships is not averaged out. In a recent analysis, Halliday et al. (2020b) also analyzed the influence of the number of ships within 10 km of an acoustic recorder at Ulukhaktok (Deployment ID 6 in Table 1) on 5-min SPLs in the 50–1000 Hz band, and found a relationship of 7.2 dB/ship within 10 km. This is more than double the effect size of the relationship found in the current study (3.2 dB/ship within 10 km). A large proportion of that difference is likely due to the daily temporal averaging that we used to make datasets comparable, but could also be due to different propagation conditions. While we show a strong trend that ship traffic is causing increased underwater noise, more detailed analyses are required at a finer temporal scale to truly assess how much underwater noise is being added to the Arctic soundscape by increased ship traffic.

Beyond the temporal scale, individual ships also vary significantly in their source levels and therefore the range at which they significantly raise SPL, where larger ships with higher source levels can raise SPL from much farther distances (such as 10 km) than smaller ships with lower source levels (Halliday et al., 2021). Ships traveling faster may also have higher source levels than similar ships traveling slower (MacGillivray et al., 2019). The received levels from ships will likely also vary significantly between sites based on local bathymetry and sound propagation characteristics, and the location of the particular ship in relation to the acoustic recorder (McDonald et al., 2006, 2008; Širović et al., 2016). There is a relatively wide range of ship types traveling through the Canadian Arctic, and all of these came within 10 km of our acoustic recorders. These ship types include large (>100 m) ships such as tankers, bulk carriers, and container ships, which likely have much higher source levels >180 dB re 1 μPa at 1 m (Halliday, 2021; Halliday et al., 2021), and smaller vessels such as coast guard ships, research vessels, icebreakers, tugs and barges, cruise ships, navy vessels, fishing vessels, and a variety of recreational vessels from small boats with outboard engines to larger private yachts. The source levels of these small vessels can be quite variable, ranging between 160 and 180 dB re 1 μPa at 1 m (Halliday, 2021; Halliday et al., 2021). Although icebreakers were present in our dataset, and icebreakers that are actively breaking ice can have very high source levels between 190 and 200 dB re 1 μPA at 1 m (Erbe and Farmer, 2000), most icebreakers in our data would not have been breaking ice, except in Eclipse Sound for the management of ice for mine-related traffic (Jones, 2021).

4.3. Site differences

Our analysis of mean daily SPL showed no obvious differences among sites that are not explained by wind speed, ice concentration, hydrophone depth, and ship traffic. Longitudinally, sites in the western Arctic were not significantly different from sites in the eastern Arctic (see Fig. 3, which is arranged by longitude), and deeper sites were not significantly different from shallow sites. However, when water depth was examined on its own, SPL tended to be lower at deeper sites (Fig. 2). In a subsequent analysis that we do not report on here, we found that proximity to land and exposure (in degrees) to the open ocean (exposure to water with >100 km to nearest land) were also not good predictors of sound levels (Halliday, unpub. data). The Baffin Bay 4 and Gascoyne Inlet sites had the highest mean SPL levels of any site, especially during the summer. These two sites are quite different: Gascoyne Inlet is close to land (~2 km) and is exposed to the Parry Passage in the east and west; Baffin Bay 4 is farther from land (~15 km) and is fully exposed to Baffin Bay for 180°. For Baffin Bay 4 in particular, the summer values are based on only 29 days of data (i.e. small sample size), and did not include a large amount of ship traffic. This site may simply be exposed to more noise propagating in from southern Baffin Bay, increased flow noise from the large tides in that area, strumming of the mooring line, instrument self-noise, or could also be linked to increased vessel traffic that is not included in the AIS data or by noise from distant seismic airgun surveys from the North Atlantic. Instrument self-noise and mooring line strumming are both important considerations that were not controlled for in this analysis. Strumming noise, for example, can elevate mean SPL more than 10 dB above actual underwater sound levels, and this effect is more prominent under high wind conditions (Halliday, *unpublished data*). More detailed analysis within these specific datasets is required to identify why they frequently had higher SPL values than all other sites. Beyond the differences in mean daily SPL among sites, some sites also differed markedly in standard error (SE) around daily SPL (Fig. 5). Gascoyne Inlet in particular showed the most extreme variability in SE, and by far had the highest SE out of any site in this study. This is likely an artefact of the extreme duty cycle (1 min recording every 2 h) used at this site, which may also be related to the high mean daily SPL values at this site.

4.4. Biological sounds

Some of the differences among sites may be due to variation in the presence of biological sounds. Marine mammals (excluding polar bears, *Ursus maritimus*) all produce underwater vocalizations, and if there are enough individuals vocalizing and they are close to an acoustic recorder, their vocalizations could significantly elevate underwater sound levels. The Canadian Arctic has six endemic Arctic marine mammal species (excluding polar bears), including bowhead whales, beluga whales, narwhal, bearded seals, ringed seals (*Pusa hispida*), and walrus (*Odobenus rosmarus*), two species of sub-Arctic ice seals (harp seals, *Pagophilus groenlandicus*, and hooded seals, *Cystophora cristata*), and a number of sub-Arctic species that migrate into Arctic waters, particularly in Baffin Bay, including sperm whales (*Physeter macrocephalus*), northern bottlenose whales (*Hyperoodon ampullatus*), fin whales (*Balaenoptera physalus*), and killer whales (*Orcinus orca*) (Laidre et al., 2015). These species can generally be lumped into pinnipeds (all of the seals), low frequency cetaceans (bowhead whales and fin whales), and medium-high frequency cetaceans (all remaining cetaceans) (Southall et al., 2007). Low frequency cetaceans produce vocalizations at frequencies typically <1 kHz, although bowhead singing can go higher (Tervo et al., 2012), whereas medium-high frequency cetaceans produce higher frequency whistles and pulsed calls (500 Hz to 10 kHz) and much higher frequency echolocation clicks (20 kHz to >100 kHz) (Southall et al., 2007). Pinnipeds produce a variety of vocalizations ranging between 50 Hz and 10 kHz (Southall et al., 2007). Within the Arctic, beluga whale and bearded seal vocalizations have both been quantitatively shown to increase underwater sound levels within the important frequency ranges for their species (10–48 kHz for belugas, 50 Hz to 10 kHz for bearded seals) (Halliday et al., 2020c; Heimrich et al., 2021). Presumably, vocalizations of the other above marine mammal species could similarly cause increases in underwater sound levels if they were present in large numbers and actively vocalizing. Vocalizations produced by these marine mammals will vary seasonally depending on both the purpose of the vocalization behaviours, as well as variation in propagation. For example, under ice, higher frequency sounds do not propagate as effectively due to increased scattering caused by the ice (Au and Hastings, 2008).

There are a number of known hotspots for Arctic marine mammals throughout the Canadian Arctic that overlap with our acoustic recording sites (Yurkowski et al., 2019). Bowhead whales are known to congregate near our recording sites at Cape Bathurst and along the east coast of Baffin Island (Citta et al., 2015; Harwood et al., 2017; Yurkowski et al., 2019), narwhal are known to congregate in Eclipse Sound (Doniol-Valcroze et al., 2020) which contains four sites and multiple years of data included in this study, and bearded seal vocalizations saturate the soundscape during the late winter and spring at recording sites near Sachs Harbour (Halliday et al., 2018a; Heimrich et al., 2021) and Cape Bathurst (Halliday, unpublished data), and likely at other sites where their vocalizations have not been quantified. Based on these known congregation areas, we might expect peaks in the 50–1000 Hz bandwidth during April to June (the bearded seal breeding season) at Sachs Harbour and Cape Bathurst, and likely other sites where bearded seals congregate, as well as peaks during the spring and summer months when bowhead whales congregate at Cape Bathurst and eastern Baffin Island. Although narwhal congregate in Eclipse Sound during the summer, their vocalizations may have limited impact on the 50–1000 Hz bandwidth since most vocalizations are at higher frequencies. Beluga whale pulsed calls, however, have been shown to affect underwater sound levels below 1 kHz (Halliday et al., 2020c). Consequently, it is possible that narwhal in close proximity to the acoustic recorder could drive elevated underwater sounds levels in the 50–1000 Hz band, since they produce similar vocalizations (Marcoux et al., 2012). In the current study, we were unable to quantify marine mammal vocalizations (i.e. biological sounds) consistently across all datasets, so future work is required to address this point. We therefore caution that some of the differences in SPL seen among these sites are likely caused by biological sounds, especially for those that are known hotspots for certain species.

Biological sounds levels might also be impacted by changes to underwater sound levels in the future, particularly those caused by anthropogenic noise. Many Arctic marine mammals have been shown to change their behaviour in response to anthropogenic underwater noise, including a flee response to the noise source (Halliday et al., 2020a). This change in behaviour could cause a reduction in biological sounds at sites with increased anthropogenic activity, and an increase in biological sounds in areas where the animals are redistributed to. For example, a recent study of beluga vocalizations showed a reduction in recorded vocalizations when ships were located within 5 km of the acoustic recorder. These data indicated that belugas were actively avoiding ships and therefore their vocalizations were no longer recorded at the site (Halliday et al., 2019).

4.5. Acoustic indicators of underwater noise

There are a number of different acoustic metrics that could be used to assess underwater sound levels and the influence of anthropogenic noise on the soundscape, including sound exposure level (SEL), continuous equivalent energy level (Leq), SPL, and exceedance percentiles, and all of these metrics can focus on different bandwidths. In this study, we have attempted to present a number of indicators that we believe to be useful for comparison with future studies, all based on daily SPL in three different bandwidths. However, the best way to examine changes in underwater sound levels through time or differences between sites is simply to design a study that includes using archived data, as undertaken in this study, and applying the same, consistent measurements and indices to all datasets. Without explicit guidelines on which metrics to use (PAME, 2019), there will continue to be variability among studies for which metrics are used, making comparisons between studies very difficult. The field of acoustics continues to advance, and guidelines, thresholds, and standards are constantly evolving. We therefore encourage those who are collecting acoustic data to strive to be collaborative, and share their archived acoustic data with those attempting to monitor changes to the world's underwater soundscapes.

Martin et al. (2019) recently recommended that daily SEL be the main indicator of underwater sound levels because SEL can allow acousticians to differentiate between soundscapes that are natural versus those dominated by anthropogenic noise (i.e. anthropogenic soundscape typically have much higher SEL values), and SEL (frequency weighted) is typically used in assessments of the impact of anthropogenic noise on marine life. While we generally agree with this idea, computing SEL from a variety of archived and disparate acoustic datasets such as the ones presented in this study has limited usefulness. For example, Martin et al. (2019) recommend a minimum sample rate of 64 kHz and a minimum duty cycle of 1 min of recording every 30 min, an excellent suggestion for future data collection but one that, if applied as a criteria, would leave only two-thirds of the datasets used in this study. Comparing measurements of SEL across datasets would require matching all datasets to the most extreme duty cycle across the datasets because SEL is a metric of the accumulation of sound level through time. Implementation of this metric would restrict our analysis to 1 min of acoustic data every 2 h, and as seen by the large SE values for the dataset with the most extreme duty cycle, this likely would have led to large biases in the results. Unlike SEL, SPL allowed us to compare across more datasets, which we think is useful in a study like this attempting to fill geographic gaps. Further work should compare various acoustic metrics across sites in the Arctic to determine which metrics are best suited for different research questions.

Beyond metrics of the soundscape, both broadband and 1/3-octave level measurements of SPL are used for the evaluation of behavioural disturbance and masking potential for marine mammals. We have already mentioned the 120 dB behavioural disturbance threshold used by the US National Oceanic and Atmospheric Administration (National Marine Fisheries Service, 2016; Southall et al., 2007), which is based on unweighted broadband levels. Masking potential is often examined within the 1/3-octave bands that are important for communication (hearing and vocalizations) for a particular species. The 1/3-octave bands that we used in this study are particularly important for three species of Arctic marine mammals: bowhead whales, ringed seals, and bearded seals, because the 250-Hz 1/3-octave band, and to a lesser extent the 63 Hz 1/3-octave band, overlaps with the vocalizations of all of these species (Cleator et al., 1989; Cummings and Holliday, 1987; Ljungblad et al., 1982; Stirling et al., 1983). The two Arctic odontocete whales, beluga and narwhal, have much higher hearing ranges and vocalizations than all other Arctic marine mammals, although their pulsed calls do go below 1 kHz and might have some overlap with the 250 Hz 1/3-octave band (Marcoux et al., 2012; Sjare and Smith, 1986), but masking potential would be much lower for these species compared to bowhead whales and seals. Future studies interested in masking potential for odontocetes would need to use higher-frequency 1/3-octave bands than we used in this study.

4.6. Conclusions and future changes to underwater sound levels

We have conducted a novel analysis of underwater sound levels from multiple sites across the Canadian Arctic, which has filled many geographic gaps in our knowledge of underwater sound levels across the region. This research builds on earlier analyses of underwater sound levels across the Arctic that have typically been based on either short recordings across multiple sites (Ganton and Milne, 1965; Hutt, 2012; Milne and Ganton, 1964) or longer recordings from a small number of localized sites (Halliday et al., 2020b, 2020c; Insley et al., 2017; Kinda et al., 2013; Roth et al., 2012; Southall et al., 2020). The results from this study can serve as a useful baseline for future studies, which is particularly important given the rapid changes in sea ice and ship traffic that are currently occurring throughout the Arctic. Although our analysis covered a large number of sites throughout the Canadian Arctic, many geographic gaps still exist that have no published studies of underwater sound levels. The Kitikmeot Region (south and east of Victoria Island), Gulf of Boothia and Foxe Basin, Hudson Bay and Hudson Strait, and further north into the High Arctic and 'Last Ice Area' are all areas from the Canadian Arctic with no published studies of underwater sound levels. For a more complete understanding of underwater sound levels throughout the Canadian Arctic, these geographic gaps should be filled.

Climate driven changes will likely lead to a longer open water season, as well as less solid ice during the winter, leading to both direct and indirect effects on underwater sound levels. These changes in sea ice will very likely lead to increased underwater sound levels overall, but especially during spring and autumn due to early melt and later freeze-up, respectively. In this study, we found increased underwater sound levels in August–October (Fig. 4), but in the future, this will likely expand into July and November due to reduced sea ice and increased shipping in both of these months. Winter SPL may also not stay as low as they currently are. For example, sites that were under solid, land-fast ice tended to have much lower SPL than sites with mobile winter ice and, under warming scenarios, there may be less solid land-fast ice in the future. Ship traffic is also forecasted to continue increasing in the Arctic, which could lead to more ships per day at each site, as well as more consistent ship traffic throughout the entire open water season. We demonstrated a strong positive relationship between the number of ships per day and underwater sound levels and if ship traffic increases, we can expect more sites to have higher numbers of ships per day and therefore higher sound levels. Given these predictions of increased underwater sound levels, acoustic monitoring should continue into the future to track these changes through time.

CRediT authorship contribution statement

William D. Halliday: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Supervision, Project administration. **David Barclay:** Methodology, Investigation, Data curation, Writing – review & editing, Supervision, Project administration. **Amanda N. Barkley:** Investigation, Writing – review & editing. **Emmanuelle Cook:** Formal analysis, Investigation, Writing – review & editing. **Jackie Dawson:** Resources, Data curation, Writing – review & editing, Project administration. **R. Casey Hilliard:** Investigation, Data curation, Writing – review & editing. **Nigel E. Hussey:** Investigation, Writing – review & editing, Project administration. **Joshua M. Jones:** Methodology, Formal analysis, Investigation, Data curation, Writing – review & editing. **Francis Juanes:** Resources, Writing – review & editing, Project administration. **Marianne Marcoux:** Investigation, Data curation, Writing – review & editing, Supervision, Project administration. **Andrea Niemi:** Investigation, Writing – review & editing, Project administration. **Shannon Nudds:** Investigation, Writing – review & editing. **Matthew K. Pine:** Investigation, Writing – review & editing. **Clark Richards:** Investigation, Writing – review & editing, Supervision, Project administration. **Kevin Scharffenberg:** Investigation, Formal analysis, Writing – review & editing. **Kristin Westdal:** Investigation, Data curation, Writing – review & editing, Project administration. **Stephen J. Insley:** Conceptualization, Investigation, Resources, Writing – review & editing, Supervision, Project administration.

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.

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