Underwater Noise in the Arctic

A State of Knowledge Report

PAME
Protection of the Arctic Marine Environment

ARCTIC COUNCIL

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Executive Summary

The Arctic region is a unique environment when it comes to underwater noise and the potential impacts that increasing noise levels could have on animals in the Arctic. There are a number of factors which contribute to its uniqueness compared to non-Arctic waters, including the sources of ambient sound, and how ice cover can affect sound propagation properties. The Arctic is also home to a number of endemic marine species, many for which the making, hearing, and processing of sounds serve critical biological functions, including communication, foraging, navigation, and predator-avoidance. Most importantly, the culture and livelihoods of Indigenous Peoples in the Arctic depend on the continued health of marine mammals, to a greater degree than in other regions of the world.

The issue of underwater noise and its effect on marine biodiversity has received increasing attention, with recognition by international and regional agencies, commissions and organisations. These include the Convention of Migratory Species (CMS), the Convention on Biological Diversity (CBD), the International Whaling Commission (IWC), the International Union for Conservation of Nature (IUCN), the International Maritime organization (IMO), the United Nations General Assembly (UNGA) and United Nations Convention on the Law of the Sea (UNCLOS), the European Parliament and European Union, the OSPAR Convention for the Protection of the Marine Environment of the North-East Atlantic and the Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM).

Internationally, work is currently underway in numerous fora to better understand the impacts and identify ways to mitigate the effects of underwater noise, including at the IMO, IWC, and at the United Nations more generally. In the 2009 Arctic Marine Shipping Assessment (AMSA) PAME first identified the issue of underwater noise as one which required further focus in the Arctic context, finding that *"sound is of vital biological importance to most, if not all, marine vertebrates and anthropogenic noise produced through shipping can have various adverse effects on Arctic species."* PAME subsequently recommended that Arctic States engage with relevant international organisations to further assess the effects of ship noise on marine mammals, and to consider developing and implementing mitigation strategies.

Due to the recent activities on this topic, PAME decided to complete this State of Knowledge Review on Underwater Noise in the Arctic in order to get a baseline understanding of underwater noise in Arctic regions, including ambient sound levels, underwater noise created by anthropogenic activities, and impacts of underwater noise on marine life, including marine mammals, fish, and invertebrates.

This report is intended to be used as an overview of the current scientific knowledge on underwater noise in the Arctic. However, in the undertaking of this work, it has become clear that there are many gaps in this knowledge which, if addressed, could lead to a more comprehensive understanding of the effects of underwater noise on species of interest. That being said, this review will serve as a useful basis for which to consider where to focus future work and resources in both studying the issue of underwater noise in the Arctic context and in considering possible approaches in terms for mitigation strategies in reducing the effects or impacts of underwater noise on the Arctic marine environment and marine species.

Michelle Munkittrick - C3

State of the Knowledge

Ambient or baseline underwater sound levels are generally lower in the Arctic than in non-polar regions. There are two main reasons for this. First, the presence of solid sea ice for at least part of the year effectively isolates the underwater environment from most weather-related noise sources. Second, compared with other regions there is less noise-producing anthropogenic activity in the Arctic, largely because of the limited accessibility due to sea ice. Ambient sound levels in the Arctic are typically higher in the summer than in the winter, and also vary geographically, with levels in the Beaufort and Chukchi Seas being lower than levels in the Greenland Sea, for example. Arctic ambient sound levels are driven largely by natural physical processes (sea ice and wind), but are also influenced by marine mammals, such as mating calls from bearded seals and songs of bowhead whales.

Anthropogenic activities such as shipping and other vessel traffic, the use of seismic airguns, and underwater drilling can also impact ambient sound levels. These sources are generally limited to summer months when sea ice is less extensive. Multiple studies have documented noisy anthropogenic activities in the Arctic, and source levels for these activities are similar to those in non-Arctic regions. One activity that is unique to ice-covered waters such as the Arctic is ice breaking, which typically has higher source levels than the noise from more common vessel activity due to the act of breaking ice by ramming into it or from other equipment used to break ice.

Arctic marine animals are likely impacted by underwater anthropogenic noise in similar ways to non-Arctic animals; however, specific impacts are highly dependent on species and context. Many Arctic animals may have a lower threshold for the onset of behavioral responses due to the lower ambient sound levels and less exposure to anthropogenic noise, and thus less chance to habituate. Studies on Arctic marine mammals have mostly focused on behavioural impacts of anthropogenic noises (e.g., changes in diving, breathing cycles, and calling rates), with only four studies on hearing damage and the impacts of noise on cardiorespiratory responses. Only two studies were found on the impacts of noise on Arctic marine fishes, and no studies were found on the impacts of noise on Arctic marine invertebrates.

Knowledge gaps identified in this review include geographic gaps, taxonomic gaps, and methodological gaps, but results from this review are limited to studies that were in English and either publicly available or made available for this review. Geographically, studies on ambient sound measurements were only found in the Bering, Chukchi, Beaufort, Greenland, and Barents Seas, as well as in the central Arctic Ocean. Measurements of the source levels of anthropogenic noise and studies of the impacts of noise of marine animals were only found in the North American Arctic and the Norwegian Arctic. Much of the Arctic remains understudied or unstudied. Taxonomically, the majority of studies on noise impacts for marine animals focused on bowhead whales, with a small number on beluga, narwhal, and ringed seals, and two studies on Arctic marine fishes: Arctic cod (*Boreogadus saida*) and shorthorn sculpin.

Key Findings

- Ambient sound levels are generally lower in the Arctic Ocean than in other oceans, although there is a high amount of seasonal and geographic variability across the Arctic.
- Ambient sound levels in the Arctic are driven, in large part by sea ice, but also by sound from wind and waves, animal vocalizations, and anthropogenic activities.
- The most commonly cited sources of anthropogenic underwater noise in the Arctic are from vessel traffic and oil and gas exploration activity; vessel activity has been increasing throughout the Arctic, and may lead to increased underwater noise, whereas oil and gas exploration activities vary greatly in space and time throughout the Arctic, and have not been increasing as a whole.
- Bowhead whales have been the main focus for studies on the impacts of underwater noise on Arctic marine mammals, and have been found to generally avoid seismic airgun noise and noise from other oil and gas activities. Bowheads also change their vocal behaviour in response to these noises. Beluga whales and Narwhal have both been found to react to noise from icebreakers. Ringed seals appear more tolerant of underwater noise than whales are, but do still avoid relatively intense noises.
- Only two studies have examined the impact of underwater noise on Arctic marine fishes, and both species, Arctic Cod and Shorthorn Sculpin, adjusted their home ranges and movement behaviours in response to noise from vessels.
- No studies have examined the impacts of underwater noise on Arctic marine invertebrates.
- Many knowledge gaps exist for underwater noise in the Arctic, including large geographic areas with no studies and a large number of species that have not been studied.

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Glossary of Terms

Absorption: An object takes in sound energy when sound waves encounter it. Contrast with reflection below.

Acoustic masking: Noise that overlaps with the hearing sensitivity of a species, reducing their ability to effectively receive a signal of interest. Example: noise from a passing ship at 200 Hz overlapping with bowhead whale vocalizations at 200 Hz.

Ambient sound: All sound in the ocean that is not the desired signal that a receiver is trying to hear. Anthropogenic sounds do contribute to ambient sound levels. "Ambient noise in the ocean is the sound field against which signals must be detected" (Hildebrand 2009, p. 5). Also known as background noise and ocean ambient noise. Typically measured as power spectral densities in 1 Hz frequency bands, but can also be measured as sound pressure levels in various frequency bands.

Audiogram: A representation of the hearing sensitivity of an animal across a range of frequencies.

Bandwidth: Frequency range (measured in Hz or kHz). Often in context of hearing capabilities (an animal can hear within a specific frequency range), or in context of a measurement of sound, such as sound pressure level.

Barotrauma: Injury caused by a difference in pressure between a gas space inside the body or in contact with the body and the gas/liquid outside the body. Barotrauma in fish occurs in the swim bladder, whereas barotrauma in marine mammals may occur in the ear cavity.

Cavitation: The rapid formation and collapse of bubbles. In reference to noise from shipping, cavitation is caused by a spinning propeller, which rapidly creates small bubbles as it rotates, which then collapse and make noise.

Continuous noise: Noise which remains constant and stable over a given period. Examples of continuous anthropogenic underwater noise include vessel noise and drilling noise (contrast with impulsive noise below).

Decibel (dB): A measure of the relative amplitude of acoustic signals, measured on a logarithmic scale. Underwater, the reference level is always 1 μPa (micro Pascal). For comparison, sound measured in air has a reference level of 20 μPa.

Frequency: Physical definition: the rate of oscillation or vibration, measured in hertz (Hz) or kilohertz (kHz). Psychoacoustic definition: the tone or pitch of an acoustic signal.

Impulsive noise: A very short, high-intensity burst of noise, with a very quick start and stop. Examples of impulsive anthropogenic underwater noise include pile driving and seismic airguns.

Power spectral density (PSD): The distribution of power across a range of frequencies, measured at a single Hz. Measured in dB re 1 μPa^2/Hz.

Received level: The sound pressure experienced by a receiver (i.e. animal or recording device). Initially measured as a power spectral density across a range of frequencies (in dB re 1 μPa^2/Hz), and often summarized into a broadband sound pressure level across some range of frequencies (in dB re 1 μPa).

Reflection: A sound pressure wave bounces off an object/surface.

Refraction: A sound pressure wave bends due to differential speed along the wavefront.

Soniferous: An animal that can actively produce sound.

Source level: The sound pressure of some noise-emitting activity, measured at 1 m distance from the source. Initially measured as a power spectral density across a range of frequencies (in dB re 1 μPa^2/Hz at 1 m), and often summarized into a broadband sound pressure level across some range of frequencies (in dB re 1 μPa at 1 m).

Sound pressure level (SPL): The sum of sound pressure within some band of frequencies. Measured in dB re 1 μPa in water.

Sound speed profile: The speed at which sound waves can travel at different depths through the water column and bottom sediment. Also known as sound velocity profile.

Threshold Shift, Permanent (PTS): An animal's hearing sensitivity is permanently decreased by a noisy event.

Threshold Shift, Temporary (TTS): An animal's hearing sensitivity is temporarily decreased by a noisy event.

Glossary of Acronyms

CAFF: Conservation of Arctic Flora and Fauna

dB: decibels

dB_{med}: decibels for a source level measurement, measured using median values

$dB_{peak\text{-}to\text{-}peak}$: decibels for a source level measurement, measured using the peak-to-peak method

dB_{rms}: decibels for a source level measurement, measured using root mean squared values

$dB_{zero\text{-}to\text{-}peak}$: decibels for a source level measurement, measured using the zero-to-peak method

Hz: Hertz

IMO: International Maritime Organization

IWC: International Whaling Commission

kHz: kiloHertz

NWP: Northwest Passage

NSR: Northern Sea Route

PAME: Protection of the Arctic Marine Environment

PSD: power spectral density

PTS: permanent threshold shift

re: reference

RMS: root mean squared

SOFAR: Sound Fixing and Ranging

SPL: sound pressure level

TTS: temporary threshold shift

μPa: micro Pascal

General Introduction

Underwater Noise

Sound is important for many marine animals in the same way that light perception (e.g., vision) is important for humans and many terrestrial species. Marine animals can only see over short distances, whereas they can hear sounds over great distances. Many marine animals rely on sound for communication, predator and prey detection, and some marine animals use sound for echolocation (i.e. odontocete whales). The impact of anthropogenic noise on marine animals has received increasing attention over the past several decades (NAS [National Academy of Sciences] 2017). Most attention has focused on marine mammals rather than fish and invertebrates. However, to date, despite a significant amount of attention, there are still many questions about how noise impacts marine animals; acute effects (i.e. hearing damage, behavioural response) are better understood than chronic effects. Moreover, there is even less clarity on how noise affects marine animals in the Arctic, one of the last largely acoustically pristine environments on the planet, although even within the Arctic, there is a high amount of variability in the acoustic environment.

Underwater noise from anthropogenic activities is a growing concern globally. In temperate regions, low frequency underwater noise has been increasing by as much as 2.5 to 3 dB re 1 μPa per decade since the 1960s (Andrew et al. 2002; McDonald et al. 2006; Chapman and Price 2011), with a slight decrease in recent years, presumably due to better ship design (Chapman and Price 2011). Since decibels are on a logarithmic scale, this increase of 3 dB is a doubling of power every decade. These increasing noise levels can be attributed almost entirely to increased motorized shipping. Seismic airguns have been shown to temporarily increase noise levels in some locations, as demonstrated at a site near the equator in the Atlantic Ocean (Haver et al. 2017). Noise from both shipping and seismic airguns can propagate over long distances. Noise from vessels has been detected > 100 km away (Halliday et al.

2017) and noise from seismic airguns can be detected as far as 1300 km away (Thode et al. 2010). Increasing underwater noise levels can impact the ability of marine animals to hear and use sound (Erbe et al. 2016), and can also represent a chronic stressor for individuals (Rolland et al. 2012).

Another pressing concern about underwater noise is how noisy individual anthropogenic activities can be, where they are taking place, and how those noises can impact marine life. Underwater noise can be divided into two broad categories: impulsive noise and continuous noise. Impulsive noise occurs over a very short period of time, with very quick start and stop times; these individual bursts of energy can be repeated over long durations. Examples of impulsive anthropogenic underwater noise include explosions, pile driving, seismic airguns, and certain types of sonar. Continuous noise lasts for longer periods of time, often with gradual changes in amplitude. If impulsive noises occur frequently, they may effectively be continuous, especially at greater distances from the source. Examples of continuous anthropogenic underwater noise include vessel noise and drilling noise. Noise can also have acute or chronic effects. Acute effects can occur over short time periods, in some cases instantaneously, whereas chronic effects occur over a long time period. Intense impulsive noises can cause temporary or permanent hearing damage in marine animals, and both impulsive and continuous noises can cause increased stress levels, behavioural disturbance, and acoustic masking, especially if an animal is exposed over long periods. Posited thresholds for these impacts are species- and context-specific (Southall et al. 2007; Gomez et al. 2016) and better established for well-studied species.

Underwater Noise in the Arctic

The Arctic is changing rapidly. Summer sea ice extent has been decreasing in recent years (Stroeve et al. 2007; Arctic Council 2017), and sea ice is breaking up earlier and forming later every year (Parkinson 2014, Stroeve et al 2014). Decreases in sea ice coupled with high wind events may be increasing the overall ambient noise levels in the Arctic (e.g. Miksis-Olds et al. 2013). These decreases in sea ice are allowing increased access for anthropogenic activities, especially for vessel traffic (Arctic Council 2009; Ho 2010; Pizzolato et al. 2014, 2016). The two main shipping routes through the Arctic are the Northern Sea Route (NSR) along the north coast of Russia, and the Norwest Passage (NWP) along the northern coast of Canada and Alaska (Arctic Council 2009). Significant vessel traffic also occurs between Europe and Svalbard (Arctic Council 2009). Vessel traffic also occurs outside of conventional shipping routes because of a wide variety of activities including fishing, community re-supply, mining, tourist and pleasure craft traffic, and military exercises. Oil and gas activities can occur throughout the Arctic (Arctic Council 2007; Reeves et al. 2014), but their occurrence varies greatly from year to year. While oil and gas operations involve noisy activities such as seismic airguns, drilling, and construction, their influence on overall noise levels will depend on the amount of activity occurring at a given time.

The Arctic is home to eleven marine mammal species (Conservation of Arctic Flora and Fauna [CAFF] 2017), seven of which are endemic to the Arctic: ringed (*Pusa hispida*) and bearded seals (*Erignathus barbatus*), walrus (*Odobenus rosmarus*), narwhal (*Monodon monoceros*), bowhead (*Balaena mysticetus*) and beluga whales (*Delphinapterus leucas*), and the polar bear (*Ursus maritimus*). Four additional species are ice-obligate sub-Arctic species: harp seals (*Pagophilus groenlandicus*), hooded seals (*Cystophora cristata*), spotted seals (*Phoca largha*), and ribbon seals (*Histriophoca fasciata*). Many other species of marine mammal also migrate to the Arctic during the ice-free season (see section 4.1 for a comprehensive list). Six hundred and thirty three species of marine fish have been reported in the Arctic (CAFF 2017), as well as > 4000 species of marine benthic invertebrates and ~350 species of zooplankton (CAFF 2017). All of these Arctic marine animals have the potential to be most impacted by underwater noise.

Scope

This report reviews the state of knowledge of underwater noise in Arctic regions, including ambient sound levels, underwater noise created by anthropogenic activities, and impacts of underwater noise on marine life, including marine mammals, fish, and invertebrates. This report does not exhaustively review literature from non-Arctic regions, but uses examples from non-Arctic regions for comparison or when no information is available for the Arctic. This report is intended to be used as an overview of the current scientific knowledge on underwater noise in the Arctic, but as noted in the summary subsections and summarized at the end of the review, there are many gaps in this knowledge which, if addressed, could lead to a more comprehensive understanding of the effects of underwater noise on species of interest. This review does not consider measures to mitigate underwater noise or assess the efficacy of those measures.

This report is limited by the accessibility of articles and reports. Peer reviewed articles that were accessible through various online academic search engines (e.g., Google Scholar, Web of Science) are included in this review, as well as other documents, such as internal reports and grey literature provided by organizations or governments. Documents or lists of literature were provided by many Protection of the Arctic Marine Environment (PAME) member states and organizations in response to the request for literature, which has made this review more comprehensive. This review is also limited to reports available in English. It is therefore entirely possible that some pertinent studies were not included. This review did not discriminate against older studies, as long as the science was sound and the results were informative.

In this review, any place north of the Arctic Circle (66°33'30" N) is considered to be in the Arctic, but as in the Arctic Council's Arctic Marine Shipping Assessment (Arctic Council 2009), areas just south of the Arctic Circle, such as Hudson's Bay and the Bering Sea, are also considered if they are important areas for Arctic marine animals.

(c) Gord Carter - C3


(c) Rory

Arctic Ocean Ambient Sound

Sound Propagation in the Arctic

The propagation characteristics of the water column (i.e. sound speed profile) have important implications for how far different sounds will travel, and therefore influence ambient sound levels and zones of impact around anthropogenic activities. Sound propagation in the Arctic differs from non-polar regions in two ways. First, sea ice affects how sound waves propagate through the water column (Au and Hastings 2008). High frequency sound waves that hit the underside of sea ice tend to attenuate by scattering caused by repeated reflection. Sound waves travelling near the surface of the water column in ice-covered water will therefore not propagate as far as sound waves travelling deeper in the water column or as far as sound waves travelling near the surface in ice-free water. Second, Arctic waters have a very different sound speed profile than in non-polar regions, which is typically caused by a layer of freshwater near the surface (Urick 1983) or by layers with different temperatures (Au and Hastings 2008). The shape of this sound speed profile causes sound waves to refract towards the surface, where sound pressure waves refract back down. This refraction up and down creates the Arctic sound channel, where sound waves tend to get trapped within a certain layer of the water column (100 to 300 m) and propagate farther than if they weren't trapped in this channel (Au and Hastings 2008). This means of enhanced sound propagation is different from what has been termed the deep sound channel or Sound Fixing and Ranging (SOFAR) channel. In the SOFAR channel, sounds produced near the point where the sound speed profile changes directions (ca. 1000 m) refract up and down around that point and so travel long distances without striking the surface or ocean floor (Au and Hastings 2008). This point of change in sound speed is comparatively very close to the surface in the Arctic (100 to 300 m), which does not allow an effective SOFAR channel to form (Urick 1983; Au and Hastings 2008). Sound propagates much farther in the SOFAR channel compared to the Arctic sound channel because sound waves in the SOFAR channel only interact with water, whereas sound waves in the Arctic sound channel may also interact with the ice, and therefore attenuate more. However, the Arctic sound channel does allow for farther propagation distances at shallow depths (100 to 300 m) compared to non-polar regions. Frequencies between 15 and 30 Hz travel most efficiently through the Arctic sound channel, and high frequency sounds do not propagate as far as lower frequency sounds (Buck 1968), which is similar for the SOFAR channel (Au and Hastings 2008). Frequencies below 15 Hz are not effectively propagated through the Arctic sound channel. One study also predicts that the Arctic sound channel will become more efficient for higher frequency sounds in the future as climate change causes increased ocean acidification (Duda et al. 2016; Duda 2017). The pH of the ocean causes increased absorption in frequencies between 400 and 5000 Hz, but a decreasing pH caused by ocean acidification may reduce absorption, and allow sounds within those frequencies to propagate farther, with the greatest increase (nearly 40%) in propagation distance around 900 Hz (Dura 2017).

Arctic Ocean Ambient Sound Levels

There are multiple ways to measure ocean ambient sound levels. Sound data are converted into power spectral densities (PSDs) in 1 Hz bins, and are often summarized using percentiles and root mean squared averages. Sound data are also summarized into broadband sound pressure levels (SPLs) across some frequency bandwidth. However, the specific bandwidth that researchers use can vary greatly between studies. For example, Insley et al. (2017) calculated SPLs within a 50 to 1000 Hz bandwidth, whereas Haver et al. (2017) calculated SPLs within a 15 to 100 Hz bandwidth. Researchers vary these bandwidths based on the capability of their recording system, the quality of their data, and the specific research question that they are trying to answer. This varying bandwidth makes a comparison of SPLs between studies difficult. In order to accurately compare between larger numbers of studies, it is necessary to compare PSDs rather than SPLs, therefore this review is limited to comparing between studies that presented PSDs.

Multiple studies have collected long-term (i.e. multiple months) underwater acoustic measurements with detailed analyses over a wide frequency range in various regions throughout the Arctic (Figure 1). See Table 1 and Figure 2 for median PSD values at multiple frequencies for these studies. The majority of these studies took place in either the Beaufort Sea (Roth et al. 2012; Kinda et al. 2013, 2015; Simard et al. 2014; Insley et al. 2017; Stafford et al. 2017; Haver et al. 2018) or near Fram Strait in the Greenland Sea or northern Barents Sea (Bourke and Parsons 1993; Klinck et al. 2012; Ahonen et al. 2017; Haver et al. 2017; Ozanich et al. 2017). Some of the studies in the Beaufort Sea were at the intersection of the Beaufort and Chukchi Seas (Roth et al. 2012; Haver et al. 2018) or had comparison sites in the Bering Sea (Stafford et al. 2017). Delarue et al. (2011, 2012, 2013, 2014, 2015) and Frouin-Mouy et al. (2016) also presented basic ambient sound data from a large-scale acoustic monitoring project in the Chukchi Sea. Deployments ranged from extremely shallow (5 m; Simard et al. 2014) to deep (500 m; Haver et al. 2018). Detailed studies on ambient sound were not available for Baffin Bay, the Kara Sea, the Laptev Sea, or the East Siberian Sea. A small number of studies collected ocean ambient sound data in the Canadian Arctic Archipelago (Heard et al. 2013) and central Arctic Ocean (Ozanich et al. 2017).

Across the Arctic, ambient sound levels were generally quite low compared to non-Arctic regions (Table 1, Figure 2; see comparison in section 2.6). In the eastern Beaufort Sea, median PSD stayed below 70 dB re 1 μPa2/Hz between 10 and 1000 Hz in the winter (ice-covered season) (Kinda et al. 2013; Insley et al. 2017), and below 75 dB re 1 μPa2/Hz in the summer (broken ice and ice-free season) (Insley et al. 2017). Ambient levels in the western Beaufort and Chukchi Sea were slightly higher during the summer, getting as high as 90 dB re 1 μPa2/Hz (Stafford et al. 2017). During the winter, levels were below 85 dB re 1 μPa2/Hz (Roth et al. 2012; Haver et al. 2018). Measurements from the Chukchi Sea Environmental Monitoring Program (Delarue et al. 2011, 2012, 2013, 2014, 2015; Frouin-Mouy et al. 2016) were on par with levels from the eastern Beaufort, with levels below 75 dB re 1 μPa2/Hz in winter and below 85 dB re 1 μPa2/Hz in summer. In the Greenland Sea and Barents Sea, ambient levels were often higher, staying between 80 and 90 dB re 1 μPa2/Hz between 10 and 100 Hz (Bourke and Parsons 1993; Klinck et al. 2012; Haver et al. 2017; Ozanich et al. 2017), or even higher in one study (Ahonen et al. 2017).

Figure 1. Location of ambient sound level studies (dots) in the Arctic. Symbols are colour-coded by the timeframe of the study, with yellow for 1960-1979, green for 1980-1999, and red for 2000-2018. Basemap credit: National Oceanic and Atmospheric Administration, National Geophysical Data Center, and International Bathymetric Chart of the Arctic Ocean, and General Bathymetric Chart of the Ocean.

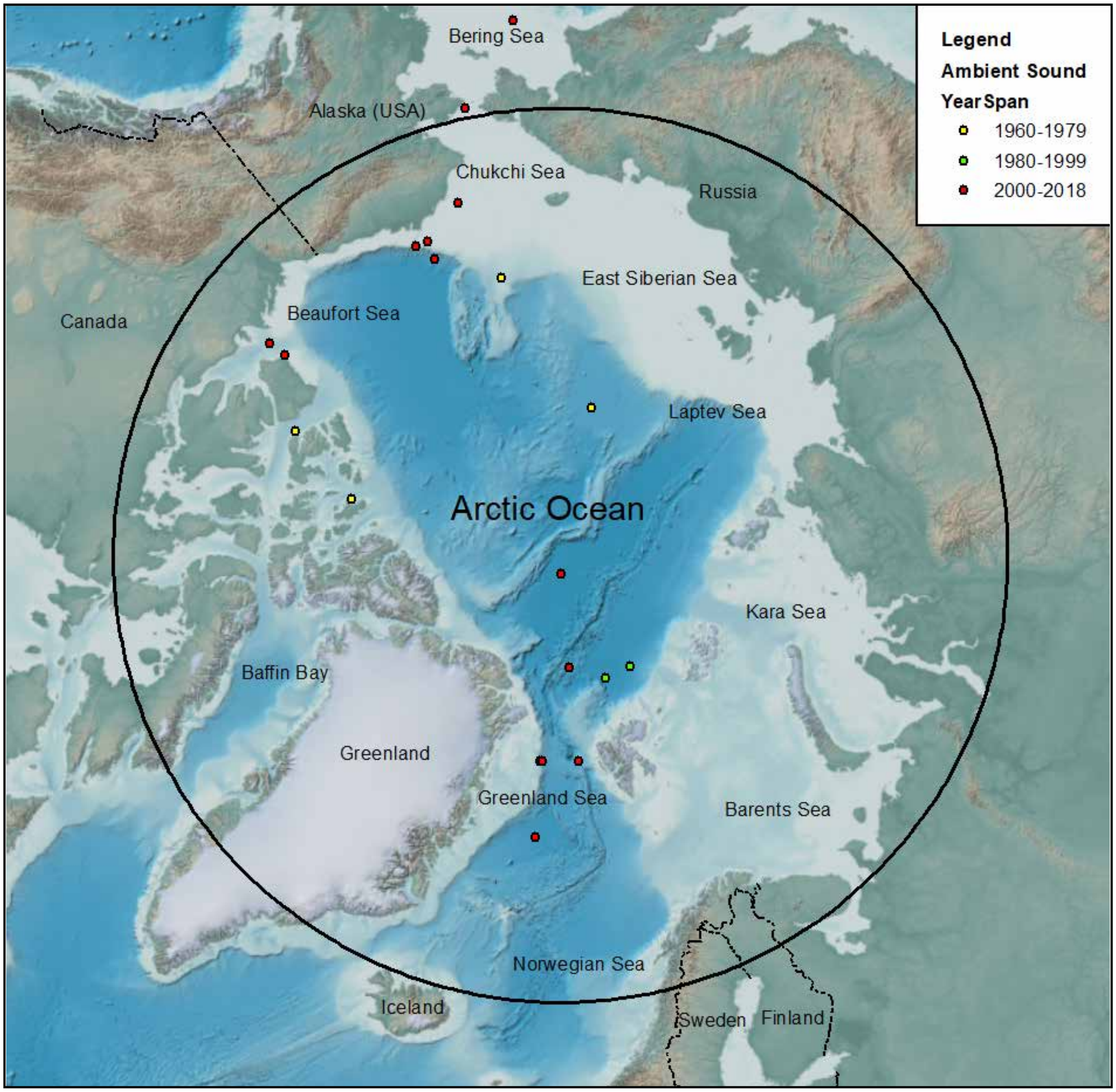


Figure 2. Median power spectral densities reported in different studies of ambient sound level. Lines are connecting the median values from each frequency for each region, and are displayed to help view the data; these lines do not represent any form of curve fitting or regression analysis. The solid line is for the Greenland Sea/Barents Sea, dashed line for the Beaufort Sea/Chukchi Sea, and dotted line for the Arctic Ocean.

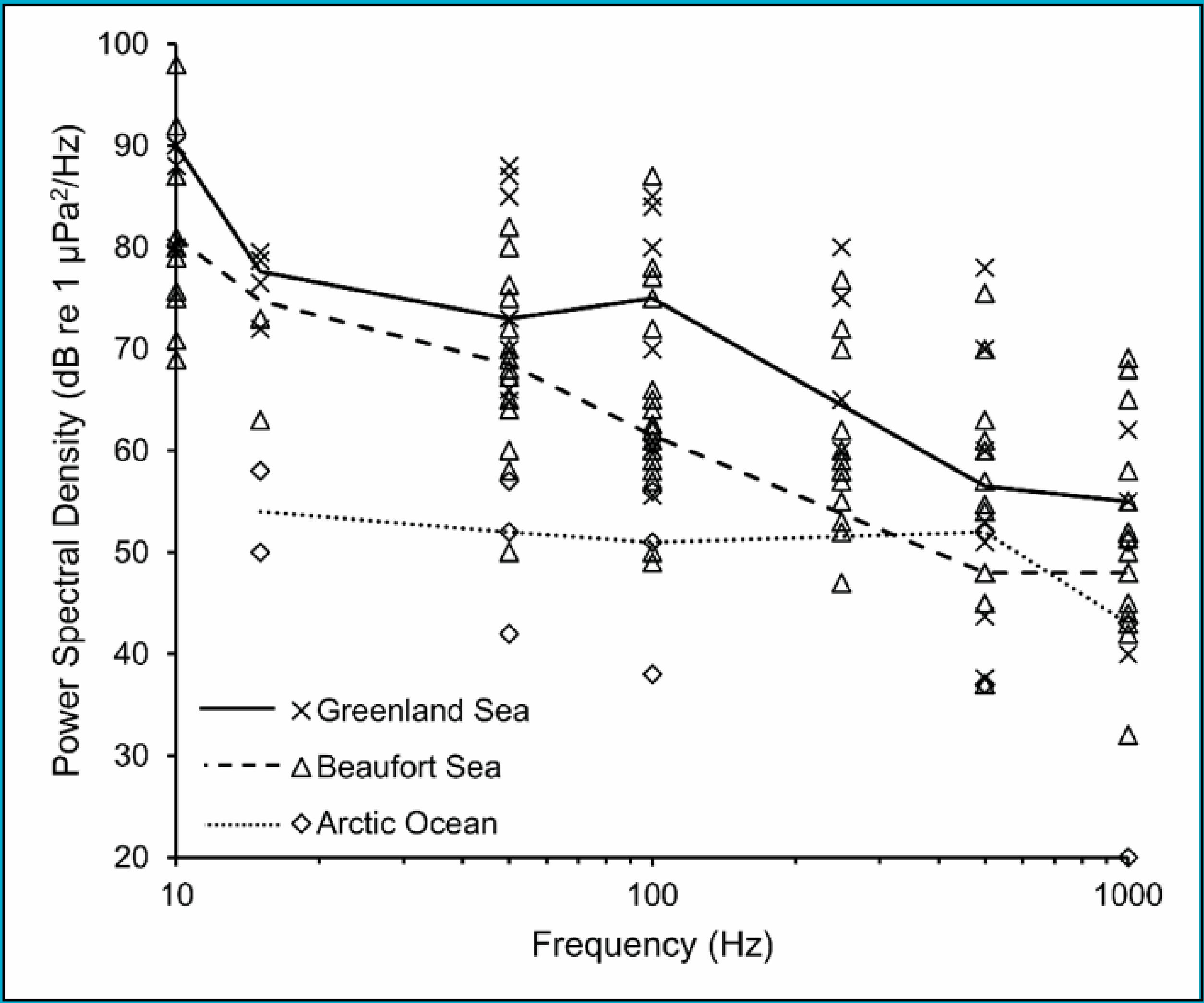


Table 1. Review of Arctic ocean ambient sound, summarized as median power spectral densities (PSD) (dB re 1 μPa2/Hz) at five different frequencies. Season was defined based on winter (November – April) and summer (May through October). *measured at 15 Hz. Locations displayed in Figure 1, PSD values plotted in Figure 2.

Season	Sea	Duration	10 Hz	50 Hz	100 Hz	500 Hz	1 kHz	Reference
Summer	Beaufort	1 month	69	58	57	45	42	Haver et al. 2018
	Beaufort	6 months		50	50	45	45	Insley et al. 2017
	Beaufort/Chukchi	2 months	87	80	87			Roth et al. 2012
	Beaufort/Chukchi	1 month	80	65	57			Roth et al. 2012
	Beaufort/Chukchi	1 month	98	80	75	60	58	Roth et al. 2012
	Beaufort/Chukchi	1 month	81	65	59	48	48	Roth et al. 2012
	Chukchi	6 years	76	76	77	76	69	Delarue et al. 2011-2015; Frouin-Mouy et al. 2016
	Chukchi	5 months	63*	64	49	37	32	Mellen and Marsh 1965
	Chukchi	5 months		75	72	61	52	Mellen and Marsh 1965
	Greenland	12 months	90	85	80	70		Klinck et al. 2012
	Greenland	2 months	72*	70	61	51	40	Mellen and Marsh 1965
	Greenland	2 months	76.5*	66	60.2	43.7		Ozanich et al. 2017
	Greenland	3 months	78.7*	64.9	55.6	37.6		Ozanich et al. 2017
Winter	Arctic Ocean	1 day		57	56	52	43	Milne and Ganton 1964
	Arctic Ocean	1 day	50*	42	38	37	20	Milne and Ganton 1964
	Arctic Ocean	1 day	58*	52	51	52	51	Milne and Ganton 1964
	Barents	6 months	80	73	70	60	55	Bourke and Parsons 1993
	Beaufort	1 month	73*	68	62	48	43	Buck 1981
	Beaufort	1 month	75	65	58	48	44	Haver et al. 2018
	Beaufort	1 month	79	69	65	54	48	Haver et al. 2018
	Beaufort	6 months		60	60	63	65	Insley et al. 2017
	Beaufort	8 months	69	69	66	57	55	Kinda et al. 2013
	Beaufort	1 month	92	82	78	70	68	Stafford et al. 2017
	Beaufort/Chukchi	6 months	87	72	64			Roth et al. 2012
	Beaufort/Chukchi	1 month	87	70	61	48	50	Roth et al. 2012
	Bering	3 months	78	75	73	76	68	Stafford et al. 2017
	Bering	3 months	107	95	85	74	68	Stafford et al. 2017
	Chukchi	6 years	71	67	63	55	51	Delarue et al. 2011-2015; Frouin-Mouy et al. 2016
	Greenland	1 month	90*	80	73	60	53	Makris and Dyer 1991
Full Year	Greenland	48 months	90	85	80	70	62	Ahonen et al. 2017
	Greenland	17 months	90	87	85			Haver et al. 2017
	Greenland	12 months	88	88	84	78		Klinck et al. 2012

Table 2. Contributors to ocean ambient sound levels, grouped into geophony (sounds from physical processes), biophony (biological sounds), and anthrophony (anthropogenic sounds). Locations displayed in Figure 1.

Season	Sea	Duration	Geophony	Biophony	Anthrophony	Reference
Summer	Beaufort	6 months	Ice, Wind			Insley et al. 2017
	Beaufort/Chukchi	1 month	Wind		Seismic airguns	Roth et al. 2012
	Beaufort/Chukchi	1 month	Ice, Wind			Roth et al. 2012
	Chukchi	6 years	Wind		Seismic airguns, vessel traffic	Delarue et al. 2011-2015, Frouin-Mouy et al. 2016
	Greenland	12 months	Wind	Blue, fin, and sperm whales	Seismic airguns, vessel traffic	Klinck et al. 2012
	Greenland	2 months	Ice, Wind, Earthquakes	Bowhead whales	Seismic airguns	Ozanich et al. 2017
Winter	Barents	6 months	Ice, Wind			Bourke and Parsons 1993
	Beaufort	6 months	Ice, Wind			Insley et al. 2017
	Beaufort	8 months	Ice, Wind			Kinda et al. 2013
	Beaufort	1 month	Wind	Bowhead and beluga whales, bearded seals	Vessel noise	Stafford et al. 2017
	Beaufort/Chukchi	1 month	Ice, Wind			Roth et al. 2012
	Bering	3 months	Ice	Bowhead whales, bearded seals, walrus		Stafford et al. 2017
	Bering	3 months	Ice, Wind	Bowhead and beluga whales, bearded seals, walrus		Stafford et al. 2017
	Chukchi	6 years	Ice			Delarue et al. 2011-2015, Frouin-Mouy et al. 2016
Full Year	Greenland	48 months	Ice	Bowhead whale	Seismic airguns	Ahonen et al. 2017
	Greenland	17 months		Blue and fin whale	Seismic airguns	Haver et al. 2017
	Greenland	12 months	Wind	Blue, fin, and sperm whale	Seismic airguns, vessel traffic	Klinck et al. 2012

Drivers of Sound Levels - Environmental Forcing

Two important environmental variables have large influences on Arctic ambient sound levels: wind speed and ice concentration (Table 2). As in non-Arctic regions, increased wind speed generally leads to increased ambient sound levels due to the sound created by breaking waves (Roth et al. 2012; Klinck et al. 2012; Kinda et al. 2013; Insley et al. 2017; Ozanich et al. 2017; Stafford et al. 2017; Williams et al. 2018). Sea ice has two main effects. First, it creates noise when cracking, forming, or under thermal stress (Kinda et al. 2015; Williams et al. 2018). Second, it dampens the impact of wind, where increased wind speed has a lower effect when ice concentration is high (Roth et al. 2012; Insley et al. 2017). In one set of comparisons, researchers found that ambient sound levels were highest at an ice edge, lowest under solid ice, and intermediate in open water with no ice (Diachok and Winokur 1974). This suggests that ambient sound at the ice edge can be very high, but is generally very low under solid ice. Ambient levels can be so low under solid ice that they are below the recording capability of acoustic dataloggers (Kinda et al. 2013; Insley et al. 2017). This general trend that ambient sound is lowest under solid ice, but much higher in open water, in stormy conditions, or when ice is forming or breaking, has been shown across many studies (e.g., Miksis-Olds et al. 2013; Miksis-Olds and Madden 2014; Clark et al. 2015).

Drivers of Sound Levels – Animal Sounds

Marine animals actively produce sounds for a variety of reasons, including for foraging, navigation, communication, and reproduction. The frequency of these vocalizations varies by species and purpose. Large baleen whales (mysticetes) produce very low frequency sounds, typically below 1,000 Hz, and below 50 Hz for the two largest whales (blue whales, *Balaenoptera musculus*, and fin whales, *Balaenoptera physalus*). Bowhead whales (*Balaena mysticetus*), the only Arctic-endemic mysticete, produce vocalizations between 50 and 1000 Hz in the summer (Tervo et al. 2009; Halliday et al. 2018), but produce higher frequency vocalizations over 2000 Hz in the winter when they sing (Tervo et al. 2009; Stafford et al. 2018). Beluga (*Delphinapterus leucas*) and narwhal (*Monodon monoceros*), the only Arctic-endemic odontocetes, produce vocalizations between 400 and 15,000 Hz (Chmelnitsky and Ferguson 2012; Marcoux et al. 2012; Blackwell et al. 2018) and echolocation clicks between 10 and 120 kHz (Watkins et al. 1971; Au et al. 1985; Møhl et al. 1990; Blackwell et al. 2018). Seals produce sounds between 100 and 10,000 Hz, but this range is very species-specific. For example, bearded seals (*Erignathus barbatus*) produce sounds in this full range, whereas ringed seals (*Pusa hispida*) typically produce lower frequency sounds below 1,000 Hz (e.g., Stirling et al. 1983; Jones et al. 2014).

Other marine animals also make sounds. Fish are known to produce sounds, although only one Arctic-endemic fish has been confirmed to make sounds: the Arctic cod (*Boreogadus saida*; Riera et al. 2018). Arctic cod grunts are fairly low frequency (100 to 200 Hz). Many fish and invertebrates in non-Arctic waters are soniferous, therefore it is likely that other Arctic marine fish and invertebrates make sounds and may influence ambient sound levels.

Arctic marine mammals can elevate ambient sound levels (Table 2). Marine animals typically make the most sound during mating season, when they are actively trying to attract mates or repel competitors using vocalizations. Bearded seals and bowhead whales have both been identified as being contributors to elevated ambient sound levels during their breeding seasons (Ahonen et al. 2017; Ozanich et al. 2017; Stafford et al. 2017). Walrus and beluga whales can also impact Arctic soundscapes (Stafford et al. 2017). Fin whales, historically a non-Arctic species, have also been recorded making a consistent impact on sound levels in Fram Strait (Ahonen et al. 2017; Haver et al. 2017). In the Atlantic Arctic, especially east of Greenland, blue whales and sperm whales contribute to increasing ambient sound levels (Klinck et al. 2012; Haver et al. 2017). Although other marine mammals are present in the Arctic, their vocalizations may be too low or sporadic to significantly raise ambient sound levels.

Drivers of Sound Levels – Anthropogenic Activity

Noise from seismic airguns (Klinck et al. 2012; Roth et al. 2012; Geyer et al. 2016; Ahonen et al. 2017; Haver et al. 2017; Ozanich et al. 2017) and vessel traffic (Klinck et al. 2012; Geyer et al. 2016; Stafford et al. 2017) are the most commonly reported sources of anthropogenic noise in studies of ocean ambient sound in the Arctic (Table 2). While other noisy anthropogenic activities occur in the Arctic, such as construction, pile driving, underwater explosions, drilling, dredging, and military sonar, none of these activities were reported in studies of ambient sound levels. Some of these noisy activities have been reported in studies that measured source levels (section 3) or studies examining impacts on marine mammals (section 4). Roth et al. (2012) observed that high levels of seismic airgun activity (at unknown distances from the acoustic recorder) could elevate ambient sound levels by 3 to 8 dB between 10 and 250 Hz. Geyer et al. (2016) found that seismic airgun activity was detected from 800 km away and elevated ambient levels by 2 to 6 dB between 20 and 120 Hz. Keen et al. (2018) detected pulses from seismic airguns from more than 500 km away in deep water, and up to 100 km away in shallow water of the Chukchi slope. Geyer et al. (2016) also found that propeller cavitation and ice breaking activity from 100 km away elevated ambient levels by 10 to 28 dB between 5 and 1950 Hz. Klinck et al. (2012) found a strong correlation between the presence of seismic airgun noise and monthly median PSD levels. Perhaps one of the most detailed, large-scale, and long-term assessment of impacts of anthropogenic activities on ambient sound levels in the Arctic was part of the Chukchi Sea Environmental Studies Program. As part of this program, the acoustic environment in the northeastern Chukchi Sea was monitored from 2009-2015 with a very large number of single acoustic recorders and arrays of recorders (Delarue et al. 2011, 2012, 2013, 2014, 2015; Frouin-Mouy et al. 2016). For example, Delarue et al. (2013) examined the noise contributions of seismic surveys and shipping in 2012, and found that shipping had a much larger overall impact on ambient sound levels than did seismic surveys, although during this year, there were relatively few seismic surveys. The presence of shipping noise added a median of 3.5 dB to ambient sound levels between 40 and 315 Hz during this summer, and vessel noise was present 5.1% of the time. Frouin-Mouy et al. (2015) found that there were more ship passages through the northeastern Chukchi Sea in 2015 than in all other years (2009-2014) of this research program, but did not assess specific contribution to ambient levels. They did, however, show a strong rise in PSD between 40 and 1,000 Hz, which was almost entirely due to ship noise.

Blackwell et al. (2004) measured broadband sound pressure levels between 10 and 10,000 Hz at a variety of distances between 200 and 7300 m from an active drilling platform that was surrounded by solid sea ice. This study found that drilling caused ambient sound levels to increase to a maximum of 124 dB re 1 μPa at a distance of 1 km from the platform, compared with ambient sound levels around 91 dB re 1 μPa at the same site in the absence of drilling. Various other operational activities did not affect ambient sound levels. Noise from the drilling platform was no longer above regular ambient sound levels at distances greater than 9.4 km, and drilling noise would only be audible to seals out to 1.5 km from the drilling platform.

The presence of anthropogenic noise in the Arctic is highly seasonal, largely determined by ice conditions. During the open water season, vessel traffic tends to be greatest, which also overlaps with important feeding periods and autumn migrations of most Arctic marine mammals. Once solid sea ice has formed, it effectively stops most anthropogenic activities, thereby reducing the contribution of anthropogenic noise to ambient levels, with the notable exception of ice breakers and year-round mechanical operations (e.g. some drilling platforms).

Comparison of Arctic to Non-Arctic Areas

There are four key differences between Arctic and non-Arctic waters regarding drivers of ambient sound levels. First, sound propagates differently in the Arctic due to the Arctic sound channel (see section 2.1), and high amplitude sounds may be detectable from farther away in shallower waters than in non-polar areas. Second, non-Arctic waters typically do not have solid sea ice (except in Antarctic waters). Third, non-Arctic waters have a different suite of soniferous animals, which make different vocalizations and therefore have different spectral properties and seasonal timing. And fourth, non-Arctic waters have higher levels of anthropogenic activities than Arctic waters. All of these drivers generally lead to lower levels of underwater noise in Arctic than in non-Arctic waters. Two recent studies compared ambient levels in Arctic versus non-Arctic sites: Haver et al. (2017) compared ambient levels from the Atlantic Ocean in the Arctic (Fram Strait), Equator, and Antarctic; and Haver et al. (2018) compared ambient levels from sites around the USA, including one site in the Alaskan Arctic.

In Haver et al. (2017), the Equator site was consistently 10 dB higher between 15 and 100 Hz than the Arctic and Antarctic sites across this frequency band. Key contributors to ambient levels at the Equator site were increased calling by fin and blue whales throughout the year, as well as signals from seismic airguns. The Arctic and Antarctic sites had seasonal peaks in calling activity from fin and blue whales, but these signals did not occur throughout the year. Seismic airguns could be heard 24 hours per day throughout the entire recording period at the Equator, but could only be heard between April and November in the Arctic, and were only heard during a short period in January in the Antarctic. This article did not include an analysis of noise from vessels, but did note that all three sites were far away (> 500 nautical miles) from any major shipping lanes.

In Haver et al. (2018), the authors compared acoustic data from five sites in coastal United States waters as part of the National Oceanic and Atmospheric Administration's national underwater noise monitoring program. The Alaskan Arctic was by far the site with the lowest ambient levels. The Channel Islands (California) had the next lowest levels, but was still at least 5 dB higher than the Alaskan Arctic across the frequency band between 10 and 1000 Hz. The site with the highest ambient levels was the Gulf of Mexico. The authors did not assess contributors to the soundscape, but based on their PSD plots, the non-Arctic sites had large peaks that resembled those caused by shipping activity. The authors also suggested that Alaska had lower ambient levels due to the presence of sea ice.

Many other studies have examined underwater noise levels in non-Arctic regions. Generally, the impacts of environmental variables, such as wind speed, are similar to those in the Arctic in the absence of sea ice: as wind speed increases, noises levels increase (McDonald et al. 2006; Wenz 1962). Non-Arctic regions also can have strong signals from soniferous animals, such as low frequency blue whales and fin whales (McDonald et al. 2006, Haver et al. 2017) and choruses from fish (Pine A et al. 2018). Non-Arctic regions typically have higher levels of shipping activity (e.g., Erbe et al. 2012), which cause the largest difference between Arctic and non-Arctic regions.

Future Scenarios

First and foremost, climate change is expected to continue to cause even more loss of sea ice cover (Zhang and Walsh 2006; Arctic Council 2017), which is predicted to make the Arctic more accessible to anthropogenic activities for longer periods of time (e.g., Smith and Stephenson 2013), which could introduce additional noise or new types of noise. Sound propagation in the Arctic has also been predicted by one study (Duda et al. 2016; Duda 2017) to become more efficient in the future, where changing pH levels near the surface will lead to reduced absorption of higher frequency sounds, which could increase propagation distance by nearly 40% for frequencies around 900 Hz over the next 30-50 years. There are, however, multiple factors at play, and this study only accounted for changing pH levels. Other factors, such as increased freshwater inputs (i.e. melting glaciers and permafrost) and warming water temperatures, may have different or confounding effects on sound propagation and ambient sound levels. The combination of increased noisy activities and more efficient sound propagation will likely lead to increased ambient sound levels throughout the Arctic.

SUMMARY

Within the Arctic, ambient sound levels are lower when sea ice is solid, and much higher when ice is forming or breaking up, or in open water under windy conditions. Ambient levels in the Arctic increase when marine mammals vocalize frequently, particularly during the mating season. Anthropogenic activities also increase ambient levels. The most common sources of anthropogenic noise in the Arctic are from seismic airguns and vessel traffic, although both of these sources vary spatially and temporally. Noise is also produced by oil and gas extraction activities, such as the construction of platforms and drilling operations. Vessel traffic has been increasing through time, whereas oil and gas activities are less predictable, and can be entirely absent in one year and widespread in another. Across the Arctic, ambient sound levels are lower in the Beaufort and Chukchi Seas, and higher in the Greenland and Barents Seas. Ambient sound levels in the Arctic are generally lower than in non-polar regions, but are similar to levels in the Antarctic. Ambient sound levels will likely increase in the future through a combination of increased noise anthropogenic activity and more efficient sound propagation.

The main knowledge gap related to ambient sound levels in the Arctic is that there are large geographic areas with no available reports on ambient sound levels, specifically in the East Siberian Sea, Kara Sea, Laptev Sea, Baffin Bay, and much of the Canadian Arctic Archipelago and Arctic Ocean. Even areas that have had studies on ambient sound still have large spatial gaps. For example, in the Beaufort Sea, there are two studies at the eastern end of the Canadian Beaufort and a handful of studies at the western end of the Alaskan Beaufort, with a gap of nearly 1000 km between studies (Figure 1). Strategically filling this spatial gap based on overlap with prioritized ecologically sensitive and/or important areas could also lead to more information on the influence of anthropogenic activities on ambient sound levels.

Arctic Anthropogenic Noise Sources

Source Levels for Vessel Traffic

Globally, commercial vessel traffic is the most constant and pervasive source of anthropogenic noise in the ocean (Hildebrand 2009). Underwater noise from commercial vessels typically peaks between 1 and 100 Hz, although vessels can cause noise above 10 kHz (Veirs et al. 2016) (Figure 3). Low frequency acoustic energy has been doubling in temperate oceans every decade, and this increase may be due to increased noise from shipping (Andrew et al. 2002; McDonald et al. 2006). Beyond commercial shipping traffic, other vessels also create noise. These vessels include recreational boats, typically found close to developed areas, passenger vessels and ferry traffic, tug boats, research vessels, government vessels, and fishing vessels. Any vessel with some form of mechanical power has the potential to create underwater noise. Most of this noise is attributed to cavitation, but vessels also have other noise sources, including noise from engines, generators, and electronic devices on board.

In this section, we report source levels for anthropogenic activities common in the Arctic. All source levels reported in this review are in the units dB re 1 µPa at 1 m, which is the sound pressure level measured or estimated at a distance of 1 m from the noise source. Unfortunately, very few studies used the same metric for source level. All source levels for continuous noise sources (i.e. vessel noise, drilling noise) were back-calculated from measurements using root mean squared averages (denoted as dB_{rms}) or median values (dB_{med}), but source levels for impulsive noise (seismic airguns) were measured using a variety of metrics, including zero-to-peak ($dB_{zero\text{-}to\text{-}peak}$, peak-to-peak ($dB_{peak\text{-}to\text{-}peak}$), and root mean squared averages; the metric used is denoted in Table 3. These metrics are not always comparable, which is why the metric used is denoted. For example, zero-to-peak source levels can be 9 to 20 dB higher than root mean squared source levels,

Figure 3. Frequency ranges of biological sounds (biophony) made by baleen whales, toothed whales, and seals and walruses, and frequency ranges containing most of the acoustic energy and source levels anthropogenic activities (anthrophony). Note that the box for "All Vessels" includes the black box and the diagonal striped box to the right; the black box represents most of the noise from shipping, and the striped box represents additional noise identified in Veirs et al. 2016. Similarly, for "Seismic Airguns", the white box represents most of the noise below 100 Hz, with some additional noise up to 1000 Hz shown by the horizontal striped box, as identified in Breitzke et al. 2008. "Naval MF Sonar" is naval mid-frequency sonar. Adapted from Moore et al. 2012, and modified using frequencies and source levels reported in this review. [1]Simard et al. 2016; [2]Veirs et al. 2016; [3]Halliday et al. 2017; [4]Erbe and Farmer 2000; [5]Miller et al. 2012..

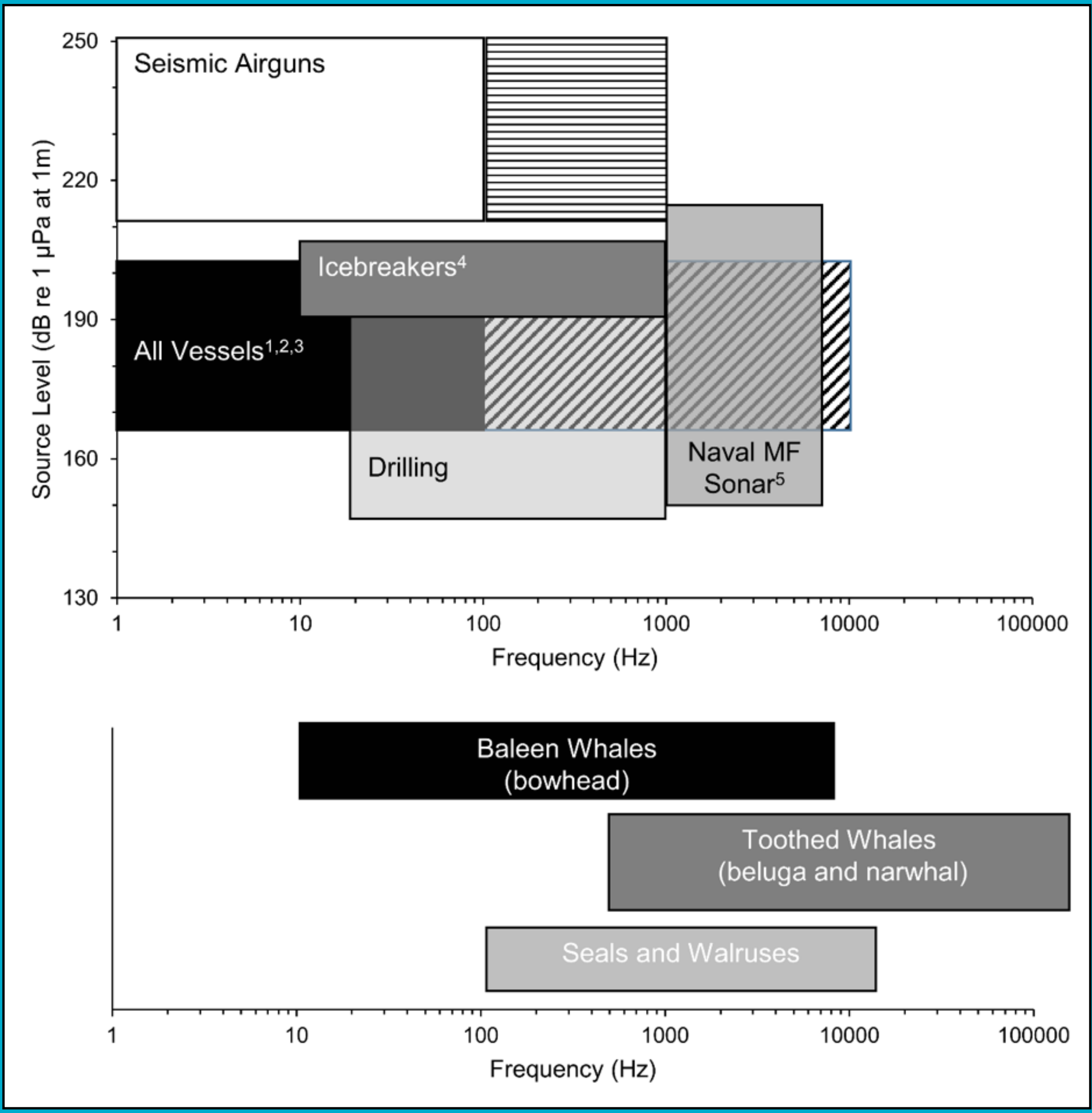


Figure 4. Location of source level measurements for anthropogenic activities in the Arctic. Most measurements were mad in shelf waters which have different acoustic properties than Arctic deep waters. Symbols are colour-coded by the timeframe of the study, green for 1980-1999 and red for 2000-2018. Basemap credit: National Oceanic and Atmospheric Administration, National Geophysical Data Center, and International Bathymetric Chart of the Arctic Ocean, and General Bathymetric Chart of the Ocean.

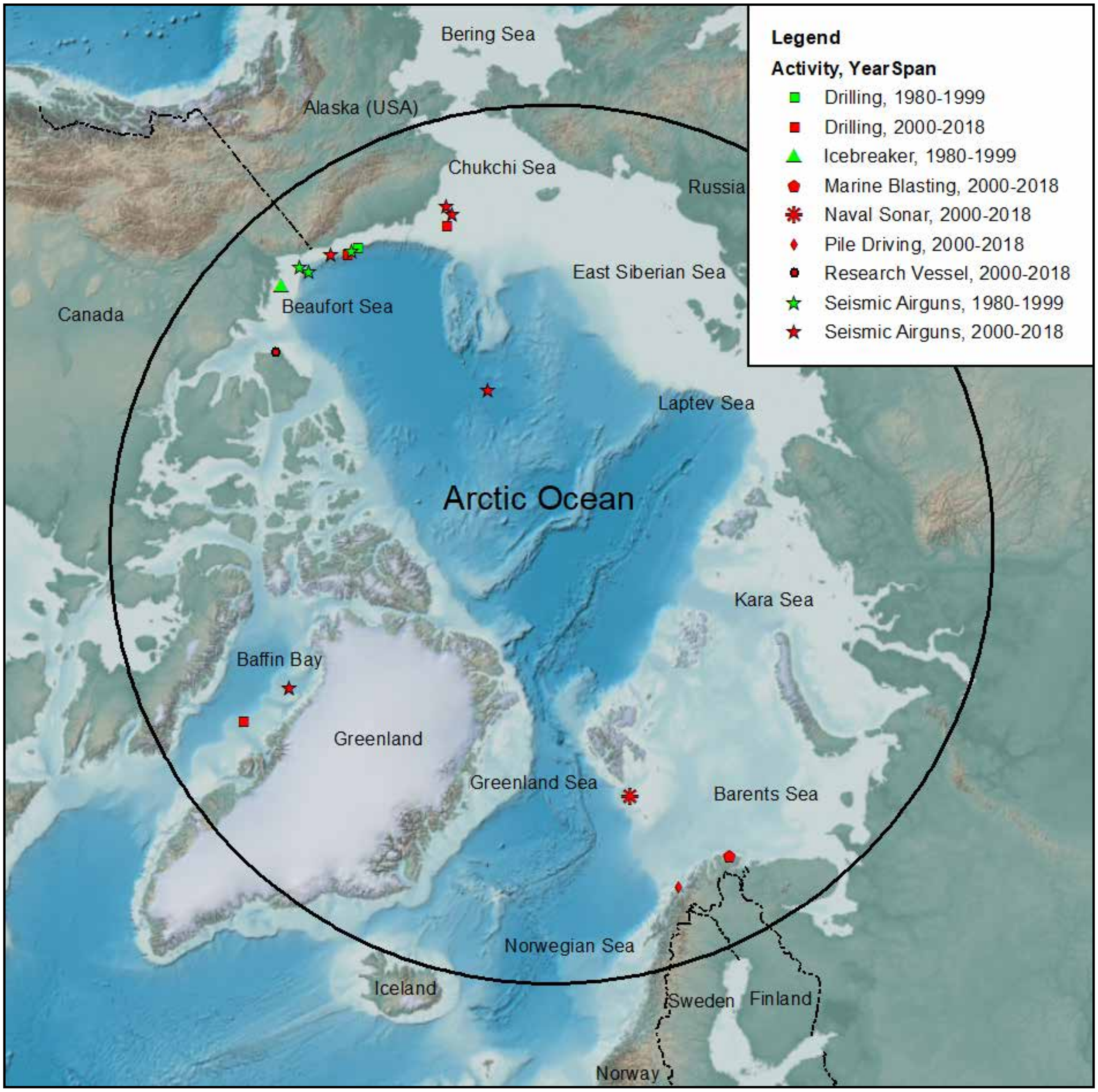


Table 3. Broadband source levels (dB re 1 μPa at 1 m) of sound from anthropogenic activities in the Arctic. Frequency range (kHz) is defined for all studies that reported it. Locations displayed in Figure 4. Method of measurement: a = root mean squared, b = zero-to-peak, c = peak-to-peak, d = median, e = unknown.

Activity	Specific Class	Comments	Source Level	Frequency Range	Location	Reference
Oil and Gas	Drilling	Bottom-mounted drill rig	146 [e]	0.02 to 20	Beaufort Sea	Brewer and Hall 1993
		Anchored drill rig	179 [e]	0.02 to 20		
		Maintenance	190 [a]	0.01 to 40	Baffin Bay	Kyhn et al. 2014
		Drilling	184 [a]	0.01 to 40		
		Drilling unit	169 [a]	0.01 to 32	Beaufort/Chukchi Seas	Austin et al. 2018
		Semi-submersible	170 [a]			
		Drillship	175 [a]			
	Excavation		192 [a]	0.01 to 32	Beaufort/Chukchi Seas	Austin et al. 2018
			193 [a]			
			193 [a]			
	Seismic airguns		238 [e]		Chukchi Sea	Delarue et al. 2011
			217 [e]		Chukchi Sea	Delarue et al. 2012
		Single airgun	222 [a]	0.02 to 1	Beaufort Sea	Greene and Richardson 1988
		47 L, 12 gun array	248 [a]	0.02 to 1		
		Western Polaris, 24 gun array	250 [e]		Beaufort Sea	Ljungblad et al. 1988
		Arctic Star, 24 gun array	246 [e]			
		Western Aleutian, 20 gun array	230 [e]			
		Western Beaufort, 11311 cm^3 single airgun	220 [e]			
		3480 in^3 array	247 [b]		Baffin Bay	Martin et al. 2017
		140 in^3 array	239 [b]			
		30 airgun array	248 [e]		Beaufort Sea	Richardson et al. 1986
		1150 in3 array	211 [c]		Arctic Ocean	Roth and Schmidt 2010
		Polarstern, 24 L array	224-240 [b]	0-80 kHz	Norwegian Sea	Breitzke et al. 2008
Construction	Underwater Blasting – Bedrock Removal	Buried blasting, 56.7 to 529 kg of dynamite	268 [c]	0.01 to 80	Barents Sea	Aune et al. 2018
	Pile Driving	Pile driving of two piles over two days, pile length = 12.5 m, diameter = 0.71 m, 7 ton hydraulic hammer	210 [b]		Norwegian Sea	Norwegian National Coastal Administration 2018
Vessel Traffic	Ice Breaker	Bubbler System	192 [d]	0.01 to 20	Beaufort Sea	Erbe and Farmer 2000
		Propeller Cavitation	197 [d]	0.01 to 20		
	Research Vessel	Transiting	176 [a]	0.063 to 20	Barents Sea	Halliday et al. 2017
Naval Mid-frequency Sonar		Controlled experiment, including ramp-up from low to high source level	158 to 197 [a]	6 to 7	Barents Sea	Miller et al. 2012
		Controlled experiment, including ramp-up from low to high source level	152 to 214 [a]	1 to 2	Barents Sea	Miller et al. 2012; Sivle et al. 2015

depending on the length of the signal that is measured (Madsen 2005).

A few non-Arctic studies have compiled large lists of source levels for vessels. For example, Simard et al. (2016) measured the source levels of 255 merchant ships (i.e. cargo and tanker vessels) in the St. Lawrence Seaway following methodology from the American National Standards Institute. These ships had source levels (calculated between 20 and 500 Hz) averaging around 197 dB_{rms} for all vessels, with the average around 196 dB_{rms} for small vessels (100 to 150 m length) and as high as 201 dB_{rms} for large vessels (> 250 m length). Veirs et al. (2016) measured the source levels of 1,582 unique vessels transiting Haro Strait near Vancouver, Canada. These authors measured source levels (between 11.5 Hz and 40 kHz) from all vessel classes, and found that the average source level across all vessel classes was 173 ± 7 dB_{rms} (± standard deviation), and ranged from as low as an average of 159 ± 9 dB_{rms} for pleasure craft to as high as an average of 178 ± 4 dB_{rms} for container vessels.

A few Arctic studies have documented noise from vessels (Table 3, Figure 4), but not nearly to the same extent as in non-Arctic areas. For example, at least two studies have measured source levels from ice breakers that were actively breaking ice (Erbe and Farmer 2000; Roth et al. 2013); however, one study was in deep water (Roth et al. 2013) and the other was in shallower waters (Erbe and Farmer 2000). Roth et al. (2013) also did not provide broadband source levels, but rather source levels within a few non-sequential octave bands making comparison difficult. Erbe and Farmer (2000) measured high source levels from an ice breaker in the Beaufort Sea, ranging between 189 and 205 dB (based on different percentiles and ice-breaking activities) between 100 Hz and 20 kHz. Roth et al. (2013) measured the source level of an icebreaker in the Arctic Ocean far north of Alaska, and measured source levels between 190 and 200 dB_{rms} in the octave bands centered on 10, 50, and 100 Hz. One other Arctic study measured the source level of one research vessel in the eastern Beaufort Sea (Halliday et al. 2017), and the source level between 63 Hz and 20 kHz was 176 dB_{rms}.

Vessel traffic has been increasing throughout the Arctic over the past few decades (Stephenson et al. 2011; Zhang et al. 2016; Dawson et al. 2018). For example, in the Canadian Arctic, all vessel traffic was three times higher in 2015 than in the 1990s (Dawson et al 2018). There are currently two main routes to transit the Arctic: the Northern Sea Route (NSR) along the northern coast of Russia, and the Northwest Passage (NWP) through the Canadian Arctic Archipelago. Currently, the NSR is used much more than the NWP (Arctic Council 2009; Reeves et al. 2014), although both are predicted to be more accessible in the near future (Stephenson et al. 2011; Smith and Stephenson 2013). The highest level of vessel traffic in the Arctic is currently in the Barents Sea and Greenland Sea, between Europe and Svalbard (Reeves et al. 2014). Based on climate change models, the Arctic will likely be more accessible to vessel traffic and thus an increase is expected (Arctic Council 2009; Stephenson et al. 2011; Smith and Stephenson 2013).

Source Levels for Oil and Gas Exploration and Extraction

Noise sources related to oil and gas exploration include seismic airguns, drilling activities, site construction (e.g., pile driving) and maintenance, and vessel activity directly related to the oil and gas operation, such as crew vessels and shipping materials and supplies to and from the oil platform. Seismic airguns are one of the most researched anthropogenic noise source in the Arctic (Table 3, Figure 3, 4). Peak source levels of seismic airguns in the Arctic ranged from 211 to 250 dB (Table 3, Figure 3); these values were measured using a variety of metrics, including zero-to-peak and peak-to-peak. Drilling was another common source of noise from oil and gas operations recorded in the Arctic, and source levels ranged from 146 to 190 dB_{rms} (Table 3). One study also measured source levels of excavation activities (mudline cellars), with source levels around 193 dB_{rms} (Table 3; Austin et al. 2018).

Oil and gas activities have historically been widespread throughout the Arctic (Arctic Council 2007; Reeves et al. 2014), but their prevalence varies greatly between locations and years. The largest impact of oil and gas activities on underwater noise levels are from seismic airguns, and most energy from seismic airguns is below

100 Hz, though some energy is produced up to 1000 Hz and higher (Breitzke et al. 2008). The geographic locations of these surveys changes yearly, but they tend to have a wide-reaching impact on ambient sound levels. Oil and gas extraction activities also increase underwater noise levels (Blackwell et al. 2004). Although drilling has a much lower source level than seismic airguns, it will increase underwater noise levels in areas close to the drilling platform (Blackwell at el. 2004). Active drilling operations will also lead to increased vessel traffic in an area for transporting crew and materials to and from an active operation (Ellison et al. 2016). Primary areas of interest for oil extraction (past or present) in the Arctic include the Barents, Beaufort, Chukchi, North, and Norwegian Seas (Arctic Council 2007; Reeves et al. 2014). Exploration activities have covered a much broader range, and are essentially circum-Arctic, but their prevalence varies greatly through time.

Source Levels for Marine Construction

Construction activities in the marine environment can include many different noise sources, but two identified in this review from the Norwegian Arctic were underwater blasting/demolition (Aune et al. 2018) and pile driving (Norwegian National Coastal Administration 2018). Source levels for underwater buried blasting were quite high (268 $dB_{peak\text{-}to\text{-}peak}$ re 1 μPa at 1 m), but source levels for pile driving were also high (210 $dB_{zero\text{-}to\text{-}peak}$ re 1 μPa at 1 m).

Construction activities such as these will occur around any active port or developed area in the Arctic, but will only happen when the area is refurbishing facilities or expanding, so may be a rare source of noise overall.

Source Levels for Naval Mid-frequency Sonar

Naval mid-frequency sonar is a source of noise rarely discussed in Arctic studies, yet it is potentially a noise source that is present wherever there is naval activity. Naval activity may be sporadic throughout the Arctic, and could occur in all regions. The only studies documenting potential source levels of naval mid-frequency sonar in the Arctic only did so for the purpose of an experiment assessing the impact of naval mid-frequency sonar on marine mammals (Miller et al. 2012; Sivle et al. 2015), so these source levels may not necessarily be representative of naval mid-frequency sonar as a whole. Source levels for naval mid-frequency sonar from these studies ranged between 152 and 214 dB_{rms} re 1 μPa at 1 m (Miller et al. 2012; Sivle et al. 2015).

Detectability Distances

Some anthropogenic noise may propagate over great distances in the Arctic, whereas others may barely propagate away from the source. The exact distances will vary temporally and spatially depending on the propagation characteristics at different sites at different times of year. The values reported in this section are simply examples, and are not representative of detectability distances for all sources throughout the Arctic. Different receivers (or listeners) will have different detection abilities. Even though humans can detect faint underwater sounds using hydrophones and computer software, a marine animal may not be able to detect that sound due to their hearing sensitivity, or the opposite may be true. We can assume that high amplitude, lower frequency sounds will have a greater range of detectability and also a greater impact than low amplitude, higher frequency noises, but the precise distance of detectability and impact will vary between receivers and locations. Seismic airguns have been detected by humans from greater than 1300 km away (Thode et al. 2010), vessel noise from greater than 100 km (Halliday et al. 2017), and drilling noise from just over 9 km away (Blackwell et al. 2004). For comparison, bowhead whales can be detected by humans from up to 130 km away (Tervo et al. 2012), bearded seals from up to 45 km away (Stirling et al. 1983), and beluga whales from 3 km away (Simard et al. 2010). There is a large amount of variation in propagation distances between different sources, which depends on how noisy the source is and what its peak frequency is. High amplitude sounds propagate farther than low amplitude sounds, and low frequency sounds typically propagate farther than high frequency sounds. Propagation also depends heavily on water depth, bottom sediment, and water characteristics (temperature and salinity).

SUMMARY

The two current largest sources of anthropogenic noise in the Arctic are vessel traffic and seismic airguns, although active drilling platforms, marine construction, and navy sonar also create noise. Source levels for vessel traffic in the Arctic have only been measured a few times, and mostly for ice breaking activity. Ice breaking noise is typically higher than normal vessel noise, and can be higher than 200 dB_{med}. Source levels for typical vessel traffic ranges between 159 and 178 dB_{rms} in non-polar regions, with an average of 173 dB_{rms}. Merchant vessels, such as cargo vessels and tankers, can have much higher source levels, with an average source level of 197 dB. Vessel traffic occurs throughout the Arctic, but tends to be greater in the Northern Sea Route than in the Northwest Passage, and even more traffic occurs between Europe and Svalbard in the Barents and Greenland Seas. These areas with greater vessel traffic should have greater noise levels.

Seismic airguns have source levels between 211 and 250 dB_{rms}. Drilling activity has source levels between 146 and 190 dB_{rms}. The prevalence of seismic airgun surveys varies greatly from year to year, but can occur throughout the Arctic.

Marine construction can involve noisy activities, such as underwater blasting (source level = 248 dB_{rms}) and pile driving (source level = 210 dB_{rms}). Marine construction may occur around any coastal settlements or ports throughout the Arctic, but likely only occur rarely.

Naval sonar likely occurs throughout the Arctic in the presence of navy vessels with sonar, but the extent of its use in the Arctic is largely unknown. One study that documented source levels of naval sonar found levels between 152 and 214 dB_{rms}.

The main knowledge gap related to source level measurements is that there have been relatively few measurements of source levels in the Arctic, especially for vessels (Table 3), and all of those measurements were in North American waters (Figure 4). Increased acoustic monitoring throughout the Arctic could help build up a more detailed library of source level measurements.

Impacts of Underwater Noise on Arctic Marine Mammals

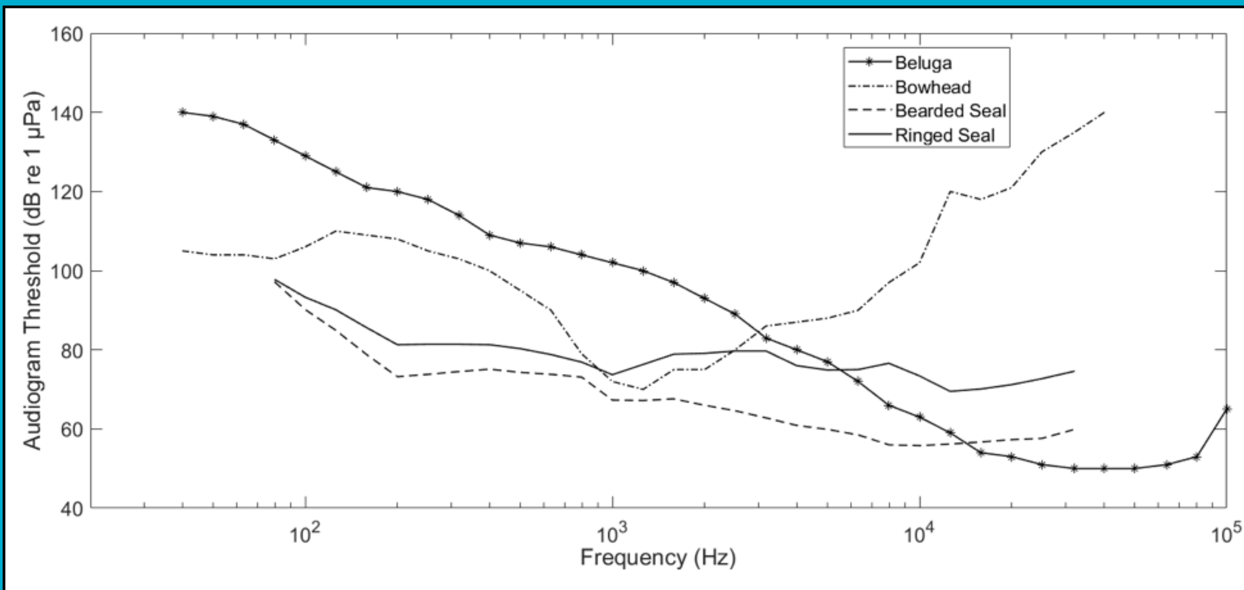
Arctic Marine Mammals

There are a limited number of endemic (resident) marine mammal species in the Arctic, which are joined by species that migrate from subarctic waters (or even farther) for the brief ice-free season. Eleven Arctic marine mammal species have been identified (Conservation of Arctic Flora and Fauna [CAFF] 2017). Of these, the six principal Arctic marine mammals that this report focuses on include ringed (*Pusa hispida*) and bearded seals (*Erignathus barbatus*), walrus (*Odobenus rosmarus*), narwhal (*Monodon monoceros*), bowhead (*Balaena mysticetus*) and beluga whales (*Delphinapterus leucas*). The additional five species include the other northern ice seals, harp seals (*Pagophilus groenlandicus*), hooded seals (*Cystophora cristata*), spotted seals (*Phoca largha*), and ribbon seals (*Histriophoca fasciata*), and the polar bear (*Ursus maritimus*). In addition, there are an increasing number of seasonal Arctic marine mammal migrants including fin (*Balaenoptera physalus*), minke (*Balaenoptera acutorostrata*), grey (*Eschrichtius robustus*), humpback (*Megaptera novaeangliae*), and killer whales (*Orcinus orca*), harbour porpoise (*Phocoena phocoena*), as well as occasionally sperm (*Physeter macrocephalus*) and blue whales (*Balaenoptera musculus*) and harbour seals (*Phoca vitulina*). As ocean temperatures increase, more subarctic species are being regularly observed in Arctic waters, particularly in areas such as the Chukchi Sea or Greenland Sea where there exists direct pathways to subarctic waters (Brower et al. 2018). Current population and conservation status of each of the eleven species of Arctic marine mammals is reviewed in Laidre et al. (2015), and the main anthropogenic threats reviewed in International Whaling Commission [IWC] (2014). In this review, we mainly focus on the six principal species of Arctic marine mammals listed above, but include other species for impacts that were not assessed on the six principal species, such as naval sonar.

Hearing in Marine Mammals

Marine mammals have an inner ear that translates sound pressure into signals that the marine mammal can discern. Hearing sensitivity of the species of marine mammal present in the Arctic differs between the three broad biological categories of pinnipeds (seals, sea lions, and walrus), odontocete cetaceans (toothed whales),

Figure 5. Audiograms for beluga, bowhead, bearded seal, and ringed seal. Audiograms for beluga and ringed seal were measured in live animals (Castellote et al. 2014; Sills et al. 2015; Erbe et al. 2016). The bowhead audiogram is based on a modeled audiogram for fin whale (Cranford and Krysl 2015), and the bearded seal audiogram is modeled based on bearded seal morphology (Li et al. 2011).



and mysticete cetaceans (baleen whales) (Southall et al. 2007). Empirical tests of hearing sensitivities have been carried out in a number of species in the first two categories, including Arctic species, but not in the last category, baleen whales (reviewed in Houser et al. 2017). Baleen whale hearing thresholds have been estimated based on morphology (Parks et al. 2007; Ketton and Mountain 2014; Cranford and Krysl 2015). Empirical hearing threshold tests on Arctic-endemic marine mammal species have only been conducted on ringed seals (Sills et al. 2015) and beluga whales (Awbrey 1988; Finneran et al. 2005; Popov et al. 2013, 2014, 2015; Nachtigall et al. 2016; Mooney et al. 2018), although other semi-Arctic marine mammals have been measured (e.g., Sills et al. 2014; Kastelein et al. 2015), and an audiogram has been modeled for bearded seals (Li et al. 2011) and fin whales (Cranford and Krysl 2015) (see audiograms in Figure 5).

Hearing sensitivities in marine mammals cover wide bandwidths and can be generally grouped into functional hearing groups for the purposes of regulation and management (Southall et al. 2007; NMFS 2018). Four of the five recognized functional hearing groups are represented in the Arctic taxa (Southall et al. 2007; Finneran and Jenkins 2012; Finneran 2016; Finneran et al. 2017; Houser et al. 2017; NMFS 2018): (1) low frequency cetaceans (i.e. bowhead, fin, grey, and minke whales) with an estimated hearing range of 7 Hz to 35 kHz; (2) mid-frequency cetaceans (i.e. beluga whales, narwhals, and killer whales) with an estimated range of 150 Hz to 160 kHz; (3) high-frequency cetaceans (i.e. harbour porpoise) with an estimated range of 200 Hz to 180 kHz; and (4) pinnipeds in water (i.e. all pinnipeds listed above) with an estimated range of 75 Hz to 75 kHz. The pinnipeds can be further divided into three main taxonomic categories or families: otariids (eared seals), phocids (earless seals), and walrus (family Odobenidae). With the exception of the walrus, all of the Arctic species of pinnipeds are phocids, whose hearing is more acute underwater; for this reason Finneran and Jenkins (2012) split the two pinniped groups: phocids (in water), 75 Hz to 75 kHz; and otariids (including odobenids (walrus), in water), 100 Hz to 40 kHz. For reference sake, hearing in humans is generally listed as ranging between 20 Hz and 20 kHz, although in practice, most adult humans do not perceive sounds well above 15 kHz (reviewed in Houser et al. 2017).

General Impacts of Underwater Noise on Marine Mammals

Substantial literature exists on the impacts of underwater noise on marine mammals spanning the past 50 years, which has been well summarized in several reviews (e.g., Richardson et al. 1995; Hildebrand 2005; NRC 2005; MMC 2007; Nowacek et al. 2007; Weilgart 2007; Tyack 2008; NAS 2017). In addition to these broad treatments of noise impacts on marine mammals, Moore et. al (2012) provides a good synthesis of the issue with respect to Arctic marine mammals. Clark et al. (2009) and Erbe et al. (2016) have reviewed the issue of acoustic masking in marine mammals. Ellison et al. (2012) and Gomez et al. (2016) reviewed the problem of context dependency of marine mammal behavioural responses to noise. And finally, Southall et al. (2016) provide a review of experimentally induced behavioural responses of cetaceans to sonar.

For the purposes of this review, a few summarizing points are important to make clear. The impacts of underwater noise on marine mammals can be thought of as either direct (affecting the species of interest) or indirect (affecting other species that in turn affect the species of interest). Most of the work to date has focused on direct impacts which can be thought of as belonging to two non-mutually exclusive categories: (1) physical and (2) behavioural. Recent studies have begun to look more closely at the interaction between these categories. Physical impacts are generally restricted to situations where the proximity to a noise source or the exposure duration is sufficient to result in physical damage to the organism exposed. Results can range from temporary or permanent hearing damage (referred to as temporary or permanent threshold shifts: TTS or PTS) to death (Finneran 2016). Behavioural impacts are wide ranging but in general refer to a shift in an organism's behaviour (e.g., increased vigilance or avoidance) that may have biologically significant implications (e.g., decreased foraging). Some behavioural effects may be obvious, while others, such as changing signal structure and amplitude, may be less so and often involve estimating a change to the animal's energetic input/output (NRC 2005; Parks et al. 2011; Tyack and Janik 2013). Behavioural changes are directly linked to the underlying physiology of the animal, which are similarly impacted by underwater noise in both the short-term (Romano et al. 2004) and long-term (Rolland et al. 2012). Behavioural changes are also linked directly to how animals perceive sound and how noisy anthropogenic activities mask biologically important acoustic signals. As noted above, acoustic masking has been reviewed thoroughly in Clark et al. (2009) and Erbe et al. (2016).

The physical impacts of noise are most severe close to the noise source, and severity generally decreases farther from the source, just as the amplitude of the signal is highest close to the source (Richardson et al. 1995). Behavioural impacts, on the other hand, have been characterized as occurring further away from the source at lower amplitudes, and covering a much larger footprint (Richardson et al. 1995). The difficulty has been in determining biological significance and other issues such as thresholds of disturbance.

The interaction between physical and behavioural noise impacts and other complex pathways of impact have been the focus of more recent attention. Examples include increased stress levels of marine mammals exposed to chronic noise (Rolland et al. 2012). Others include behavioural responses that lead to physical damage, such as the escape response of beaked whales surfacing quickly in response to naval sonar (Southall et al. 2016).

Indirect pathways of impact have also been considered but not clearly demonstrated and may often be more important than direct pathways of impact (Ockendon 2014). One example of an indirect effect pathway is noise affecting the behaviour of a prey species (e.g., fish dispersing or relocating; Ivanova et al. in press), which in turn affects the marine mammals (Mann et al. 1998; Wilson et al. 2011; Simpson et al. 2015). All of these considerations are important with respect to Arctic marine mammals.

The biological significance (i.e. impact on individual fitness or population demography) of both physical and behavioural impacts and their interactions is also difficult to determine. If an impact results in an animal's death, the impact is relatively straightforward but still needs to be scaled to the population level to

determine to what extent it impacts the population viability of the species. However, most impacts are not lethal, and even when they are (e.g. mid-frequency military sonar and beaked whale deaths: Tyack et al. 2011), the number of animals affected is often difficult to accurately determine. Furthermore, determining how a sub-lethal noise impact affects the animal's net fitness, and ultimately the species success, is very difficult, especially for long-lived animals such as marine mammals (New et al. 2013; Pirotta et al. 2018). In most cases, only correlative studies over broad geographic or time scales are available.

Impacts of Underwater Noise on Arctic Marine Mammals

A number of studies have outlined the potential for and approaches to biological impacts of underwater noise on marine mammals in the Arctic (e.g., Moore et al. 2012), although only limited empirical data exist. Most of these studies examined behavioural disturbance, but three (Finneran et al. 2002; Popov et al. 2013; Reichmuth et al. 2016) assessed temporary hearing damage, and one assessed cardiorespiratory responses to noise (Lyamin et al. 2011). Essentially all of the early work on noise impacts on marine mammals in the Arctic began with the oil and gas development push in the 1970s and 1980s focusing on the Alaskan North Slope (e.g., Malme et al. 1983, 1984; Richardson and Malme 1993; Richardson et al. 1995) (Figures 6, 7). The oil and gas activity, primarily in Alaska but also in the Canadian Beaufort, set the stage for an ongoing set of noise impact assessments, primarily aimed at bowhead whales.

BOWHEAD WHALES

Results from a large volume of work clearly showed that bowhead whales would react to seismic airgun noise, usually by avoidance (Richardson et al. 1986). Airgun noise caused the whales to regularly remain 20 km away from the source (Richardson 1999). Depending on the location of the source, the whales would often (but not always) swim closer to the shore (Richardson et al. 2008). The results also raised the issue of whether distant airgun activity, in addition to nearby airgun activity, affected bowhead behaviour (Richardson et al. 2010). Bowheads would also react to airgun noise by changing their calling rates (Richardson et al. 2012; Blackwell et al. 2013); at the first detection of airguns, bowhead calling rates would increase. However, as airgun noise reached a certain loudness threshold, calling would decrease and terminate (Blackwell et al. 2015). Robertson et al. (2013) and Robertson (2014) also found that bowhead dive cycles were disrupted by seismic activity. This is not only a potentially important behavioural impact, but could also cause a significant change in the estimation of numbers of whales present. Finally, several studies have indicated that bowhead responses to seismic activity were context-dependent, with the whales tolerating higher noise levels during feeding than when migrating (Koski et al. 2008; Robertson et al. 2013).

Figure 6. Location of studies on the impacts of underwater noise on marine animals in the Arctic. Symbols are colour-coded by the timeframe of the study, green for 1980-1999 and red for 2000-2018. See Figure 7 for a zoomed-in view of the North Slope of Alaska. Basemap credit: National Oceanic and Atmospheric Administration, National Geophysical Data Center, and International Bathymetric Chart of the Arctic Ocean, and General Bathymetric Chart of the Ocean.

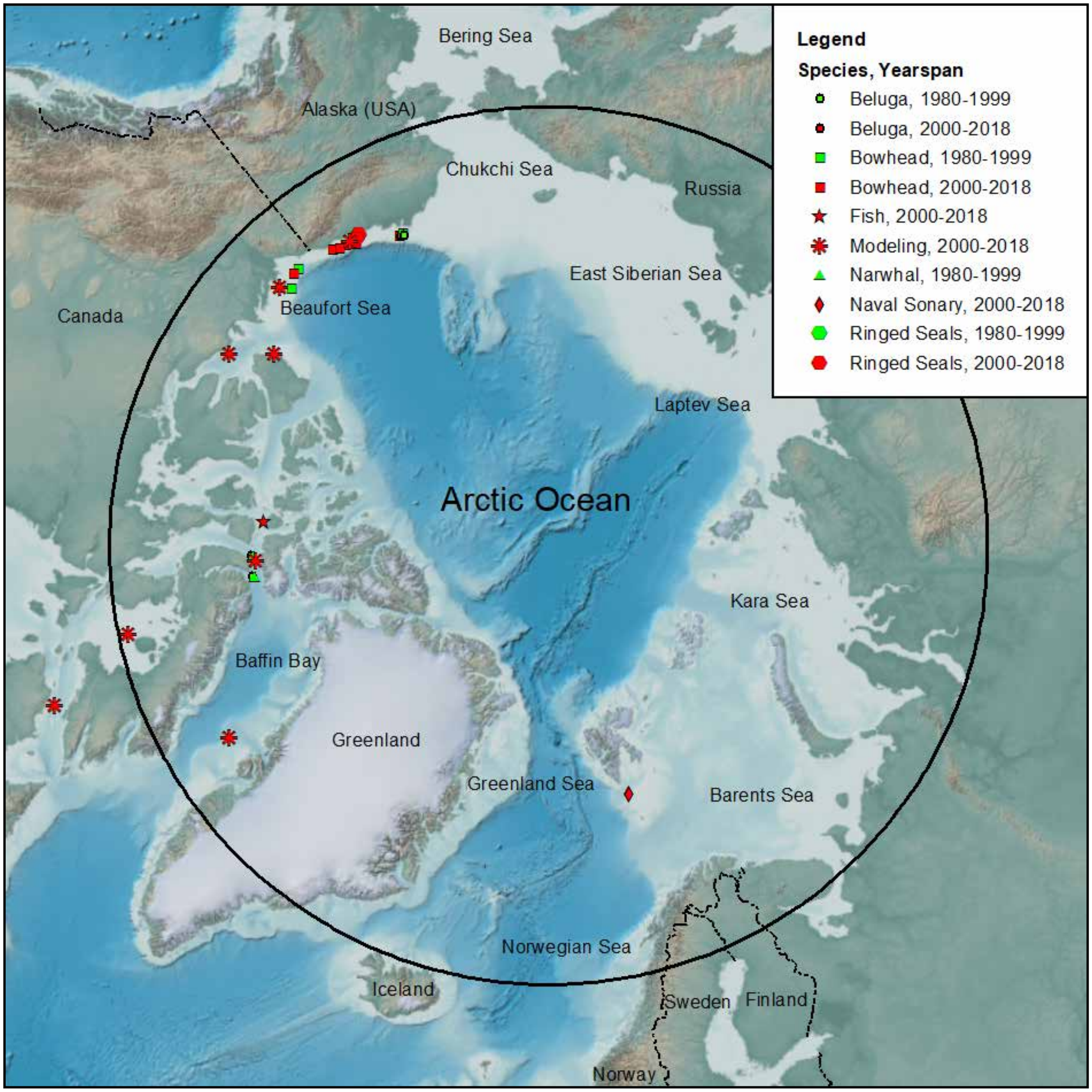
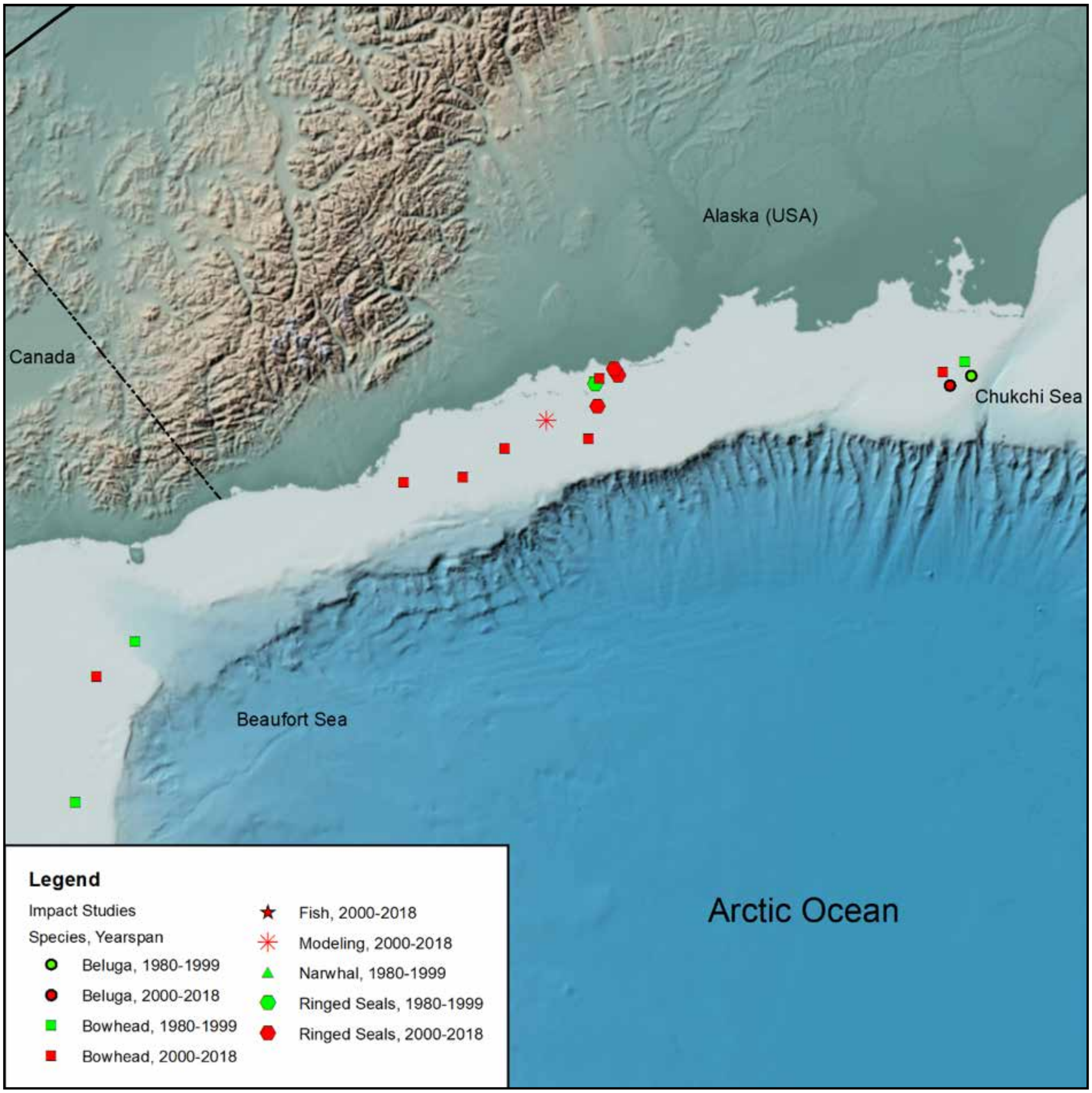


Figure 7. Location of studies on the impacts of underwater noise on marine mammals along the Arctic North Slope of Alaska. Symbols are colour-coded by the timeframe of the study, green for 1980-1999 and red for 2000-2018. Basemap credit: National Oceanic and Atmospheric Administration, National Geophysical Data Center, and International Bathymetric Chart of the Arctic Ocean, and General Bathymetric Chart of the Ocean.



Bowheads also react to other oil and gas operational noise such as drilling and dredging activity through avoidance (Richardson et al. 1990) or changes in calling behaviour; calling rates first increased and then decreased after a certain level in response to continuous, tonal noise from oil rigs, similar to the response to airgun noise (Blackwell et al. 2017). Bowheads have also been shown to react to, by avoidance, other noise sources such as aircraft (Richardson et al. 1985; Patenaude et al. 2002). Note that while aircraft make a substantial amount of noise in air, that noise also then propagates into the water, and is a form of underwater noise. Reactions became strong when the aircraft was closer than 305 m and difficult to detect at distances greater than 610 m. Additionally, Richardson et al. (1985) made observations and recorded reactions of bowheads to boats approaching and noted among the responses, movement away and changes in dive cycles. Attempts were made to conduct playback experiments of icebreaker sounds to bowheads; however, the results were inconclusive largely due to weather (LGL and Greenridge 1995).

BELUGAS AND NARWHALS

A number of studies focused on reactions of both beluga whales and narwhals to ship sounds, primarily icebreakers, indicating a degree of negative responses (Cosens and Dueck 1988; Finley et al. 1990; Blevins 2015). Heide-Jørgensen et al. (2013) presented data suggesting a correlation between seismic survey activities and narwhal entrapments between 2008-2010.

Acoustic playback experiments of icebreaker sounds to beluga whales were inconclusive (LGL and Greenridge 1995). At least some of these results indicate that a significant degree of habituation or learned tolerance by beluga whales can occur that can be specific to certain vessel types (Lesage et al. 1999). In addition, measurements of received levels from ice breakers and ambient sound levels indicated the definite potential for noise impact on beluga whales (Cosens and Dueck 1993; Erbe and Farmer 2000). Patenaude et al. (2002) also tested beluga whale responses to aircraft and found the belugas to be more sensitive than bowheads.

Two studies also assessed temporary threshold shifts (TTS) in beluga (Finneran et al. 2002; Popov et al. 2013). In Finneran et al. (2002), the tested belugas showed onset of TTS at 226 dB re 1 μ$Pa_{peak\text{-}to\text{-}peak}$ (186 dB re 1 μPa_2/s) when exposed to noise from seismic airguns; TTS of 6 and 7 dB at 0.4 and 30 kHz were observed after 2 minutes of exposure, and returned to within 2 dB of the original hearing threshold approximately 4 minutes post-exposure. Popov et al. (2013) examined the reaction of a beluga to half-octave band noise centred at 32 kHz (with an intensity of 140, 150, and 160 dB re 1 μPa) and measured up to 40 dB TTS after a maximum of 30 min exposure duration.

One study (Lyamin et al. 2011) measured the response of the cardiovascular system of a beluga to acoustic noise at 140-160 dB (frequencies between 19 and 108 kHz). The beluga showed an increase of up to 60% in heart rate, which is the first component of the "acoustic startle response".

PINNIPEDS

The empirical studies of noise impacts on pinnipeds all focused on ringed seals. These studies generally found that ringed seals were far more tolerant of noise than whales, whether it be construction-based noise such as from pile driving (Blackwell et al. 2004), drilling (Moulton et al. 2003), or seismic airguns (Harris et al. 2001). Although avoidance behaviours were observed in response to airgun sounds (Harris et al. 2001), it was only at the most intense noise levels (i.e. full seismic array firing) and even then, individuals only moved relatively short distances (~ 250 m away from the source). Richardson (1999) noted that observations of seals were less frequent during seismic activity. One lab study with two captive ringed seals also tested if low frequency (< 100 Hz), low power (190 to 207 $dB_{peak\text{-}to\text{-}peak}$ re 1 μPa at 1 m) air guns could cause temporary threshold shifts, and this study found no evidence of hearing damage (Reichmuth et al. 2016). However, this study did find behavioural responses to increased noise levels. Note that the low power of the airgun used in this study is below the levels predicted to cause a temporary threshold shift in pinnipeds (Southall et al. 2007).

NAVAL MID-FREQUENCY SONAR

a group of studies examined the behavioural impacts of naval mid-frequency sonar on marine mammals in the Norwegian Arctic between Bear Island and Spitsbergen. None of the species that were studied are classified as Arctic species, however, given that this is the only set of studies examining the influence of naval mid-frequency sonar on marine mammals in the Arctic, it is included in this review. The species studied in the first study were killer whales (*Orcinus orca*), long-finned pilot whales (*Globicephala melas*), and sperm whales (*Physeter macrocephalus*) (Miller et al. 2012), and those studied in the other study were humpback whales (*Megaptera novaeangliae*), minke whales (*Balaenoptera bonaerensis*), and northern bottlenose whales (*Hyperoodon ampullatus*) (Sivle et al. 2015). Some animals across all sizes of species showed avoidance behaviour when presented with mid-frequency sonar signals, and other common responses included changing locomotion/orientation, changing in vocal behaviour, change in dive cycle, and cessation of foraging. A related study also found that humpback whales responded similarly to a full blast of mid-frequency sonar versus a ramp-up of sonar from low to high amplitude (Wensveen et al. 2017). Mid-frequency naval sonar has been linked to a variety of impacts on cetaceans in non-Arctic areas (Tyack et al. 2011; Southall et al. 2016).

Modeling the Impacts of Underwater Noise on Arctic Marine Mammals

A small number of studies have modeled the impacts of underwater noise on Arctic marine mammals. These results are grouped into a separate section because these are results from modeling studies, rather than impacts that have been measured. Modeling studies allow for examination of potential noise levels and impacts on animals in regions where direct empirical measurements are difficult to obtain. Modeling studies can also be used to forecast future impacts that have not occurred yet. Challenges associated with modeling studies in the Arctic, especially for all of the studies reported here, is that there has been almost no ground-truthing, so the precision and accuracy of the results are unknown.

Erbe and Farmer (2000) modeled how beluga whales living in the Beaufort Sea are affected by underwater noise from ice breaking activities, and specifically examined acoustic masking, audibility, behavioural disturbance, and hearing damage (TTS). TTS was assumed if a beluga was exposed to a noise at least 96 dB above their audiogram threshold for at least 30 minutes. The model suggested that noise from ice breaking can be audible to belugas out to 32 or 40 km, could cause masking between 14 and 71 km, and behavioural disturbance out to 32 and 46 km. Belugas staying within 40 to 120 m of the ice breaker for at least 20 minutes would have a TTS of 12 to 18 dB.

Ellison et al. (2016) modeled the cumulative noise exposure to bowhead whales migrating past an active oil and gas operation, including noise from vessel traffic and drilling. Approximately 2% of their modeled whales would experience sound levels > 180 dB_{rms} re 1 μPa if they did not change their migratory route in response to noise, whereas if they did change their route, < 1% of the population would experience levels > 160 dB_{rms} re 1 μPa. The majority of bowhead whales that were simulated would have been exposed to audible levels of sound from the oil and gas operation.

Aulanier et al. (2017) modeled noise from shipping at four sites in the Canadian Arctic using 2013 Canadian Coast Guard ship transit information in order to estimate and forecast the distribution of shipping-noise levels and risk of impact on marine habitat based on the predominant 63-Hz 1/3 octave shipping noise band, the probability of exceeding ambient sound levels, and the risk of impact on low-frequency marine mammals. These authors found the greatest impacts on marine mammals in Hudson Strait and Lancaster Sound due to greater vessel traffic, with the least impact in the Amundsen Gulf and Foxe Basin. The authors also note that these areas of high impact only occur during about 2.5% of the shipping season in these regions. However, these authors predicted a large increase in impacts on marine mammals at all four sites based on a 10-fold increase in vessel traffic in the future.

Halliday et al. (2017) modeled sound propagation from two different vessels (research vessel and tanker) transiting the proposed shipping corridor through the western Canadian Arctic, and assessed zones around the vessels where behavioural disturbance were predicted to occur (according to an unweighted 120 dB disturbance threshold), and zones where vessel noise was above ambient levels. The authors also assessed the overlap of these noise levels with two marine protected areas in the region where marine mammals occur.

Their models indicated that vessel noise would be above ambient levels, and therefore likely to be audible beyond 100 km away under low ambient conditions. A noisy vessel could affect behaviour of marine animals as far as 52 km away, whereas a quieter vessel may only affect behaviour of marine mammals 2 km away. They also made in situ acoustic recordings of a vessel from distances up to 135 km away.

Schack and Haapaniemi (2017), using a simple propagation model, modeled distances at which different marine mammals in Baffin Bay could detect vessels during open water and ice covered seasons for vessels traveling to and from Baffinland on Baffin Island, Canada. Based on this model, ringed seals could hear vessel noise from more than 100 km away, beluga whales more than 50 km, and walrus close to 40 km in open water. Under ice-covered conditions, ringed seals and walrus could hear vessel noise from more than 70 km away, and belugas could hear vessel noise from more than 40 km away. Given the simple model used and that available noise data for the model was more than 30 years old, these distances include a large degree of uncertainty. However, this highlights the current lack of available data and the importance of gathering new and improved recordings in a wider part of the Arctic.

Pine et al. (2018B) modeled noise from vessels traveling through the western Canadian Arctic, and assessed how this noise could cause auditory masking in all four marine mammals plus fish in this region. They found that masking was species-specific, but was highest for vessels traveling faster than for slower vessels. Seals were more prone to masking than whales, and fish were the least sensitive to masking.

SUMMARY

Multiple studies have examined the behavioural impacts of anthropogenic underwater noise on Arctic marine mammals, especially for bowhead whales, three studies have examined temporary hearing damage to Arctic marine mammals (belugas and ringed seals), and one study examined cardiorespiratory responses to noise by a single beluga. However, studies on non-Arctic species show that different taxonomic groups of marine mammals have varied sensitivity to noisy anthropogenic activities.

Bowhead whales alter their behaviour in the presence of noise from seismic airguns by avoiding the survey vessel, changing calling rates, and altering their dive cycle. These reactions are also context-dependent, where foraging bowheads would tolerate higher noise levels than would migrating bowheads. Bowheads showed similar responses to drilling and dredging activities by avoiding these activities or changing calling rates. Bowheads also react to noise from aircraft and boats by avoiding them and changing their diving behaviour. Fewer studies have focused on belugas and narwhals, but both species appear to be sensitive to intense noises from ice breaking activities and other shipping noises. Arctic seals appear to be much more tolerant of anthropogenic underwater noise than the whales are, although they still tend to avoid intense noise from seismic airguns. Low power air guns do not cause temporary threshold shifts in ringed seals, but do cause behavioural reactions.

There are several knowledge gaps related to noise impacts on Arctic marine mammals. Geographically, all studies in this review were in North America. Taxonomically, the majority of studies focused on bowhead whales, with only a handful on belugas, narwhals, and ringed seals. Given that CAFF identifies 11 species of Arctic marine mammals, there are an additional seven species that have not been studied in relation to noise impacts. All studies on noise impacts focused on behavioural impacts, and none focused on physiological effects, physical damage, chronic effects, or population-level effects, and the effects of long-term exposure were only mentioned, but not extensively studied. Moreover, no study assessed the cumulative impacts of underwater noise along with other stressors.

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Impacts of Underwater Noise on Arctic Marine Fishes

Hearing in Marine Fishes

Similar to marine mammals, fish have evolved to detect and respond to sound for a variety of life processes. They also produce sounds, either intentionally (i.e. mating calls during courtship) or incidentally (i.e. sudden changes to swimming directions or during feeding). All fishes have ears that detect sound and convey information about gravity and acceleration (Popper et al. 2014). Several reviews have been published on fish hearing and relative sensitivities to underwater sound (Fay 1988; Fay and Simmons 1999; Popper et al. 2003; Popper and Schilt 2008; Fay and Edds-Walton 2008; Sand and Bleckmann 2008).

In general terms, sound underwater is detected by fishes through the inner ear and swim bladder (if present) (Moyle and Cech 2004). Most fish have swim bladders used in buoyancy control. The main structures of the ear responsible for sound detection are the otolithic organs (saccule, lagena and utricle), with the semi-circular canals also comprising the inner ear. Otoliths contained within the otolithic organs respond to particle motion of a sound wave. The greater density of the otoliths results in them moving at a slower rate (amplitude) and different phases compared to the surrounding tissue. The severity and orientation of the epithelium stimulation by contacting the otolith (otoliths are surrounded by sensory epithelia) corresponds to the intensity and direction of the receiving stimulus.

Some fishes are also able to detect the pressure component of a sound wave through their swim bladders, or other gas-filled structures. Such anatomical adaptations allow for the transformation of sound pressures into displacement movements which cause stimulation in the otolithic organs (the vibrations in the surrounding tissue from the compression of air inside the gas-filled structure causes this). Some teleosts have a chain of small bones, called Weberian ossicles, which provide a physical connection between the swim bladder and inner ear for vibration energy to transfer through. Fish that can detect sound pressure as well as particle motion have higher sound sensitivities compared to those that do not; they also have a wider hearing bandwidth (Sand and Enger 1973A,B; Sand and Hawkins 1973, 1974; Fletcher and Crawford 2001; Popper et al. 2014). Atlantic cod is an example of fish that detect sound pressure as well as particle motion. Some fish, like the Atlantic salmon, have swim bladders but only detect particle motion (Hawkins and Johnstone 1978). Fish with no swim bladder or other gas chamber only detect particle motion and not sound pressure. Arctic cod and polar cod, as well as most other Arctic species, do have swim bladders, and thus may detect both pressure and particle motion. If so, they could be more susceptible to noise impacts than fish species without swim bladders.

The lateral line does not play a large role in hearing in fish, and likely only detects particle motion one to two body lengths from the source (Popper et al. 2014). Lateral lines are unlikely to be damaged by anthropogenic noise (Popper et al. 2014).

General Impacts of Underwater Noise on Marine Fishes

Similar to marine mammals, some fish are also highly sensitive to anthropogenic noises. Acute and chronic sound exposures to anthropogenic noise can lead to a range of detrimental impacts. Listed impacts commonly reported in the literature are (1) barotrauma (leading to injury and death); (2) impaired hearing sensitivities; (3) auditory masking; and (4) altered behaviours, which raise questions about population-level effects on fitness and survival. Popper et al. (2014) review these impacts individually for fish, as well as providing noise exposure guidelines for fish.

Barotrauma is tissue damage caused by sudden changes in pressure (Popper et al. 2014). For fish, sudden changes in depths (through startle responses) or pressure waves from sound can lead to barotrauma. Sudden decrease in pressure, such as from impulsive sounds and explosions, can lead to gasses in the blood becoming insoluble, causing damage to surrounding tissues (injury), and changes to gas volumes within gas-chambers causing the chamber to expand and collapse rapidly (Popper et al. 2014). Many different studies have experimentally determined that barotrauma can occur in a variety of fish, including salmonids (McKinstry et al. 2007; Stephenson et al. 2010; Halvorsen et al. 2011, 2012a; Brown et al. 2012; Casper et al. 2012), acipenserids, cichlids, and achirids (Halvorsen et al. 2012b), and moronids (Casper et al. 2013).

Intense noise, either impulsive or continuous, may reduce hearing sensitivities by damaging the sensory hair cells of the inner ear. This is known as a hearing threshold shift. A temporary threshold shift (TTS) is when hearing sensitivities are lower following sound exposure but recover after a period of time. The effect on hearing is likely TTS, as opposed to permanent threshold shifts (PTS) (Popper et al. 2014), since fish constantly add sensory hair cells (e.g., Corwin 1981; 1983; Popper and Hoxter 1984; Lombarte and Popper 1994) and sometimes replace damaged cells (Lombarte et al. 1993; Smith et al. 2006; Schuck and Smith 2009).

As discussed in Section 2.5, the main sources of intense anthropogenic underwater noise in the Arctic are from seismic airguns, vessel traffic, and to a lesser extent, noise from pile driving and drilling. The impacts of these activities on non-Arctic fish are reviewed here. Seismic airguns can cause fish to change their behaviour by fleeing an area and forming more cohesive groups while fleeing. This response increased as the noise level increased (Wardle et al. 2001; McCauley et al. 2002; Fewtrell and McCauley 2012), but fish do become habituated through time (Wardle et al. 2001; McCauley et al. 2002), and, once acclimated, fish may behave normally (Wardle et al. 2001). Fish may even fully leave their preferred habitats if noise from seismic airguns is too high (Paxton et al. 2017), which therefore affects the distribution and abundance of fish in an area (Slotte et al. 2004; Paxton et al. 2017). Hastings and Miksis-Olds (2012) found that seismic airguns did not cause

TTS in fish. However, McCauley et al. (2003) did find evidence of damage to fish ears (sensory epithelia) after exposure to seismic airguns, with no evidence of repair or replacement 58 days post-exposure. Another study, however, found no damage caused to the ears of freshwater fish in northern Canada, although both species have previously shown TTS (Song et al. 2008).

Vessel noise may also cause acoustic masking (Codarin et al. 2009; Putland et al. 2018; Stanley et al. 2018), changes in behaviour (Sara et al. 2007), and increased stress hormone levels (Wysocki et al. 2006; Celi et al. 2015; Cox et al. 2018).

Although noise from drilling activities is not as high as seismic airguns and does not have as widespread an impact as vessel noise, it may still affect fish. Spiga et al. (2017) found that fish move around their environment more, show behavioural signs of increased stress, and show reduced predator inspection behaviours in response to drilling noise.

Impacts of Underwater Noise on Arctic Marine Fishes

The impacts of underwater noise have been studied in very few Arctic marine fish species. The only Arctic-endemic marine fishes identified in this review that have been studied are Arctic cod (Ivanova 2016) and shorthorn sculpin (*Myoxocephalus scorpius*) (Ivanova et al. in press). In both of these studies, the authors used acoustic telemetry to study how the movement behaviour of both species was impacted by noise from vessel traffic in Resolute Bay, Canada (Figure 6). Both species altered their home range and movement patterns in the presence of vessels, even when the vessels were stationary. This suggests that these species have not habituated to any noise from vessels, regardless of whether the vessel is moving or stationary.

Atlantic cod is found in the eastern Arctic, and has been well-studied in its range outside the Arctic. Moreover, studies conducted on Atlantic cod may be directly relevant to Arctic-endemic cod species (i.e. Arctic cod, *Boreogadus saida*, and polar cod, *Arctogadus glacialis*). For example, Stanley et al. (2018) found that vessel noise caused significant acoustic masking in Atlantic cod, which suggests that Arctic-endemic cods likely would also experience acoustic masking.

Two studies also examined the impact of seismic airguns on Arctic freshwater fish in the Mackenzie River Delta, Canada. Cott et al. (2012) assessed hearing damage and inner ear damage in *Couesius plumbeus* (lake chub), a hearing specialist; *Esox lucius* (northern pike), a hearing generalist (both juvenile and adults); and *Coregonus nasus* (broad whitefish) in the presence of a 730 in3 seismic airgun array. The authors found TTS in all species, no evidence of permanent damage, and no evidence of startle or herding responses associated with air gun noise. Jorgenson and Gyselman (2009) studied the same fish community around the same time, and found no evidence of behavioural disturbance (i.e. fish did not change their behaviour). Small airgun arrays and single-pass nature of riverine seismic programs may mean that they are not comparable to marine seismic surveys.

Although there is a wide-range of studies on the impacts of underwater noise on non-Arctic marine fish, it may be difficult to infer similar responses of Arctic marine fish. One obvious reason is that Arctic marine fish live in much colder water, often near 0°C. These low temperatures likely mean that the physiological processes occurring in Arctic fish are occurring at different rates than for non-Arctic species. Generally, Arctic species may even have slow response rates in behavioural changes simply due to the slower underlying physiological mechanisms. However, given the very recent studies on Arctic cod and shorthorn sculpin by Ivanova (2016) and Ivanova et al. (in press), Arctic marine fish do appear to be mobile enough to demonstrate avoidance behaviours. Barotrauma injuries for Arctic cod from noisy, impulsive sounds are also possible since they have internal gas chambers.

SUMMARY

The impacts of anthropogenic underwater noise have only been studied for two of the 633 species of Arctic marine fishes: Arctic cod and shorthorn sculpin. Both species altered their home range size and movement patterns in the presence of noise from vessels. Two other Arctic studies examined the influence of seismic airguns on freshwater riverine fishes in the Mackenzie River. One study found temporary threshold shifts in all species examined, but did not find any permanent hearing damage, and neither study found any influence of seismic airguns on the behaviour of the fishes. No other studies were found that examine the influence of underwater noise on fishes in the Arctic. However, based on studies with non-Arctic fishes, anthropogenic underwater noise is capable of causing barotrauma (leading to injury and death), impaired hearing sensitivities, auditory masking, and altered behaviours in Arctic fishes.

The knowledge gaps for noise impacts on Arctic marine fish are large, as only two species of the 633 species of Arctic marine fish have been studied, both at the same location in the Canadian Arctic. Studies need to be conducted on a more diverse range of Arctic marine fishes at sites throughout the Arctic before firm conclusions can be drawn. These studies can be conducted on a variety of aspects of underwater noise, including physiological impacts and physical damage, population-level impacts, effects of long-term exposure, chronic impacts, and cumulative impacts. A good starting point would be to focus on fish species with the greatest ecological and social importance or greatest potential sensitivity to noise.

Impacts of Underwater Noise on Arctic Marine Invertebrates

Hearing in Marine Invertebrates

There is very little information on hearing in marine invertebrates (Roberts and Elliott 2017). Marine invertebrates are sensitive to low frequency sounds, but only the particle motion component; marine invertebrates do not have an air chamber, and therefore cannot detect the pressure component of sound waves (Breithaupt and Tautz 1990; Goodall et al. 1990; Popper et al. 2001; Carroll et al. 2017; Roberts and Elliott 2017). Sound receptors may be many and varied in marine invertebrates, but two organs have been suggested as likely candidates: the wide range of statocyst or otocyst organs in aquatic organisms and water flow detectors (Normandeau Associates, Inc. 2012). Statocysts are found in cephalopods, some bivalves, echinoderms, and crustaceans (Carroll et al. 2017). In addition to statocysts, cephalopods have epidermal hair cells that help detect particle motion in the near field (Kaifu et al. 2008). Sensory setae on the body and antennae of decapods may be sensitive to low frequency sounds (Popper et al. 2001; Montgomery et al. 2006).

Marine invertebrates are capable of detecting vibrations (Breithaupt and Tautz 1988, 1990; Goodall et al. 1990; Monteclaro et al. 2010; Plummer et al. 1986; Roberts and Breithaupt, 2015; Tautz and Sandeman, 1980). Superficial receptor systems are for the detection of water disturbances (Budelmann 1992), and are found throughout the external body surface of many crustaceans (Breithaupt and Tautz 1990) and consist of either a single cuticular hair or a group of hairs. Cuticular hairs have been described in decapod crustaceans and particularly in lobsters and crayfish (Budelmann 1992). Chordotonal organs can also be used to detect vibrations, and are widespread across crustaceans. These organs are generally associated with joints of flexible appendages (Budelmann 1992). In water, these appendages follow an oscillation caused by a sound wave in the seawater around it, whereby they stimulate the basal chordonal sensory cells.

General Impacts of Underwater Noise on Marine Invertebrates

Multiple studies have examined the influence of anthropogenic underwater noise on non-Arctic marine invertebrates, but no studies have examined the impacts of anthropogenic noise on Arctic invertebrates. The impacts found in non-Arctic species may still be relevant to Arctic species. Here, the focus is on sources of noise that occur in the Arctic: seismic airguns, vessel traffic, pile driving, and drilling. Seismic airguns have been shown to cause mortality in zooplankton, reducing the abundance of zooplankton in an area by up to 64% (McCauley et al. 2017). Other studies have found no impact of seismic airguns on crabs (Pearson et al. 1994; Christian et al. 2003; Boudreau et al. 2009) or lobster larvae (Pearson et al. 1994; Day et al. 2016B). Three studies on lobsters found no damages caused by seismic airguns, but did find sub-lethal effects in feeding behaviour (Payne et al. 2007), serum biochemistry (Payne et al. 2007; Fitzgibbon et al. 2017), and reflexes (Day et al. 2016A). Day et al. (2016A) found delayed mortality in scallops following exposure to seismic airguns, and Anguilar de Soto et al. (2013) found significant body malformations on scallop larvae. Day et al. (2017) found significant physiological harm, increased mortality, and altered behaviour in scallops. However, another study found no effect of seismic airgun surveys on scallops (Harrington et al. 2010). Seismic airgun noise could also cause lesions on the statocysts and other organs of cephalopods (Solé et al. 2013). Cephalopods may also display an alarm response when presented with intense noises from seismic airguns (McCauley et al. 2000; Fewtrell and McCauley 2012), and noise can cause injuries to the statocysts of cuttlefish (Solé et al. 2017)

A few studies have also examined the influence of vessel noise on marine invertebrates. Vessel noise impacts the behaviour of lobsters (Filiciotto et al. 2014), crabs (Wale et al. 2013a), and prawns (Filliciotto et al. 2016). Noise from vessels can also impact the biochemistry and physiology of crabs (Wale et al. 2013b) and prawns (Filliciotto et al. 2016). Small boat noise can also stop the development of nudibranch embryos and can increased mortality in nudibranch larvae (Nedelec et al. 2014). One study also found that shipping noise can modify how sediment-dwelling invertebrates mediate ecosystem properties, specifically related to nutrient cycling in benthic sediments (Solan et al. 2016).

Finally, one study (Tidau and Briffa 2016) reviewed the behavioural impacts of noise on decapod crustaceans, including noise from pile-driving, seismic airguns, vessel traffic, and white noise and pure tones. Studies reviewed by Tidau and Briffa (2016) suggest a variety of behavioural responses (like locomotion changes) and stress, reduced and slower antipredator behaviours, changes in foraging, suppressed behaviours with an ecological function, and changes to intraspecific social behaviour.

SUMMARY

There have been no studies on the impacts of underwater noise on Arctic marine invertebrates. In light of the critical importance of invertebrates at the base of the Arctic food web, it would be helpful to have a better understanding of the effects of anthropogenic noise on a diverse range of Arctic invertebrates at a variety of locations around the Arctic, and the indirect impact of these effects on the species that depend on them.

No studies were found that examined the impacts of underwater noise on Arctic marine invertebrates, therefore this review draws on studies on non-Arctic invertebrates, which may still be relevant for Arctic species. Studies of non-Arctic marine invertebrates have found that seismic airguns can cause mortality in zooplankton and scallops, and sub-lethal impacts, including altered behaviour and serum biochemistry, malformations and lesions, and physiological change in scallops and lobsters. Other studies found no impacts of seismic airguns on crabs, lobsters, and scallops. Vessel noise impacts the behaviour of lobsters, crabs, and prawns. Noise from vessels can also impact the biochemistry and physiology of crabs and prawns, and can modify how sediment-dwelling invertebrates mediate ecosystem properties. Low-frequency noise can severely damage the hearing system of cephalopods.

In Summary

Ambient sound levels are generally lower in the Arctic than in non-polar regions, but are similar to levels in Antarctica. With the reduction of sea ice, ambient levels are expected to increase in the Arctic. The presence of solid sea ice for at least part of the year greatly decreases ambient sound levels, and sea ice also limits the accessibility of the Arctic to anthropogenic activities. On the other hand, ice is itself the cause of increased ambient sound, especially during the period of time when ice is breaking up. Ambient sound levels in the Arctic are typically higher in the summer than in the winter, and also vary geographically, with levels in the Beaufort and Chukchi Seas being lower than levels in the Greenland Sea. Arctic ambient sound levels are driven mostly by natural physical processes (sea ice and wind), but are also influenced by marine mammals and anthropogenic activities during the summer. Multiple studies have documented noisy anthropogenic activities in the Arctic, and these levels are similar to those in non-Arctic regions. Anthropogenic activities are also increasing in the Arctic, so ambient sound levels may increase from increased anthropogenic noise. One activity that is unique to ice-covered waters and polar regions is ice breaking. Source levels for ice breaking are typically higher than the usual noise from vessel activity because ice breakers ram into ice and use other noisy equipment to break ice. Anthropogenic activities in the Arctic may be detected from farther away due to the lower ambient noise levels and unique sound propagation characteristics in the Arctic; therefore, anthropogenic activities have a wider geographic footprint in the Arctic, and may impact marine animals from farther away.

Arctic marine animals are likely impacted by noise-producing anthropogenic activities in the same ways as non-Arctic animals, with one exception: many endemic Arctic animals are likely still not habituated to intense anthropogenic noises because they simply have not been exposed to much anthropogenic activity, and may therefore have a lower threshold for behavioural responses. Studies on Arctic marine mammals have mostly focused on behavioural impacts of anthropogenic noises (i.e. changes in diving, breathing cycles, and calling rates), and the majority of these studies were on bowhead whales. However two studies tested belugas and one ringed seals for hearing damage, and one tested a single beluga for cardiorespiratory response to noise. Only two studies were found on the impacts of noise on Arctic marine fishes, and no studies were found on the impacts of noise on Arctic marine invertebrates. Thresholds for hearing damage and injury for non-Arctic animals may apply well to Arctic animals. However, behavioural disturbance thresholds and acoustic masking are likely very species-specific due to differences in hearing thresholds and acclimation to anthropogenic noise, and may require additional studies on Arctic species of interest. An example is the narwhal, where an initial behavioural response to a novel disturbance could have lethal physiological consequences (Williams et al. 2017), which is possibly analogous to beaked whale reactions to mid-frequency military sonar (Tyack et al 2011).

Is the Arctic a Special Case for Underwater Noise?

The Arctic is a unique case for underwater noise in several ways. First, ambient sound levels are relatively low due to the seasonal presence of solid sea ice and low levels of anthropogenic noise. Second, sound propagation characteristics are unique because of the Arctic sound channel, where sound becomes trapped near the surface of the water, and can propagate over much farther distances at this depth than in non-Arctic waters. Third, the species affected are not only unique but have been largely unexposed to anthropogenic noise (at least to chronic shipping noise). Finally, the endemic species affected are in the midst of massive ecological changes, and are consequently facing a variety of concurrent stressors (e.g., shifts in food, new competitors, new and increased pathogens). Sub-Arctic migrants that rely on the Arctic as a seasonal foraging area may also be impacted by increased underwater noise. It is beneficial to consider the impact of noise as a cumulative stressor, in addition to these other factors, and not in isolation (Moore et al. 2012; NAS 2017). Anthropogenic noises may therefore have a complex range of influence around them in the Arctic.

Gaps in Knowledge and Next Steps for Research

Gaps in knowledge are summarized in Table 4. Several gaps exist in the geographic coverage of this review. This review does not include a single study from the East Siberian Sea, Laptev Sea, Kara Sea, and only a few studies from the Barents Sea, Baffin Bay, and the Canadian Arctic Archipelago. The majority of studies were in the Beaufort Sea, Greenland Sea (Fram Strait), and the Chukchi Sea. Given the higher volume of vessel traffic transiting through the Northern Sea Route, it can be assumed that ambient sound levels are generally higher in areas along that route compared to the Northwest Passage during the summer months. However, this cannot be confirmed without data. There would be strong benefits to conducting studies on ambient sound levels in all of these areas where studies have not been conducted yet. Studies conducted over long-term would be most beneficial in order to monitor changing ambient sound levels. Moreover, a large number of acoustic moorings exist throughout many parts of the Arctic, including the Alaskan Arctic (e.g. Clark et al. 2015) and Fram Strait, which have either not been analyzed in such a way that they could be included in this review or the results of analyses are not readily available. More valuable comparisons of ambient sound levels and underwater noise could be made if acoustic data that are available from across the Arctic are analyzed in a consistent manner. A continually-updated collection of metadata from all recordings across the Arctic would also be useful for future comparisons and collaborations focused on Arctic-wide impacts of underwater noise.

Noise impacts have been studied in very few species of Arctic marine animals: four species of marine mammal (bowhead whales, beluga whales, narwhal, and ringed seals) and two species of marine fish (Arctic cod and shorthorn sculpin). Eleven species of Arctic marine mammals have been identified, yet only four have been studied for noise impacts, and the majority of studies have focused on bowhead whales. 633 species of marine fish have been reported in the Arctic, as well as > 4000 species of marine benthic invertebrates and ~350 species of zooplankton (CAFF 2017). Yet the impact of noise has only been studied on two species of fish, and no noise impact studies have been conducted on Arctic marine invertebrates. More work is needed to understand how underwater noise impacts the diversity of marine animals in the Arctic, including studies on a larger number of species, especially for fish and invertebrates.

All but four of the studies of noise impacts have focused on behavioural responses, such as avoidance reactions, changes in movement patterns, or vocalizations rates. Further studies could also assess physiological impacts, physical damage such as TTS or PTS, population-level consequences, long-term consequences of noise exposures, the ability of species to acclimate or habituate to increased noise levels, as well as any cumulative effects with noise and other stressors.

Hearing sensitivity has only been measured in two Arctic marine species: beluga whales and ringed seals. Audiograms measured in more Arctic species could contribute to understanding how their hearing and communication will be influenced by noise pollution. This is crucial for Arctic marine fishes, since we do not understand how these species perceive sound.

On the technical side, it would be beneficial to standardize measurements of ambient sound levels and source level measurements between studies, and greater collaboration among researchers could ensure consistent methodologies. International standards already exist, and could be used in Arctic studies. Measurements of sound pressure level have varied bandwidths between various studies (see Table 3), which makes comparison between studies impossible. Finally, considering particle motion, especially for fish and invertebrates, could contribute to a more comprehensive understanding of the effects of underwater noise on species of interest.

Table 4. Knowledge gaps identified in this review.

Knowledge Gap	Description
Geographic Coverage	This review does not include a single study from the East Siberian Sea, Laptev Sea, Kara Sea, and only a few studies from the Barents Sea, Baffin Bay, and the Canadian Arctic Archipelago. This gap applies to measurements of ambient sound levels, measures of anthropogenic noise, and impacts on marine animals.
Standardization in measuring ambient sound levels	Many studies were not comparable due to the way that ambient sound levels were measured. Future studies could report new data on ambient sound level in a wide frequency range of power spectral densities, and could use some standardized bandwidth of sound pressure levels.
Measurements of source levels for anthropogenic activities	Source levels have only been measured for a handful of activities in the Arctic. Data is still lacking for these activities, and is non-existent for others, including underwater construction (pile driving, explosions), dredging, a variety of vessels, etc.
Standardization in measuring source level.	Bandwidth for source level measurements, as well as the metric used, varied greatly between studies (see Table 3). These bandwidths and metrics could follow international standards.
Impact of underwater noise on Arctic marine animals	There is no work on Arctic marine invertebrates and only two studies on Arctic marine fish. Studies on Arctic marine mammals all focused on behaviour for four species. Data are lacking for a variety of species of marine invertebrates and fish, as well as studies on other species of marine mammals. This review found very few studies on physiology or hearing damage. Real-time studies would also help fill some of these gaps.
Chronic/cumulative effects of underwater noise on marine animals	No studies have documented the chronic/long-term impacts of underwater noise on any Arctic marine animals, and no studies have looked at the cumulative effects of underwater noise with other stressors. These gaps are also relevant outside of the Arctic.
Hearing sensitivities of Arctic marine animals	There is no information available on hearing sensitivities of Arctic marine fish or invertebrates. For Arctic marine mammals, audiograms have only been measured for beluga whales and ringed seals.
Identify priority areas for monitoring	Information is lacking on locations with the most vessel traffic or greatest likelihood of future vessel traffic, as well as for oil and gas operations (both active drilling and exploration).


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