

UNDERWATER NOISE POLLUTION FROM SHIPPING IN THE ARCTIC

A REPORT TO PAME

APPLIED OCEAN SCIENCES
DW SHIPCONSULT



ARCTIC COUNCIL

| PAME

Protection of the Arctic Marine Environment

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ACRONYMS

AIS – Automatic Identification System

AMAP – Arctic Monitoring and Assessment Programme

AMSA – Arctic Marine Shipping Assessment

AOS – Applied Ocean Sciences

ASTD – Arctic Ship Traffic Database

CAFF – Conservation of Arctic Flora and Fauna

CICE – Los Alamos sea ice model

CMRE – Centre for Maritime Research and Experimentation

dB - decibel

DGPS – Differential (or Digital) Global Positioning System

EBSA – Ecologically and Biologically Significant Area

EEZ – Exclusive Economic Zone

ETA – Estimated Time of Arrival

GEBCO – GEneral Bathymetric Chart of the Oceans

GODAE – Global Ocean Data Assimilation Experiment

GPS – Global Positioning System

GT – Gross Tonnage

HP – Horsepower

HYCOM – HYbrid Coordinate Ocean Model

Hz – Hertz

IACS – International Association of Classification Societies

IHO – International Hydrographic Organization

IMO – International Maritime Organization

IOC – Intergovernmental Oceanographic Commission

IQR – Interquartile Range

IUCN – International Union for Conservation of Nature

kHz – kilohertz, equals 1,000 Hertz

km – kilometer

KMZ – Keyhole Markup language Zipped file

kts – knots

LME – Large Marine Ecosystem

MB – Megabyte

MMSI – Maritime Mobile Service Identity

MPA – Marine Protected Area

μPa – microPascal

NAIS – Nationwide Automatic Identification System

NATO – North Atlantic Treaty Organization

NAVCEN – Navigation Center

NMEA – National Marine Electronics Association

NOAA – National Oceanic and Atmospheric Association (United States of America)

OGA – Oil and Gas Assessment

PAME – Protection of the Arctic Marine Environment

PE – Parabolic Equation

PL – Propagation Loss

PSSA – Particularly Sensitive Sea Area

RAM – Range-dependent Acoustic Model

SDWG – Sustainable Development Working Group

SEL – Sound Energy Level

SO FAR – SOund Fixing and Ranging

SOLAS – Safety of Life at Sea

SOTDMA – Self-Organized Time Division Multiple Access

UBA – Umweltbundesamt, German Environment Agency

UN – United Nations

UNESCO – United Nations Educational, Scientific, and Cultural Organization

UTC – Coordinated Universal Time

VHF – Very High Frequency

VSTW – Speed through water

VTS – Vessel Traffic System

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EXECUTIVE SUMMARY



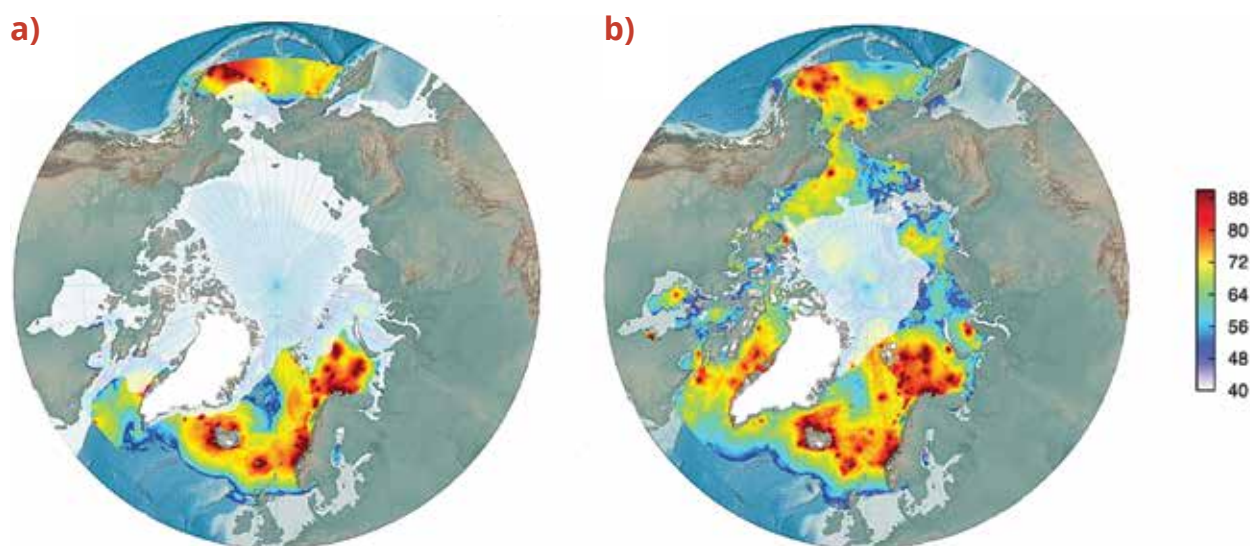


Figure 1. Pan-Arctic 25Hz decade band weekly median SEL for a) March 2015 and b) September 2015 (SEL is in units of $\text{dB}/\mu\text{Pa}^2$). Sea ice is represented by white shading.

One of the starkest signs of global climate change is the loss of sea ice in the Arctic. With this loss of sea ice, there has been an increase in Arctic marine shipping as new sea routes are opening for the first time and existing routes are open for longer than they have been before. This has potentially serious ecological consequences for Arctic marine ecosystems. Ships are a source of marine pollution through emissions and potential oil spills. They create the possibility of ship strikes to the many marine mammals that travel through the area, and they introduce underwater noise into the ocean. The Arctic Ocean's underwater acoustic properties differ from non-polar waters, being primarily affected by sea ice, which is a source, shield, and diffuser of underwater sound. Cold water and changing salinity gradients also affect sound propagation underwater. This, together with the shallowness of the Arctic Basin, means the addition of even a small number of ships can have a substantial effect on the underwater soundscape.

This project provides new knowledge on underwater noise pollution from shipping in the Arctic. Multiple data sources, including PAME's Arctic Ship Traffic Database (ASTD), were used to generate information on source levels of underwater noise produced by ships operating in the Arctic between 2013 and 2019. The contribution of these ships to the underwater soundscape was modelled and changes explored over space and time. Finally, underwater noise from shipping was discussed in relation to potential effects on noise-sensitive species, with a focus on marine mammals, due to their reliance on underwater sound and importance to Arctic coastal Indigenous peoples.

Here, the frequency range of sound use by marine mammals was compared with that of underwater noise from ships (including ice breakers) to identify acoustically sensitive species. Additionally, underwater noise was modelled at a fine-scale resolution in three locations identified as having relatively high presence of shipping and marine mammals (Baffin Bay/Davis Strait, Barents Sea, and Bering Sea). Estimates of excess noise (the amount of additional noise contributed to the ambient underwater soundscape, in this case, by shipping) were generated in these locations and across the Arctic.

SYNOPSIS OF RESULTS

The modelled underwater noise from every AIS-recorded ship in the Arctic from 2013 through 2019 across the Arctic (referred to as the Pan-Arctic) was computed. Shipping noise is reported both as a Sound Energy Level (SEL) and excess noise level. With significant temporal and spatial averaging windows, the median, 75th percentile, and 95th percentile noise values are reported. In this report we show a sample of model products to illustrate the approach and the relevant results, and to guide the conclusions. All model results will be available for viewing on a web-portal currently under development.

Underwater noise levels:

An example of the weekly median shipping SEL for the 25 Hz decade band for March 2015 and September 2015 is shown (Figure 1). In winter there are high shipping noise levels in the Barents Sea, the Kara

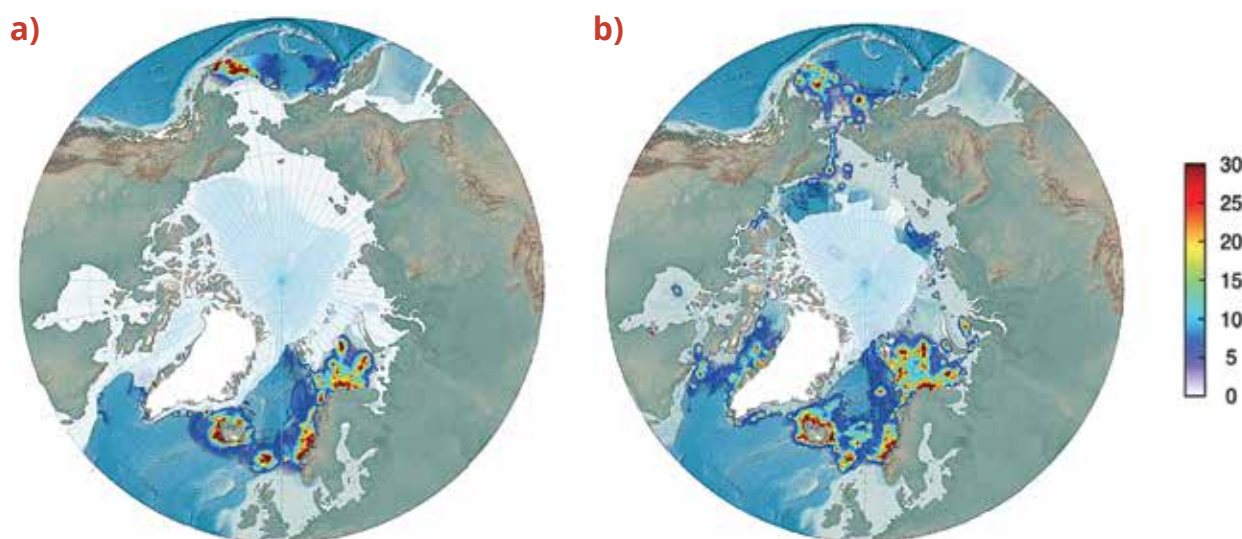


Figure 2. Pan-Arctic 25Hz decidecade band weekly 75th percentile excess noise for a) March 2015 and b) September 2015 (in units of dB/μPa²). Sea ice is represented by white shading.

Sea, southern Bering Sea, and in Baffin Bay along the Greenland coast (Fig. 1a). Note that these are weekly medians, and the “average” noise levels without ships are on the order of 50-70 dB/μPa². In the ice-free summer (Fig. 1b), shipping noise is distributed much more broadly across the Arctic and concentrated in the central Arctic Ocean, the Canadian Archipelago, the Chukchi Sea, and the Beaufort Sea. The sound levels in the Barents Sea, Beaufort Sea, and Baffin Bay are substantially higher and spread out farther in summer than winter.

Excess noise levels:

An example of the 25 Hz excess noise level for the 75th percentile for March 2015 and September 2015 is shown in Figure 2. The excess noise is the sound level above 68 dB/μPa² at 25 Hz decidecade band, a number taken to be a quiet background level. The 75th percentile is relevant to ecosystem impacts because it can be 10-20 dB higher than the median and persists for 6 hours a day (by definition). The peak levels are often driven by the positions of individual ships. In Figure 2a, we see a typical mid-winter, maximal ice extent Pan-Arctic soundscape. Shipping is concentrated in the Barents Sea, up to Svalbard and across the northern Norwegian coast, as well as along the southwest coast of Greenland. There is no shipping in the Bering Sea, or along the northern coast of Russia. In the Arctic summer, with minimal ice cover, the situation changes substantially, as is evident by the modeled excess noise in September 2015 (Figure 2b). The high volume of ships in the Barents has extended well north of Svalbard and there are many ships along the Greenland coast in Baffin Bay. Here we see regions with 15-30 dB excess noise

in the eastern and western Bering Sea, up through the Chukchi and Beaufort Seas, as well as along the Russian northern coast, the Canadian Archipelago (and western Baffin Bay), and even in the central Arctic. Although these are seemingly small increases in shipping excess noise, increases in noise levels on the order of 3-6 dB can have significant impacts upon marine mammals’ ability to communicate.

Changes in underwater noise over time:

While soundscape and excess noise maps like those in Figures 1 and 2 are useful for displaying the spatial distribution of underwater noise (SEL and excess noise levels) from shipping, they are not well suited for evaluating changes in shipping noise over time (intra- and inter-annually). To measure this, we looked at time series of underwater noise from shipping at seven locations, taken from and largely representative of the Arctic’s regional seas, and important for marine mammals in the Bering, Barents, Kara, Laptev, and Beaufort Seas, Baffin Bay, and the Canadian Archipelago. A selection of four of these results for the 63 Hz decidecade SEL is shown over the page (Figure 3). The western portion of Baffin Bay (Figure 3a) shows an increase in noise level of 15-25 dB SEL from 2013 through 2019. This region is covered in ice for much of the year and is very quiet, and thus the intra-annual variation in noise is very high. The northern Barents Sea (Figure 3b), however, shows a significant seasonal rhythm, with median sound levels annually going from 50 to 80+ dB/μPa², but no strong increase in levels across years. The same general conclusions for the North Slope (Beaufort) and Kara and Laptev Sea (Figures 3c and 3d) can be made. In these regions, the number of ships is

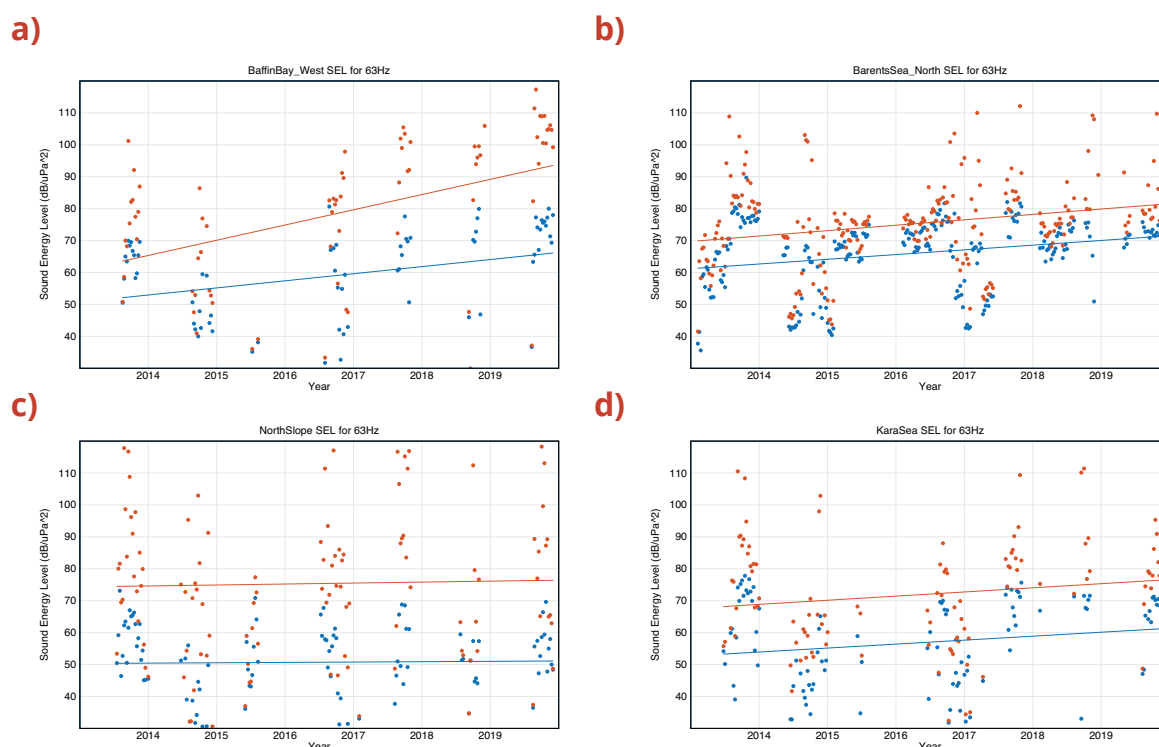


Figure 3. Time series of 63 Hz decidecade SEL ($\text{dB}/\mu\text{Pa}^2$) from 2013 to 2019 showing the median (blue) and 95th percentile (red) in four regional seas: a) Western Baffin Bay, b) Northern Barents Sea, c) North Slope Beaufort Sea, and d) Kara Sea. Each closed circle represents a weekly average SEL, calculated when ships were present.

currently quite small (2-4), so the increase in sound level on the ecosystem is from the new presence of ships, not the increased level of many ships.

CONCLUSIONS AND RECOMMENDATIONS FROM RESULTS

Climate change is transforming the Arctic Ocean and opening it to unprecedented levels of industrial development, including the expansion of commercial shipping. This report presents the first long term, basin-scale shipping noise model of the Arctic Ocean and its regional seas. The Arctic underwater acoustic environment, with its sound-absorbing ice cover, and with the exception of ice-ridging events and wave ice interaction in the marginal ice zone, is substantially quieter than temperate oceans. In this quiet ocean environment and with very little access to light, Arctic marine mammals have evolved unique acoustic capabilities for navigation, hunting, and finding mates. Estimating the extent to which shipping is altering the ambient underwater soundscape is a first step towards understanding potential effects on Arctic marine mammals, other noise-sensitive species and more broadly, Arctic marine ecosystems.

The spatial distribution and levels of underwater noise from shipping in 2013 – 2019 differed between periods of ice cover (November through May) and relatively open ocean (June through October). During periods of ice cover, shipping was limited to the open waters of the Barents Sea and the western coast of Greenland. These areas had a relatively high number of ships and the local soundscapes were dominated by shipping noise. Individual peak levels for a single ship passing a position were on the order of $110 \text{ dB}/\mu\text{Pa}^2$. As the ice retreated, shipping activity increased, with concurrent excess noise levels as high as $30 \text{ dB}/\mu\text{Pa}^2$ (over a week average) in the Bering Sea, Chukchi/Beaufort Sea, Kara Sea, northern Barents Sea, Baffin Bay and the Northwest Passage, as well as in the central Arctic Ocean. Excess noise levels of 3 dB account for a reduction by 50% of acoustic communication ranges for marine mammals.

Over seven years, from 2013 – 2019, underwater noise from shipping increased substantially in multiple locations across the Arctic. This increase in some places effectively represents a doubling in noise levels – some parts of the Arctic are twice as loud as they were in 2013. This is likely a change in marine soundscapes never experienced before. In particular, western Baffin Bay and the Northwest Passage and the Kara Sea, which are ice-covered and therefore extremely quiet for much of the year, experienced increases in underwater noise. For western Baffin Bay, this

increase was by 10 to 20 dB. Regions with limited ice cover in winter showed smaller changes over the same time period, with underwater noise from shipping increasing by approximately 5 – 10 dB in eastern Baffin Bay and Bering Sea. There was also substantial and predictable intra-annual variation in underwater noise in the Barents Sea, in the order of 10-15 dB each year between 2013 and 2019. For reasons that are not clear in the present analysis, the 2013 summer saw substantial shipping traffic in the Arctic. It should be noted that the presence of a single ship can raise the weekly average sound level significantly.

There are areas of uncertainty in this analysis which should be examined to improve our understanding of the impacts of underwater noise from shipping on species, ecosystems, and Indigenous peoples' cultures and food security. The first source of uncertainty is an understanding of the current and historical ocean soundscape prior to the presence of shipping. In this

paper, we have used a combination of ambient sound observations from the Chukchi Sea and historical wind curves to estimate the ambient underwater soundscape. With a 20 to 30 dB/ μPa^2 disparity between ice-covered waters and open water noise climatology, clearly measurements from additional regions should be developed and used to accurately estimate excess noise levels. The Arctic environment is poorly sampled so there is uncertainty in the seafloor topology, the sediment characteristics, and the oceanography, thus there is uncertainty in the acoustic propagation. The impact of sea ice on acoustic propagation has seen significant advances in the past 30 years, but there is still a challenge of sea ice morphology parametrisation which needs to be addressed. Soundscape modeling needs to be validated with observations, and needs to include ice, wind, biological, and anthropogenic sources. Nevertheless, this study is a significant step forward in modelling the effects of increased shipping on the Arctic soundscape.

INTRODUCTION AND JUSTIFICATION

Kolidzei

FOR THIS REPORT



Shipping in a changing Arctic:

A significant observable impact of global climate change is the dramatic reduction in sea ice extent in the Arctic Ocean. Warming in the Arctic Ocean has been particularly significant in recent years compared to the past century. With sea surface temperature warming rates three times that of the global rate, winter sea ice thickness has been reduced by as much as 0.75 m since 1965 and has declined 11.5% per decade since 1979^{1,2}. The annual duration of the ice melt and ice formation seasons have also been changing³. The area covered in four-year or older sea ice decreased from 2.7 million square kilometers in September 1984 to 53,000 square kilometers in September 2019⁴. As sea ice coverage reduces, an ice-free Arctic Ocean is a real possibility by the boreal summers of the 2030s⁵. This brings greater opportunities for commercial, leisure, military, and fishing vessels to transit through the Arctic during, at least, the boreal summer. As the Northwest Passage opens to shipping traffic, the impact on this relatively pristine, remote ecosystem must be understood and monitored.

In the past two decades, shipping activity during the Arctic summer has increased, concurrent with reductions in Arctic sea ice extent and a shift to predominantly seasonal ice cover. A recent assessment of shipping trends in the Arctic by the Arctic Council's PAME working group estimated that the number of ships entering Arctic waters (defined by IMO Polar Code boundaries) grew by 25 percent between 2013 and 2019 (PAME – Arctic Shipping Status Report #1 2020). As well, the total distance sailed by ships during that time grew by 75 percent, from 6.51 million nautical miles in 2013 to 9.5 million nautical miles in 2019 (PAME – Arctic Shipping Status Report #1 2020). The PAME report also found that the distance sailed by bulk carriers in the Arctic Polar Code area has risen 160 percent. Increased shipping is likely to lead to a louder underwater Arctic soundscape⁶, as ship noise is considered to be the biggest contributor to underwater anthropogenic noise globally^{7,8}.

The Arctic Ocean soundscape:

The soundscape in the Arctic is quite unlike those of temperate oceans⁹. Sea ice cover, when present, prevents abiotic (e.g., wind) and anthropogenic sources (e.g., oil exploration, ship traffic) from contributing to ambient sound levels. Sea ice is both a scatterer (by way of surface roughness) and an attenuator (through conversion to shear waves in the ice), so it reduces acoustic propagation when present¹⁰. This can lead to relatively quiet ambient sound levels. Conversely, the ice itself can generate significant sound during ridging events and cracking. Marine mammal vocalisations can also be a significant contributor to the soundscape when animals are present. Arctic biophonies largely include sounds from residential species such as walrus

knocking, bowhead singing, beluga whistling and buzzing, and ringed seal calling^{11,12,13}.

The Arctic Basin is shallow compared to other oceanic regions around the world¹⁴. Because sound travels quite far through the shallow basin¹⁵, there is potential that small numbers of ships transiting Arctic waters can contribute substantially to the underwater soundscape. Sound propagation is also different in the Arctic compared to temperate oceans. Due to cold surface temperatures of the Arctic Ocean, a phenomenon called 'surface ducting' often takes place. Sound speed is a function of temperature, salinity, and pressure, and in temperate regions this creates a sound speed minimum at some depth, often a few hundred meters below the surface, where the water is cold (which leads to slower sound propagation), but the pressure is not yet high enough to cause the speed of sound to increase again with depth. This causes sound to propagate great distances at this sound speed minimum depth, which is sometimes referred to as the 'deep sound channel' or 'sound fixing and ranging (SOFAR) channel'¹⁶, because of the refraction of sound energy towards slower speeds due to Snell's law. In high latitudes, with colder sea surface temperatures, the sound speed minimum moves to shallower depths. In the Arctic, the sound speed minimum is at the ocean's surface¹⁷. This causes sound to refract upward everywhere, in the process known as surface ducting. This allows sound generated near the surface, such as noise from ships, to propagate great distances. Climate change is predicted to affect the Arctic Ocean's soundscape. Changes in pH, temperature, upper-ocean stratification and sea ice characteristics (including sea ice age and cover) will affect ambient sound levels and sound propagation.

Arctic marine species and sound:

There is a growing body of literature on the use of underwater sound by marine species, including marine mammals, fishes, and invertebrates. Marine mammals sense their environment using primarily underwater sound, which they use to navigate, communicate with conspecifics, detect prey, and avoid threats/predation¹⁸. The Arctic is home to 35 species of marine mammals for at least part of the year, and it is reasonable to assume that these species have adapted acoustic communication strategies to be effective in propagation environments both with and without sea ice.

Arctic marine mammals are strongly associated with or even dependent on sea ice. Climate change makes them especially vulnerable to habitat loss and increased competition with more temperate species, such as fin whales and humpback whales, which are extending their ranges into the warming Arctic⁶. Industrial development, including the expansion of shipping, has the potential to place additional

pressure on these species, and changing underwater soundscapes resulting from climate change and increased anthropogenic noise are particularly likely to affect endemic species, which have, until recently, had very limited exposure to such sources of noise.

Healthy populations of marine mammals, fishes, and invertebrates are critical for the functioning of Arctic marine ecosystems and for the livelihoods and cultures of many Indigenous coastal communities. It is important to understand how activities such as Arctic shipping are contributing to the underwater environment as a first step to ensuring that anthropogenic noise is managed at safe levels for biodiversity.

The aim of this project is to determine the spatial distribution, trends, and levels of underwater noise from Arctic shipping between 2013 and 2019 and to explore the implications of these findings for noise-sensitive species, focusing here on Arctic marine

mammals. This report presents the following analyses with associated products:

1. Source levels of underwater noise produced by ships operating in the Arctic from 2013 – 2019.
2. Underwater noise levels from shipping across the Arctic from 2013 – 2019, including the spatial distribution of underwater noise and changes in noise levels over time.
3. Implications for marine mammals of underwater noise from shipping, through:
 - a. Exploring the overlap in acoustic frequencies produced by ship noise and used by marine mammals.
 - a. Underwater noise levels and excess noise in three regions of the Arctic with high densities of ship traffic and marine mammals.

DATASETS USED IN ANALYSES



***HYCOM:***

The ocean environment used for all computations will be the 4- dimensional ocean field (US Navy Polar HYCOM model, CICE, and the Pan-Arctic Ice-Ocean Modeling and Assimilation System) hind-casts dating back to 2013.

The HYCOM consortium is a multi-institutional effort sponsored by the National Ocean Partnership Program (www.nopp.org) as part of the U. S. Global Ocean Data Assimilation Experiment (<https://nrlgodae1.nrlmry.navy.mil>), to develop and evaluate a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model (called HYbrid Coordinate Ocean Model or HYCOM).

The GODAE objectives of three-dimensional depiction of the ocean state at fine resolution in real time, provision of boundary conditions for coastal and regional models, and provision of oceanic boundary conditions for a global coupled ocean-atmosphere prediction model, are being addressed by a partnership of institutions that represent a broad spectrum of the oceanographic community.

Sediment data:

The seafloor type model will be the US Navy Bottom Sediment Type database. The Naval Oceanographic Office maintains a bottom-sediment province database at three levels of resolution: (1) a low-resolution legacy dataset derived from secondary sources for the low- and mid-latitude ocean basins; (2) medium-resolution, actively maintained “Regional Sediments” datasets covering most of the continental margins of Eurasia and North America; and (3) high-resolution, limited-extent datasets derived from acoustic imagery. The high-resolution set derives from multiple sources. These include the analyses of grabs and cores collected during surveys conducted by NAVOCEANO, National Imagery and Mapping Agency (NIMA) charts, side scan imagery, seismic, bathymetry, and public literature. The low-resolution set is assembled from various high-level sources, including maps, atlases, and regional studies of ocean basins.

Sediment provinces are categorized via an “Enhanced” sediment classification consisting of seven locational, ten compositional, and 97 textural components. To provide accessibility and consistency to a variety of users, the Enhanced categories are reclassified into simplified or specialized sediment category sets. These include the High Frequency Environmental Acoustics categories for performance prediction, a mean grain-size set, a non-technical littoral set, as well as other bottom characteristics such as burial potential and bottom type. The Enhanced categories have also been assigned a limited number of geoacoustic and physical properties. Although the province approach and the reclassification schemes produce useful inputs for

models and other predictions, users must recognise that they are subject to inherent limitations and ambiguities.

Bathymetry data:

The bathymetry data used was the most recent (2019) release of the GEBCO world-wide database. GEBCO's aim is to provide the most authoritative publicly available bathymetry of the world's oceans. It operates under the joint auspices of the International Hydrographic Organization (IHO) and the Intergovernmental Oceanographic Commission (IOC) (of UNESCO). GEBCO produces a range of bathymetric datasets and products. This includes global gridded bathymetric datasets, the GEBCO Gazetteer of Undersea Feature Names, the GEBCO world map, and the IHO-IOC GEBCO Cook Book— a reference manual on how to build bathymetric grids.

ASTD:

PAME's Arctic Ship Traffic Data (ASTD) System collects a wide range of historical information, including ship tracks by ship type, information on number of ships in over 60 ports/communities across the Arctic, detailed measurements on emissions by ships, shipping activity in specific areas (e.g., the EEZs, Arctic LMEs and the Polar Code area), and fuel consumption by ships.

PAME and the Arctic Council use the data from the System to conduct analyses and develop projects that benefit many different projects across working groups. Participant countries, currently seven of the eight Arctic States, have access for their own research and analysis, while Permanent Participants, Arctic Council Observers and other subsidiary bodies can gain access to the system upon request. Each user is designated access via a username and password and can download the data for their own analysis. Users are also provided with the ability to add their own data to the system, including shapefiles, to display in the System.

AIS data:

Most modern commercial vessels regularly transmit their location via Very High Frequency (VHF) radio using the Automatic Identification System (AIS). AIS is an automated system of tracking ships for the purposes of collision avoidance and safety of life at sea. AIS was not designed to function as a global monitoring system or for use in research applications, but the data can be logged and used to track ships for the purposes of using them as acoustic sources of opportunity. AIS utilises standard VHF radio communications to transmit name, identification number, course, speed, position, and other various data for ships equipped with the system. AIS can be picked up by satellites.

AIS was originally developed in the early 1990s as a short-range identification and tracking system for avoiding vessel collisions. In 2002 the International

Maritime Organization (IMO) Safety of Life at Sea (SOLAS) mandated most vessels over 300 gross tons be equipped with AIS. Over the next three years individual nations and the IMO started to implement stricter and more comprehensive mandates requiring vessels be equipped with AIS. In 2005, some government entities and private companies began experimenting with collecting AIS data via satellite, and by 2006 most maritime nations had mandated large commercial vessels on international voyages be equipped with some form of AIS.

By 2010, all commercial vessels in European Internal Waterways were mandated to use AIS. In 2012, over 250,000 vessels worldwide were equipped with AIS, with over one million vessels expected to be outfitted in the next few years. In 2013 and 2014 the United States and Europe (respectively) expanded AIS carriage requirements further and all of the aforementioned requirements became enforceable by law without exception. Currently the IMO requires all vessels over 300 gross tons on international voyages, all vessels over 500 gross tons on domestic voyages, and all passenger vessels regardless of size be outfitted with AIS. In the United States, commercial vessels over 65 ft in length, except small passenger vessels and fishing vessels, all tanker vessels, and passenger vessels over 150 GT wishing to travel internationally, must transmit AIS. Additionally, most vessels 65 ft in length or more operating in or near a Vessel Traffic System (VTS; present in most major ports), and all towing vessels over 26 ft and more than 600 HP must always transmit AIS. Vessels classified as warships are exempt from this requirement but nearly always transmit when near areas of high vessel traffic for safety purposes. There are additional rules going into effect in the United States and Europe that will require fishing vessels over 15 m in length and vessels on domestic voyages to carry AIS as well.

All vessels that carry AIS must always be transmitting. This means that any vessel that could potentially operate in a Vessel Traffic System (VTS), travel internationally, or carry passengers must always be transmitting their location via AIS. Nearly all commercial vessels, and pleasure craft of any considerable size, are transmitting on AIS, which means the location of nearly all acoustic radiators in the frequency range between about 10 and 300 Hz is known at all times. The potential applications of this knowledge to acoustic sensing techniques is exciting.

AIS uses standard VHF Radio Communications, which means it is limited in range to nearly line of sight communications. For the 12 W class A AIS transmitters that most large vessels are equipped with, this limits the range, under ideal atmospheric conditions, to about 74 km. Under more typical conditions this number is more realistically closer to half of that. This depends on

the height and quality of the transmitters and receivers. AIS transmissions are time multiplexed using Self-Organized Time Division Multiple Access (SOTDMA) and there are 4500 time slots per minute, which can be overloaded by 400-500% by sharing time slots between ships. This system of sharing bandwidth amounts to each ship in a crowded port being able to transmit their location every 2-4 seconds depending on the amount of vessels in the area sharing the time slots. Larger commercial vessels equipped with Class A transmitters transmit their location every few seconds, while smaller vessels equipped with class B transmitters only transmit their location every 30 seconds. Faster moving vessels will automatically transmit their location more often (every 2 seconds) while ships at anchor only transmit every 60 seconds.

Standard AIS integrates the ships' GPS navigation system, electronic charting systems, and VHF radio transceiver. There are 27 possible types of AIS messages. For class A systems, navigational data including vessel name, Maritime Mobile Service Identity (MMSI) number, course, speed, rate of turn, position, and a time stamp in UTC seconds are transmitted every few seconds. The latitude and longitude can be transmitted with up to 0.0001 minute precision; but is limited by the accuracy of the GPS which can potentially be accurate to less than a meter when within 370 km of land where the signal can be corrected by a Differential (or Digital) GPS (DGPS) tower, and accurate to within 2-15 m when further offshore. In addition to navigational data transmitted every few seconds, ships equipped with class A AIS units also transmit static reports every 6 minutes, which include type of cargo, type of vessel, dimensions of the ship (to the nearest meter), surveyed location of ship's positioning system antennae (GPS) in meters from bow, stern, and port and starboard sides. Additional information transmitted in the static reports includes the type of positioning system the ship is equipped with, the draft of the ship, destination, ETA, and an optional high precision UTC time stamp. All of this information makes it possible to characterize the ship as an acoustic radiator with great precision. AIS data is available anywhere in the world. Between

government agencies that log the data from arrays of shore-based radio towers, and private companies that record massive databases of satellite-derived AIS ship tracking data, one could reasonably obtain AIS data for any experiment conducted from 2009 through the present. In United States' coastal waters, the United States Coast Guard Navigation Center (NAVCEN) Nationwide AIS (NAIS) database uses a network of 200 VHF radio transceiver towers nationwide to record all AIS data within about 100 km of the US coast for the primary purpose of Maritime Domain Awareness. NAIS provides historical data upon request to most organisations, and institutions affiliated with the United States Government can request live-feed access to their database for real time coverage. NATO has a similar system which records AIS data along the European coast that is also sometimes available upon request. Other sources of AIS ship tracking data include NATO's Centre for Maritime Research and Experimentation (CMRE), which records AIS ship tracking for several European and international regions for research purposes and is often willing to share data with outside researchers.

AIS Data is originally transmitted in the standard National Marine Electronics Association (NMEA) format. There are a total of 27 different types of NMEA messages utilised by AIS systems, but we are primarily concerned with message types 1-3 which relay navigational data, and message type 5 which relays static reports including information about the ship.

IHS Fairplay data:

IHS Fairplay is the largest maritime database in the world, evolved from the Lloyd's Register of Ships published since 1764, covering ship characteristics, movements, ownership, casualties, ports, news and research.

IHS Fairplay Movement information enables the user to track live ship positions with unrivalled AIS coverage, analyse the risk profiles of ships entering a jurisdiction's waters, and watch the global flow of energy commodities across the waves.



PROCESSING THE ARCTIC SHIP TRAFFIC DATABASE DATASET



The Arctic Shipping Traffic Data (ASTD) AIS dataset was provided to AOS by PAME and was processed by Dr. Chris Verlinden (AOS) in November 2020. The objective was to develop a list of reliable shipping tracks through the Arctic from 2013 through 2019. AIS data is infamous for its lack of data reliability and for the need for stringent filters to find ships that actually transit the ocean basin.

AOS was provided with raw ASTD data from January 2013 to April 2020. These monthly files were between 1.5 and 6 GB; the entire dataset was 335 GB with over 1.37 billion ship positions. 99.99% of these reports had an MMSI (Maritime Mobile Service Identity) number associated with them; 62.02% had an IMO (International Maritime Organization) number. There were 362,009 unique MMSI numbers and 37,276 unique IMO numbers represented. The vessels which had valid MMSI numbers but not IMO numbers did not have any vessel class, fishing/non-fishing, size, or

flag information in the dataset. Some of the vessels which had MMSI numbers but not IMO numbers were autonomous platforms, military vessels, pilot vessels, recreational vessels, etc., but others were standard container/cargo vessels. Vessels with MMSI numbers but not IMO numbers were also more likely to plot on land, or in other non-physical locations.

Figure 4 shows the number of unique MMSI and IMO numbers by LME in the raw dataset. Large marine ecosystems (LMEs) are large areas of coastal ocean space, spanning 200,000 square km or more, extending from estuaries or river basins to the edges of continental shelves or the margins of major currents. There are currently 18 LMEs in the Arctic¹⁹.

The next step was to quality control the database, i.e., eliminate spurious, aliased, spoofed, or other false reports, conduct some preliminary data-discovery analysis, and interpolate vessel tracks to hourly

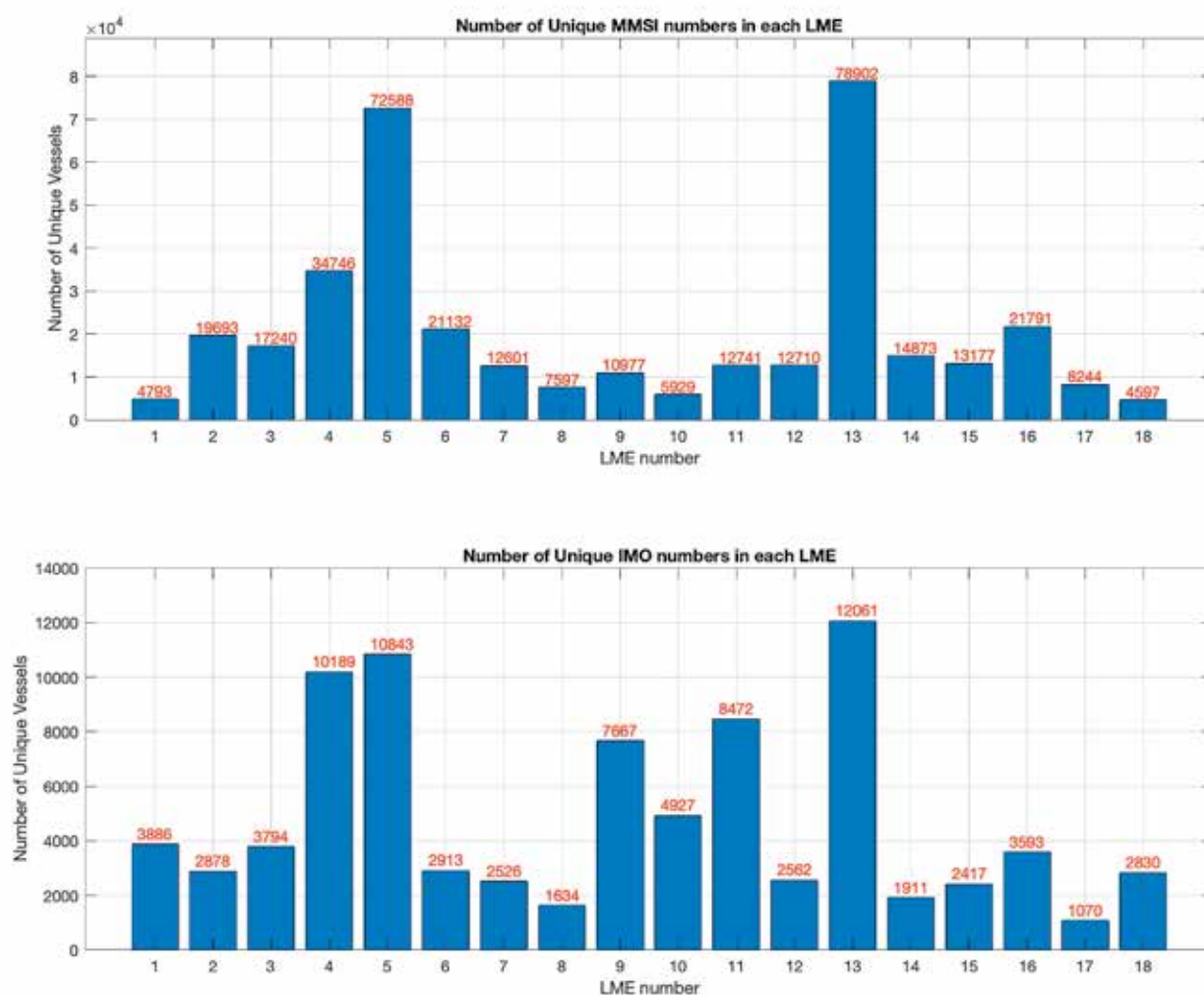


Figure 4. The number of unique MMSI and LMO numbers by LME in the raw Arctic Shipping Traffic Data AIS dataset

snapshots for acoustic simulations. The filtering applied by Dr. Verlinden to obtain a clean set of ship tracks from 2013 through 2019 is provided below. The first pass of this processing was to provide DW ShipConsult with a list of large vessels that they could generate source signatures for. It is expected that that list contains a small list of mostly non-fishing vessels that are regularly present in arctic waters.

The vessels were sorted based upon their reported gross tonnage, and only those vessels with greater than 1000 GT were kept. This removed a large number of fishing vessels. Sorting by gross tonnage thinned the total number of unique vessels in the dataset from over 100 thousand vessels to 19,731 vessels.

Each ship kept for this analysis must have:

- Gross Tonnage (GT) > 1000 GT.
- More than 100 points total of AIS data in the 7-year dataset.
- No gaps between reports larger than 200 km (if there were any such gaps the ship track was

broken into multiple parts at these gaps).

- An MMSI number or an IMO number. Vessels with multiple MMSI numbers were joined into a single entity with a single IMO and MMSI number.
- 60+ hits over a month time period.
- A speed between 1 kts and 50 kts.

It is of note that after joining multiple MMSI number vessels, a vast majority of >1000 GT vessels had both MMSI numbers and IMO numbers, which is an indication of reliability. After applying the above filtering to the dataset, there were only 9,724 vessels that met that criteria over 1000 GT, and 17,285 unique vessels of any size class including the 9,724 vessels meeting the criteria. The filtered monthly files, with interpolated 1-hr intervals between reports, contained between 900,000 and over 2 million vessel locations, with file sizes ranging from 90 to 235 MB. The files contained the following columns: [Lat, Lon, Y-Coordinate (m from North Pole), X-Coordinate (m from North Pole), Unix Time, MMSI Number, IMO Number, Speed (kts), Heading (degrees true), Vessel size (GT)].



An aerial photograph of the Arctic region, showing a dense field of icebergs and ice floes of various sizes. The ice is a mix of white and light blue, with dark blue water visible in the channels between the ice. The overall scene is a complex, textured mosaic of ice and water.

METHODOLOGY

1. CALCULATING UNDERWATER NOISE SOURCE LEVELS OF SHIPS OPERATING IN THE ARCTIC

From processing the ASTD AIS data, 9,724 large ships (over 1000 GT) were identified transiting the Arctic from 2013 – 2019. These were used in analyses of ship source levels. Today, there are software tools available to predict radiated noise of ship engines and other machinery. Propeller noise can also be modelled but the accuracy of these hydrodynamic calculations is significantly lower than modelling of mechanical effects of engines. However, all deterministic engineering tools for noise prediction require a degree of detailed information. This includes characteristics of engines, their integration into the ship, properties of the ship's

steel structure and hull shape and geometric details of the propeller. These data are generally difficult to access and if at all, are typically only available at the building shipyard.

In the context of environmental modelling there is a high number of ships to consider, these are typically built in very different locations of the world. Therefore, it appears unfeasible to collect all required input data for prediction of radiated ship noise with above mentioned tools. In order to generate source levels for propagation modelling nevertheless, various empirical tools have been developed, as shown in Table 1.

Selection of prediction model to calculate source levels

To estimate underwater noise source levels of ships, current models such as AQUO²⁰, Wales & Heitmeier²¹ mainly consider the speed through water (VSTW) and

size or less information of a ship and neglect ship-specific design parameters. Table 1 lists current models by year of publication with input parameters taken into account. Only the AQUO and Wittekind model use the cavitation inception speed (VCIS) while only the Wittekind model makes use of additional information about the engines (main engine, generator).

Year	Model	V _{STW}	V _{CIS}	Size	Engine	Ship category	f _{min}	f _{max}
1964	Ross & Alvarez	✓	×	✓	×	None	100	10,000
1976	Ross	✓	×	×	×	< 30,000 t	100	10,000
1983	Urick	✓	×	✓	×	None	100	10,000
1988	IFREMER	✓	×	×	×	Research		
1990	ANATRA	×	×	×	×	Noise Type	10	10,000
1996	RANDI	✓	×	✓	×	Ship Type	10	10,000
2002	Wales	×	×	×	×	None	30	1,200
2014	Wittekind	✓	✓	✓	✓	Merchant	10	10,000
2015	AQUO	✓	✓	✓	×	Ship Type	10	10,000
2015	SONIC	✓	×	×	×	Ship Type	10	10,000

Table 1. Overview of existing models for underwater noise predictions (Daniel, 2020)

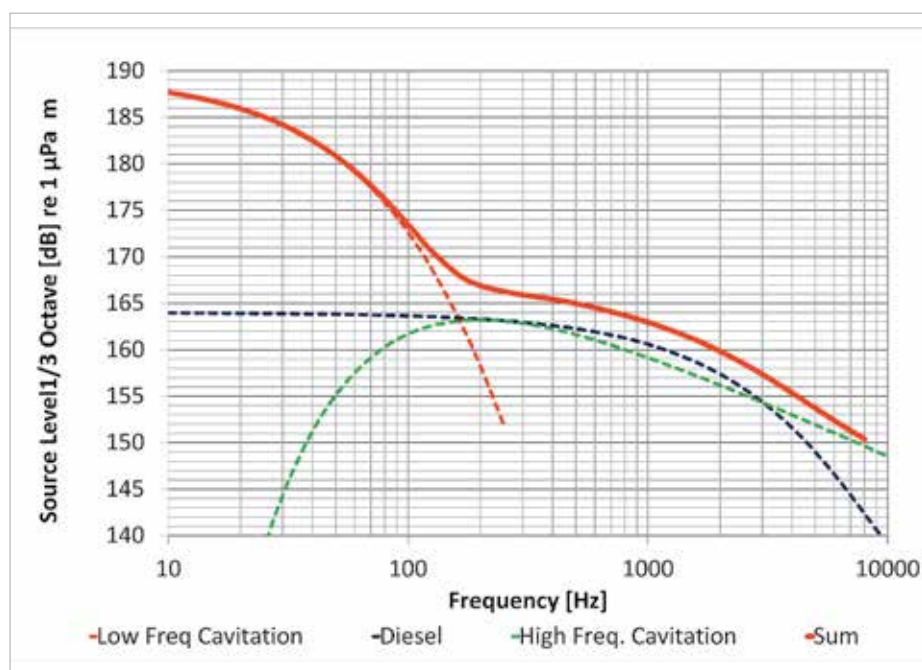


Figure 5. Illustration of individual noise sources as described in the Wittekind model V0, shown for medium sized container vessel.

For accurate modelling of distribution of ship noise, it is necessary to minimise the error of source levels. The available models were tested by comparison of predicted source level versus measured levels. A series of long-term measurements in the German Baltic Sea and North Sea in combination with AIS data and IHS data was used to gather required input for this benchmark. Further description of the benchmarking procedure is found in Appendix C. The Wittekind model was chosen for further modelling of ship source levels in this project.

Methodology of the Wittekind Model

The Wittekind model approaches calculation of radiated noise by description of the typical, dominant noise sources on board. These are main engines and auxiliary engines as well as the propeller, which is distinguished by high frequency and low frequency cavitation (Figure 5). Design specific parameters of the individual ship are taken into account by means of the block coefficient, the speed relative to the cavitation inception speed, the mass and mounting of the diesel engines as well as the displacement. DW-ShipConsult has been working continuously on the further development and overall validation of the Wittekind model since its release in 2014. The modelling of small vessels, such as fishing vessels, was developed additionally to supplement modelling of Arctic waters where a high number of fishing vessels is present.

The initial version of the model required input which was not explicitly contained in AIS data, e.g. engine power, mounting type of engines and cavitation inception speed. In order for the model to be applicable with typically available data, it was further developed for application on basis of AIS-data, to cover additional noise sources (two-stroke engines) and more operating conditions (speed dependence of engine noise). Additionally, the input was simplified to minimise the number of required input parameters. A summary of all available versions of the model is found in Table 2, Appendix C.

Input data

The model to calculate ship source levels was applied in combination with ASTD data. These contain a reduced subset of AIS data broadcast by ships in Arctic waters. The remaining information in ASTD data can primarily be used to describe ship tracks. Information on the characteristics of individual ships is only contained in the parameter “GT group” which coarsely classifies the vessel as small or large in 7 groups from <1,000GT to >= 100,000GT and “Lloyds Cat5 ship type” which describes the task of the ship. To gain more detailed knowledge on the ships, additional IHS data was purchased for proper technical description. summarises available data in comparison to required input data of the Wittekind model.

IHS data description

IHS data were purchased based on a filtered list of ships operating in the Arctic (see section on Processing of ASTD dataset, above). This list contained unique IMO and MMSI numbers of ships contained in the entire ASTD data set. The delivered data set from IHS contained a total of 8630 ships with a possible description of 43 parameters. These parameters describe e.g., main dimensions, ship type, classification, consumption, deadweight, displacement, service speed, engine characteristics and propulsion characteristics. The main focus for this project is on ship type, main dimensions, speed and engine parameters. For 6051

ships this information was available. For an additional 1733 ships, the relevant information could be derived by statistical approaches (see Appendix C).

The calculation of source levels was integrated into processing of ASTD data as shown in Figure 6.

2. UNDERWATER NOISE

PROPAGATION FROM SHIPPING

Propagation models and parameters

To understand the contribution of underwater noise from shipping in the Arctic, noise propagation was completed at two spatial scales: a) across the Arctic (Pan-Arctic model) and b) in three regional seas where shipping overlaps with high densities of marine mammals.

a. Noise propagation across the Arctic: Pan-Arctic model

The geographic scope included all Arctic LMEs, with a geographic filter applied to remove the large number of fishing vessels near Iceland, the large number of ships directly off the Norwegian coast and in the Norwegian fjords, as well as the large number of ships very close to the Aleutian Islands. These two regions could be explored further using a regional modelling approach. As a result of this filtering, the sound levels in the western Norwegian sea are underestimated. Vessels of all sizes, including large and small ships, were used in the computation of the sound maps below. We are developing an individual ship source level database using the Wittekind model for the 9375 ships identified in the Arctic with vessel weight over 1000 GT. In this document, a source level based upon the combined work of Wales and Ross & Alvarez was used.

The workhorse model AOS used is the Parabolic Equation (PE), the Range-dependent Acoustic Model (RAM) developed by Michael Collins. RAM is the industry standard for low-frequency acoustic modelling. The AOS C language version of RAM efficiently handles the environment in 3D and is tuned for the point-to-everywhere problem (rather than the single slice method) which is important for soundscape modelling. With the very large number of ships and time snapshots to be computed, the PE model is prohibitive at higher frequencies. For frequencies above 200 Hz, the Bellhop ray model, developed by Michael Porter, was used. Sound attenuation in seawater is strongly dependent upon frequency. Low frequency sounds can travel across the entire Arctic, whereas higher frequency sounds such as 10 kHz can only be heard tens of kilometers away. The propagation range for each computation was tailored to each frequency (from 1000 km for 25 - 125 Hz down to 150 km at 10 kHz) in order to compute the shipping noise and

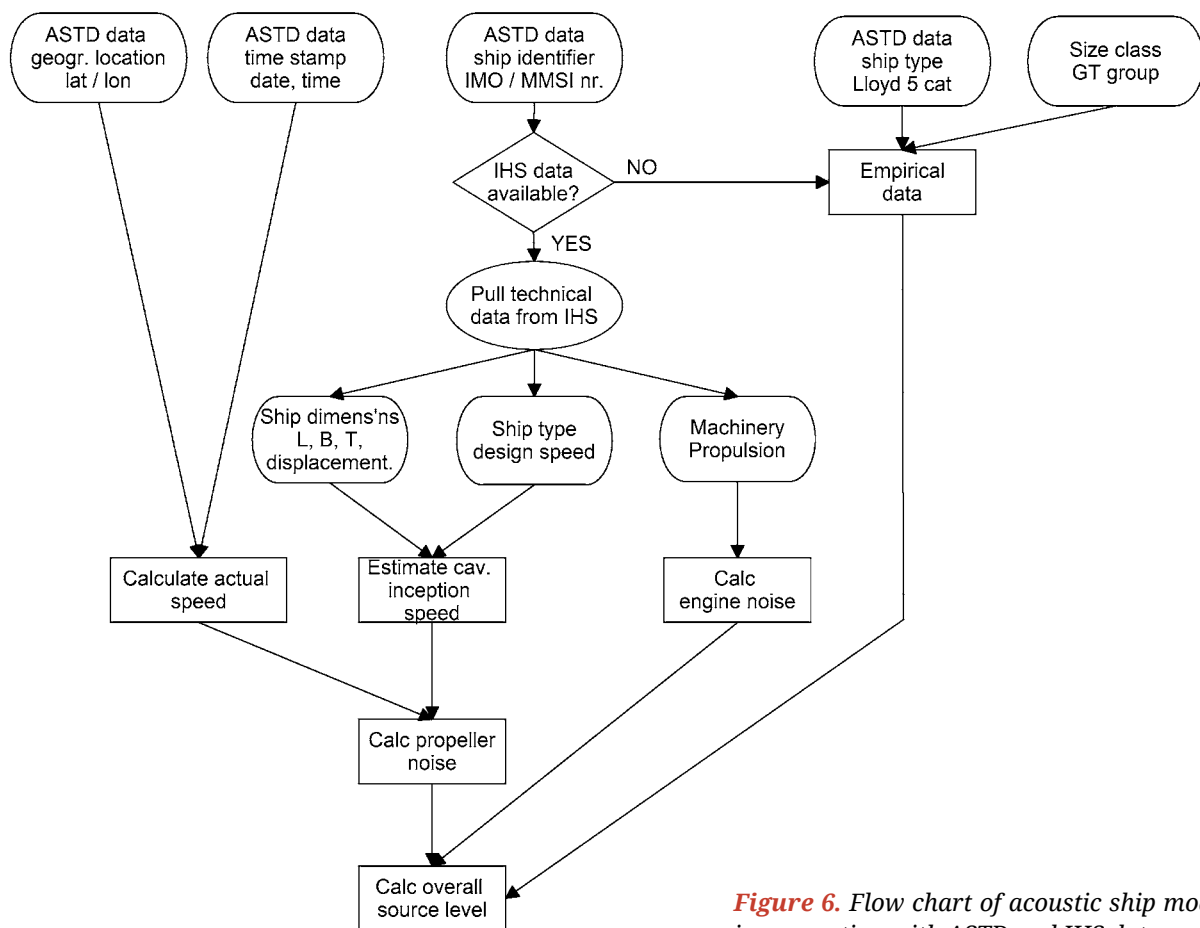


Figure 6. Flow chart of acoustic ship model in connection with ASTD and IHS data

include sufficient sound from sources a distance away. The acoustic models are computed in polar coordinates using 18 radials for the Pan-Arctic runs and 72 radials for the regional model results. Although we believe 18 radials is too few for an accurate acoustic computation, particularly in regions of complex bathymetry or oceanography, for a basin-scale (Pan-Arctic) shipping noise model this is sufficient.

One of the requirements for accurate acoustic modelling is an understanding of the environment (temperature and salinity for sound speed, bathymetry, seafloor type, and surface conditions such as wind or ice). The ocean environment used for all computations was the 4-dimensional ocean field (US Navy Polar HYCOM model, CICE, and the Pan-Arctic Ice-Ocean Modeling and Assimilation System) hind-casts dating back to 2013. The bathymetry data used was the most recent (2019) release of the GEBCO worldwide database. The seafloor type model was the US Navy Bottom Sediment Type database. This database categorises the ocean seafloor in terms of a mean sediment grain size.

The metric produced will be the decidecade band sound energy level (SEL) which is the sound spectral pressure squared summed across the band. Decidecade bands, similar to third-octave bands, are devised such that

there are 10 bands per octave. The decidecade bands are in Appendix B. The PE and ray models computed the propagation loss (PL) from each ship source position (or possible position) to a high-resolution fixed geographic output grid. Multiplication of the PL with the decidecade band shipping source level provided the sound energy level (SEL) (in μPa^2) for each ship at each position. Note that the higher frequencies have larger bands, so there is a 3 dB increase in decidecade SEL for each doubling in band center frequency for noise levels with the same spectral energy level (per Hz). The modeled sound field at each point is then the sum of the levels from all of the ships. Two methods for generating solutions (instantaneous and average) are described below.

b. Noise propagation in three regions of the Arctic where shipping overlaps with high densities of marine mammals

As part of the current PAME project, Dr. William Halliday conducted a preliminary analysis for Transport Canada of overlap between vessel traffic and important marine mammal regions in the Arctic, looking at data from September 2016-2018²². He also examined July-October of 2018 for monthly variation in vessel traffic. Using ASTD data, he calculated the distance traveled by different classes of ships and the area-corrected distance traveled, to see which regions

of the Arctic had the most vessel traffic. The area with the most vessel traffic was the Norwegian Sea, followed by the Bering Sea and North Atlantic, the Barents Sea, and Baffin Bay/Davis Strait regions.

Halliday then looked at areas with the most marine mammals in September, using data from Hauser et al. (2018)²³, and comparing marine mammal presence in September in a region to area-corrected vessel traffic in that region. The three regions that had the most vessel traffic using both studies' metrics were the Bering Sea, the Barents Sea, and Baffin Bay/Davis Strait²².

Here, we explore underwater noise propagation from shipping in the Bering Sea (from north of the Aleutian Islands to the Bering Strait), Barents Sea (the region north of Iceland to north of Svalbard, extending from the Greenland coast to the beginning of the Kara Sea. In order to cut out the large number of coastal ships off of Norway, the bounds excluded 20°W through 30°E. The latitude boundaries are from 65°N to the North Pole) and Baffin Bay/Davis Strait (including all of Baffin and Hudson Bay as well as the Archipelago up to Nares Strait. The AIS bounds and computational domain are 120°W, 40°W and 51°N, 79°N) in September 2019 to understand noise levels in areas important for marine mammals.

September was selected because historically it is the most ice-free month in the Arctic, and thus most often the month with the most ship traffic²³. The spatial resolution of these model runs was much higher than that of the Pan-Arctic model, with a range resolution of 200m used for the radial runs. In order to capture the bathymetry (and coastline) range dependence of the acoustic field at this higher spatial resolution, 36 radials were used for all regions except for Davis Strait, where 72 radials were used. The model was run in 1-hour increments.

The mapping from PL to decidecade-band SEL was performed in the same fashion as for the Pan-Arctic model, mapping from polar coordinates (runs per bearing) through the ice-loss algorithm (see below for further details), then to cartesian coordinates. The shipping decidecade source level was multiplied and then the sound from all ships was added in power.

Acoustic frequencies selected

In order to cover a wide range of hearing bands for marine mammals, the frequency range from 25 Hz to 10 kHz was covered for all noise propagation models. Shipping source levels peak in the 25-60 Hz band and drop off significantly beyond 500 Hz, but so does the average background noise due to increased propagation loss for the higher frequencies. The decidecade band levels were computed for 25, 63, 125, 250, 500, 1000, 2000, 5000 and 10000 Hz (or 10 kHz). This corresponds to decidecade (one-third octave)

band numbers: -16, -12, -6, -3, 0, 3, 7, and 10. The PE was used for frequencies 25 through 250 Hz and the Bellhop raytrace model was used for frequencies 500 Hz to 10 kHz. In this report, we present only a small subset of frequencies for clarity and brevity.

Statistical processing of acoustic fields and products

Pan-Arctic model:

Ambient sound levels in the ocean vary greatly on multiple space and time scales. With propagation falling off quickly, particularly near a source (30 dB in the first kilometer for spherical spreading), the levels can be driven by the nearest ship. In regions of high shipping, the sound field will approach a uniform level, but in regions of sparse shipping, the soundscape will be dominated by the location in time and space of a single ship. To accurately model the instantaneous soundscape would require time snapshots on the order of 10 minutes and spatial snapshots on the order of 1 km. This level of precision is prohibitive for a basin-wide, long term study. In order to generate statistics that are meaningful (accurate and unbiased) for a lower resolution model, we averaged in space in the propagation loss computation, and then computed statistics in larger spatial and temporal scales. The individual propagation runs were computed for every ship in a 12-hour snapshot. The output field was averaged to 1 km range bins. For the 1-week averages there are therefore 14 time snapshots (12 hour intervals). The statistics for the spatial bins are generated with 100 km resolution. This smooth approach provides accurate statistics for places with many ships, and for a single ship, has the distribution characteristics that include the peaks where the ship position was, and median levels driven by the number of ships present.

To this end, the products generated are the percentile shipping noise level over the week and within the 100 km spatial bin. The percentiles reported are 5, 25, 50, 75, and 95 percent. This permits analysis of the median, the maximum (95th percentile) and the interquartile (75th percentile – 25th percentile) distance. The median and maximum both have implications for ecosystem health and the impact on marine mammals and fishes. The interquartile distance is a measure of the variability of the sound within a region. Places with small numbers of ships passing by can have a very large interquartile distance. Ports and shipping lanes, which uniformly have very high levels of shipping noise, can have low variability because the location of specific ships doesn't matter very much.

Three regional models overlapping with marine mammals:

The regional products include percentiles (5th, 25th, 50th, 75th, 95th) averaged per day. The output spatial grid for averaging is roughly 10 km x 10 km in size. This is significantly higher resolution in time and space than the Pan-Arctic results. At this resolution the movement

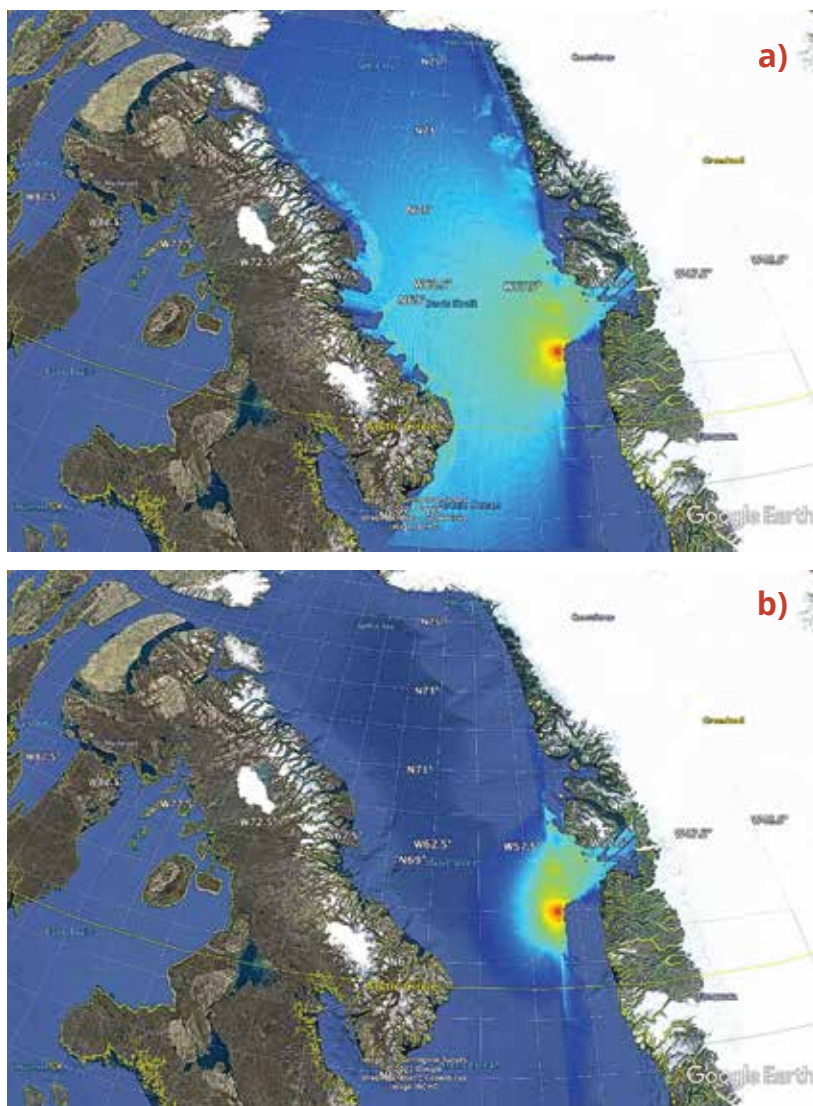


Figure 7. The impacts of sea ice on acoustic propagation at 250 Hz, a) ice-free summer where a single ship off the west coast of Greenland insonifies the entirety of Baffin Bay, b) whereas in the winter the sound is confined to within 100 km of the source. The figure's dynamic range is 50 to 110 dB/ μPa^2 .

of individual ships can be discerned. The large spatial and temporal averaging (100 km/12 hours over a week, respectively) of the Pan-Arctic runs is consistent with the higher resolution averaging (10 km/1 hour over a day) of the regional runs.

Inclusion of sea ice in noise propagation models

The impact of the ice cover on propagation loss is an important factor for computing the soundscape in regions and seasons where the ice extent is significant. Sound interaction with sea ice is a very complex physics phenomenon (with shear in the ice) and accurate modeling of this phenomenon is an area of active research. Dr. Heaney, the AOS Principal Investigator, has developed a method for including the scattering and loss effects of sea ice on low-frequency sound within the Parabolic Equation model²⁴. The modelling approach is to approximate the ice cover as a lossy, dense, fluid layer. Comparisons with observations for

multi-year and single-year sea ice are used to set the “modelled ice” acoustic parameters. The benefit of this approximate solution is that the efficient PE model can be used for all computations with and without sea ice. Extending this model to the ray code and to the massive problem of a 7-year time series of Pan-Arctic shipping noise required the use of a simpler ice scatter model. An additional frequency-dependent data-derived attenuation per km was added to the shipping propagation loss when the sound traveled under ice. The additional attenuation ranged from 0.01 dB/km at 25 Hz to 1 dB/km above 2 kHz.

When there is ice and no ships, versus no ice and just a few ships, there is a profound difference in the underwater soundscape. This is why this environment is essential to study. An illustration of the impacts of sea ice on acoustic propagation at 250 Hz can be seen in Figure 7). In the ice-free summer, a single ship off the west coast of Greenland insonifies the entirety of Baffin Bay, whereas in the winter the sound is confined to within 100 km of the source.

The Arctic's upward-refracting sound channel leads to sound travelling long distances in the Arctic, whereas that sound is lost much faster in other deeper ocean

basins (Figure 8). The same number of ships operating in the tropical Pacific Ocean is therefore likely to make a much smaller underwater noise contribution than the same number of ships operating in the Arctic (Figure 9).

3. DETERMINING TRENDS IN UNDERWATER NOISE FROM ARCTIC SHIPPING OVER TIME

In order to evaluate the extent to which underwater noise from shipping has changed from 2013 to 2019, we extracted modeled decidecade band SELs at seven locations across the Arctic Ocean and plotted them as a function of time to investigate the intra- and interannual variability. The seven locations were North Barents (80°N, 40°E), northwestern Baffin Bay (73°N,

74°W), eastern Baffin Bay (68°N, 56°W), the northern Bering Sea (61°N, 169°W), the Beaufort Sea (70°N, 164°W), the Kara Sea (78°N, 115°E), and the Canadian Archipelago (70°N, 120°W, Figure 10).

These locations were selected because they largely represent regional seas across the Arctic Ocean and also comprise sensitive environments for marine mammals. The North Barents location is the intersection of feeding and wintering grounds for marine mammals. In particular, blue whales and fin whales are documented nearby in the OBIS Seamap database and the location is also part of the feeding habitat for the humpback whale Cape Verde and West Indies distinct population segments²⁵. The northwestern Baffin Bay coordinates lie along the Baffin Bay shelf break where killer whales and seals have been observed (OBIS Seamap). The eastern Baffin Bay coordinates lie in a “core area” and serve as a feeding ground for the West Indies humpback whale distinct population segment. The northern Bering Sea coordinates are an important wintering ground for marine mammals. Bowhead and fin whales frequent this area (OBIS Seamap), and it is east of an acoustic

mooring that documented presence of Risso’s dolphins, a Northern right-whale dolphin, and a Pacific white-sided dolphin¹⁵, so it is an area of current habitat

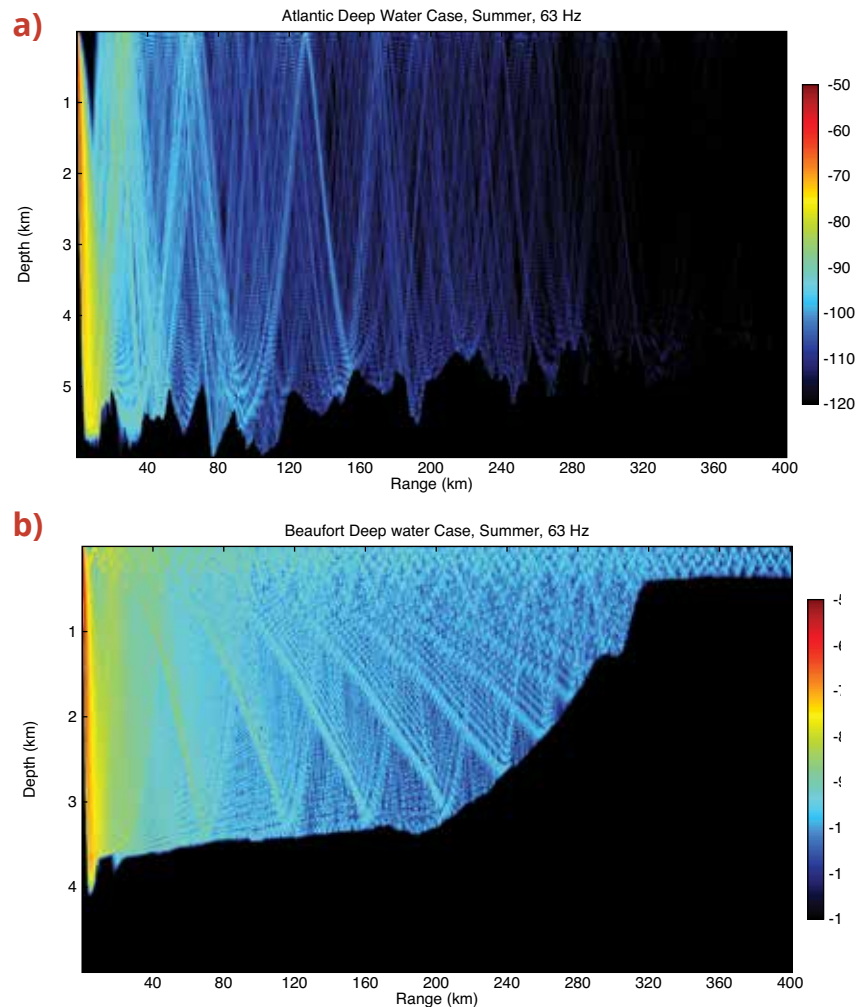


Figure 8. Propagation Loss (PL, in dB) at 63 Hz for a surface ship in the a) Atlantic temperate deep ocean and b) the Beaufort Sea showing the impact of the upward refracting Arctic profile on propagation.

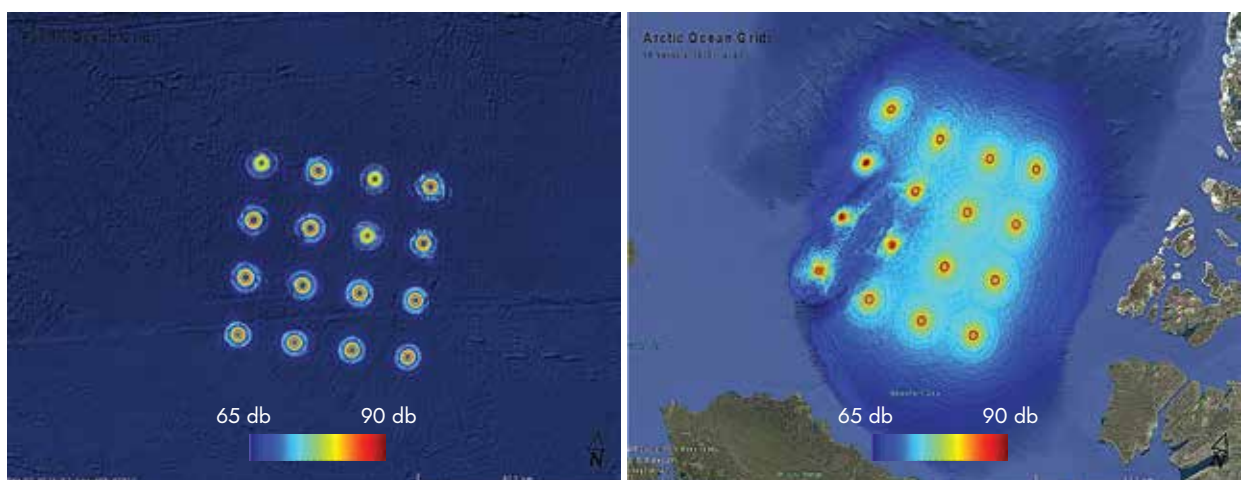


Figure 9. Comparison between the noise levels from 16 ships spaced 200 km apart in the tropics (left) and the Arctic. All ships had source levels of 165 dB. Simulations were run for 20 Hz using GEBCO bathymetry and WOA summer sound speed profiles. Receiver depth is 20m. Color bar ranges from 65dB (blue) to 90dB (red). In the Arctic these 16 vessels insonify the entire Beaufort Sea.



Figure 10: Seven sites selected across the Arctic Ocean to assess trends over time in underwater noise from shipping

expansion for typically temperate species. The Kara Sea coordinates are each of a large marine mammal feeding area along the nearby islands. OBIS Seamap datasets have documented beluga whales in this area. The Canadian Archipelago coordinates are an eastern extreme of the Beaufort Sea where ribbon, ringed, and bearded seals, beluga whales, and particularly bowhead whales, frequent (OBIS Seamap). Finally, the Beaufort Sea location is frequented by ringed, bearded, spotted and ribbon seals, beluga and bowhead whales.

For each of the seven locations, underwater noise levels - the median, 75th, and 95th percentile SEL – were plotted. Within each year, data points were generated to represent the weekly average SEL and linear trend lines were fitted to determine changes over the seven-year period.

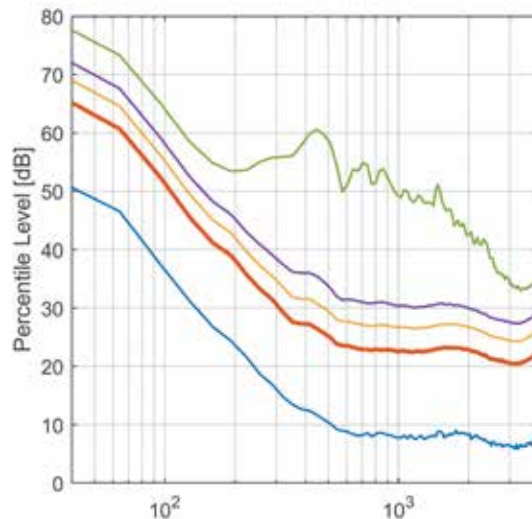


Figure 11a. Sound spectral level percentiles (dB/μPa²/Hz) from Ballard and Sagers (2020)30, taken in the Chukchi Sea for all of 2019.

4. IMPLICATIONS OF UNDERWATER NOISE FROM SHIPPING FOR MARINE MAMMALS

Acoustic overlap between Arctic marine mammals and underwater noise from ships

The degree to which noise-sensitive species are affected by underwater noise from shipping depends, in part, on the sound frequencies they use and the extent of acoustic overlap with ship noise, which in the Arctic includes noise generated by icebreaking ships. We described, through extensive analysis and literature review, the acoustic ranges used by marine mammals in the Arctic, including in three regions of interest

FREQUENCY BAND	CHUKCHI 25% NOISE (DB/μPA²)	WENZ 25% (SS2) (DB/μPA²)	VALUE FOR CURRENT STUDY (DB/μPA²)
25 Hz	71	55	68
63 Hz	72	57	68
125 Hz	67	72	68
250 Hz	57	75	65
500 Hz	49	75	65
1000 Hz	49	75	65
2000 Hz	52	76	66
5000 Hz	56	74	66
10000 Hz	59	74	66

Table 2. Decade quiet noise levels from Chukchi observations, Wenz deep water climatology, and a mixture of the two used for this report. All levels include sum over decade band.

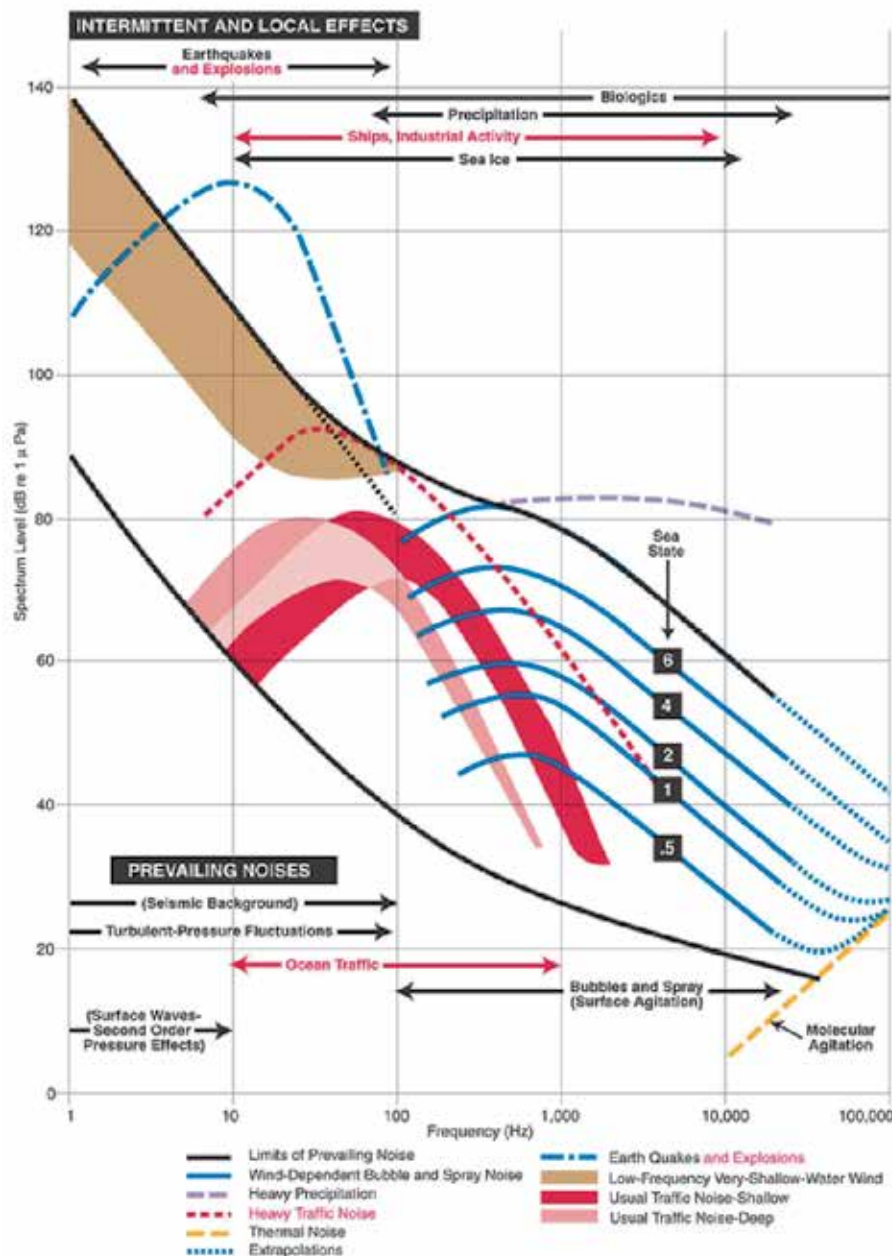


Figure 11b. Typical sound levels (dB/μPa²/Hz) for different frequencies as measured by Wenz (1962)³¹, adapted by National Research Council (2003)³².

where noise propagation was modelled at a fine scale: the Barents Sea, Bering Sea and Baffin Bay/Davis Strait. We then compared it with the frequency ranges of noise produced by ships, including icebreakers, based also on a literature review, to provide a comprehensive picture of acoustically sensitive species.

Determining excess noise levels

To further understand the implications of underwater noise from shipping on noise-sensitive species such as

marine mammals, we also estimated excess noise levels in both Pan-Arctic and regional analyses (for both the median and the maximum (95%)). Excess noise is considered the amount of noise above the expected background level on a moderately quiet day²⁶. Specifically, where there were measured data, we used the 25% measured noise as the quiet day average. The ambient sound level is a combination of measurements from the Chukchi Sea in 2019 taken by Ballard and Sagers (2020)²⁷ (with percentiles, Figure 11a) and the Wenz curves²⁸ (Figure 11b). The Chukchi sea measurements are mostly for ice-covered periods, which have much lower ambient sound levels in winter than for open water, which is when the Wenz curves, a climatology taken for open water, were used. Note the sound levels under ice are much lower (in Figure 11a) than in open water (Figure 11b).

The background (average quiet day) levels for each frequency are reported in Table 2. The Wenz levels were taken at sea-state 2. Note that the Wenz levels at frequencies

below 250 Hz are likely to have shipping noise in them. The Chukchi measurements are likely to be completely dominated by ice noise. For many regions in the marginal ice zone there will be noise from ice-wave action, and ice-ice interaction, but there will be significantly less wind noise (from 250-10000 Hz) than in open water. Ideally, ambient sound levels would be available for all Arctic Ocean regions to evaluate excess noise with greater accuracy. However, this is beyond the scope of the current project.





RESULTS

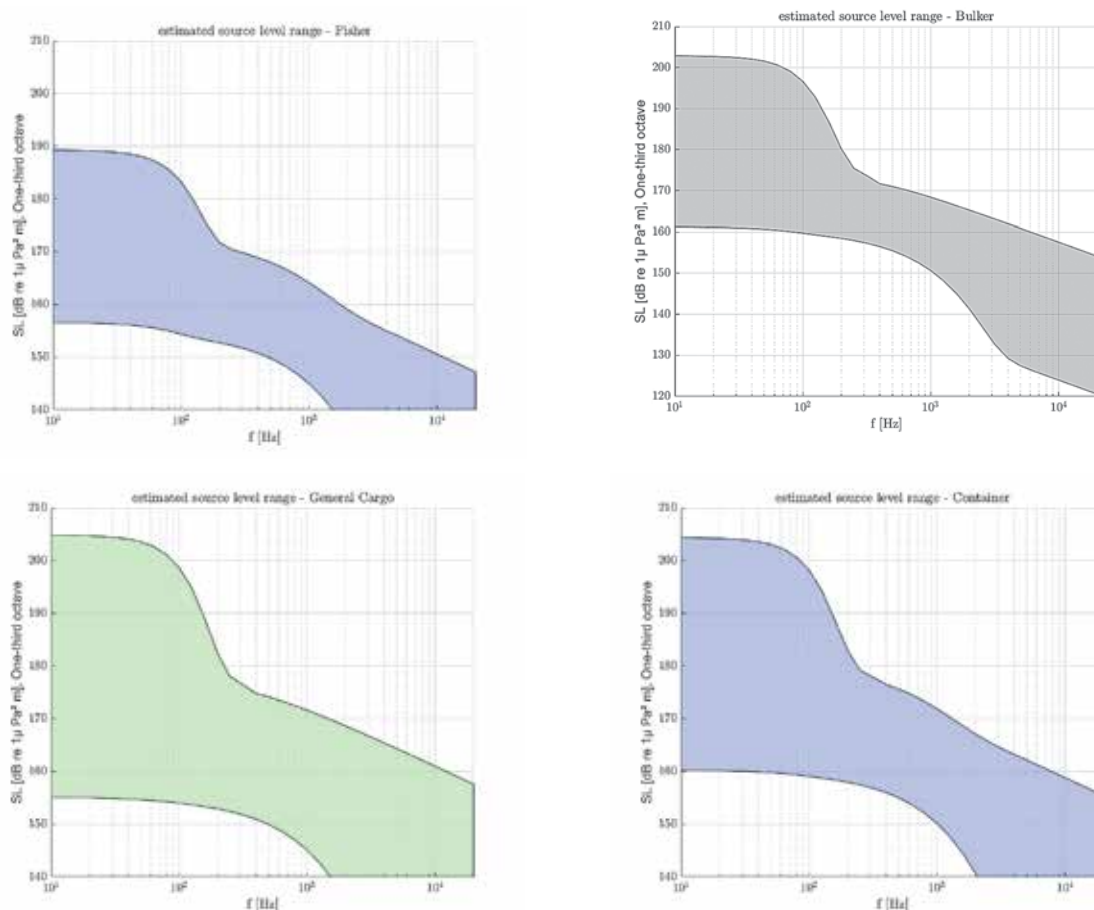


Figure 12. Initial underwater noise source level ranges for four vessel types operating in the Arctic from 2013 – 2019 (clockwise, from top left): fishing vessels, bulk carriers, general cargo and containerships. These estimates do not include variations in noise source levels resulting from speed variations.

Completed analyses yielded 3,276 individual acoustic sound maps of the median sound levels of the Pan-Arctic, as well as 13,106 readings of the 5th, 25th, 75th, and 95th percentiles. In this report we present a subset of these, focusing mostly on low frequencies (25 Hz and 63 Hz) because they are in the range of peak ship noise, as well as in the range of many marine mammals' sound use ranges, especially those of baleen whales. However, we also include results showing the spatial distribution of underwater noise from shipping at higher frequencies (125 Hz, 1 kHz and 10 kHz) to compare noise propagation with that at lower frequencies and to encompass acoustic ranges relevant to seals and other Arctic marine mammals (e.g., beluga whales and narwhal).

1. UNDERWATER NOISE SOURCE LEVELS OF SHIPS OPERATING IN THE ARCTIC

Since the calculation of ship source levels is speed-dependent, it needs to be applied to a data set which contains information on speed. The modelling of source levels is therefore integrated in a processing routine of the entire ASTD data set where source levels are calculated for every detection separately. An overview of ship source levels is presented shown in Figure 12. Bulk carriers, tankers and container vessels represent the noisiest group across all ships operating in the Arctic from 2013 – 2019 (Figure 12). These initial results do not include variations in noise source levels due to speed variations, especially slow steaming or slow transit speeds. It is expected that the range of all calculated source levels will further extend to lower values (lower noise source levels) once speed profiles from ASTD data are taken into account. This will be the focus of future work. In addition, the future integration of ship source levels into noise propagation models will determine which of these ships radiate significant acoustic energy into biologically sensitive areas.

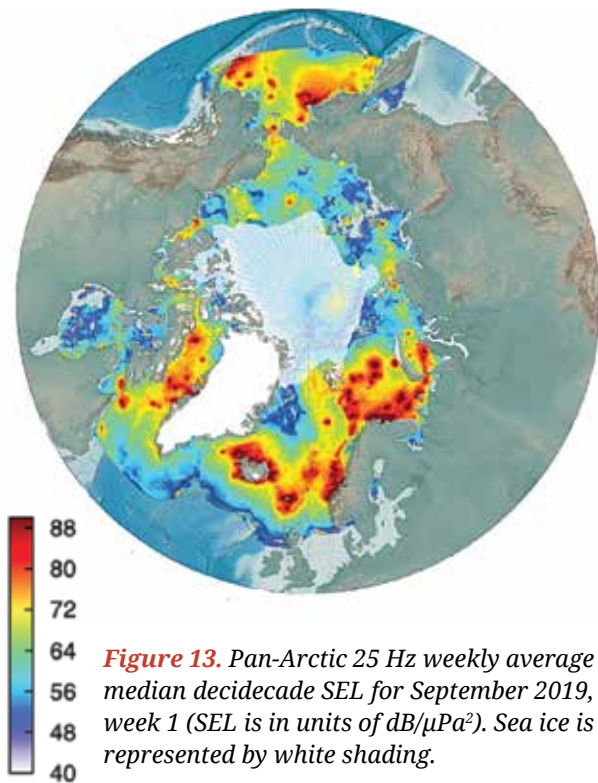


Figure 13. Pan-Arctic 25 Hz weekly average median decedecade SEL for September 2019, week 1 (SEL is in units of dB/μPa²). Sea ice is represented by white shading.

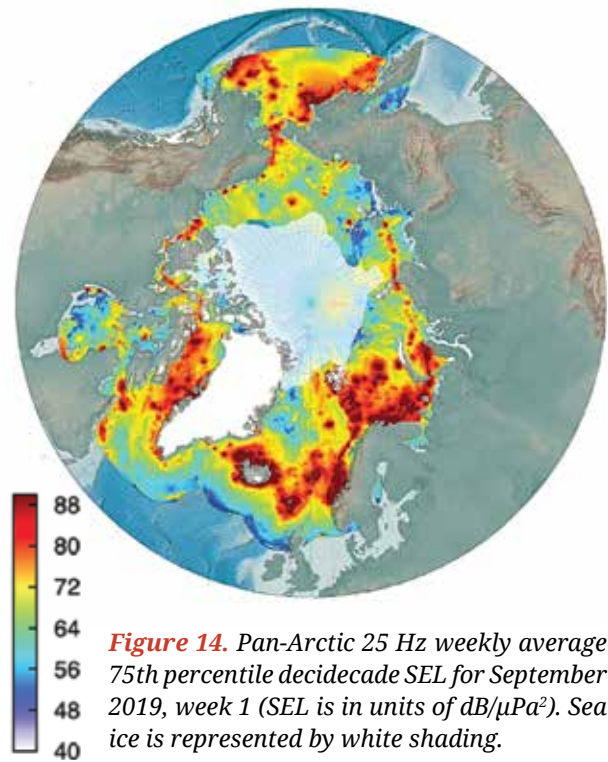


Figure 14. Pan-Arctic 25 Hz weekly average 75th percentile decedecade SEL for September 2019, week 1 (SEL is in units of dB/μPa²). Sea ice is represented by white shading.

2. SPATIAL DISTRIBUTION OF UNDERWATER NOISE FROM SHIPPING IN THE ARCTIC

Low-frequency underwater noise propagation

The median, 75th, and 95th (peak) percentile Sound Energy Levels (SEL) for the entire Arctic Ocean and regional seas are presented for two frequencies, 25 Hz and 63 Hz. The median SEL for week 1 of September 2019 at 25 Hz is shown "in Figure 13. For this relatively ice-free time period (except in the central Arctic Basin), there is shipping noise in all regions, particularly the Barents Sea (30°E), the Kara Sea (90°E), the Bering and Chukchi Seas (180°E), and Davis Strait (300°E).

The 75th percentile statistic is relevant to the discussion of the impacts of shipping noise on the marine ecosystem because these levels are significantly higher than the median, so they measure the levels of sound (minimum) for six hours every day, and they are not driven by the specific locations of the individual ships. The 75th percentile SEL for the 25 Hz decedecade band for week 1 of September 2019 illustrates high levels of shipping noise in the Barents Sea, southern Bering Sea, and Baffin Bay (Figure 14).

The 95th percentile (peak) SEL for week 1 of September 2019 (25 Hz) is shown in Figure 15. Here we see that there are regions that experience 30 dB/μPa² or more above the median sound level, driven by the passing

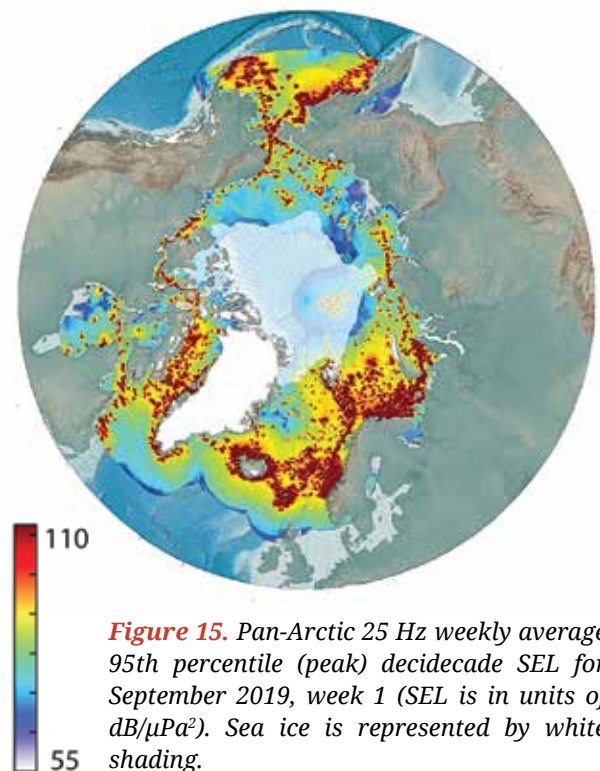


Figure 15. Pan-Arctic 25 Hz weekly average 95th percentile (peak) decedecade SEL for September 2019, week 1 (SEL is in units of dB/μPa²). Sea ice is represented by white shading.

of individual ships. we can clearly see the underwater contribution of individual ships in the Barents Sea (north of Norway 30°E), the Kara Sea and Russian coastal traffic (60-90°E), the Bering Sea and Beaufort Sea (180°E), as well as Davis Strait and the Canadian Archipelago traffic (270-330°E). The likely presence of a single ship in the central Arctic Basin (60-90°E, far north) can be seen as well.

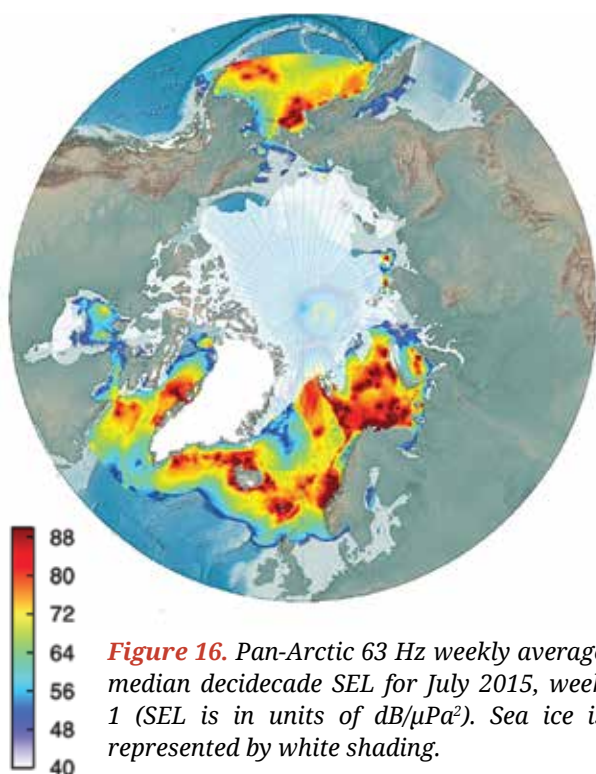


Figure 16. Pan-Arctic 63 Hz weekly average median decedecade SEL for July 2015, week 1 (SEL is in units of dB/μPa²). Sea ice is represented by white shading.

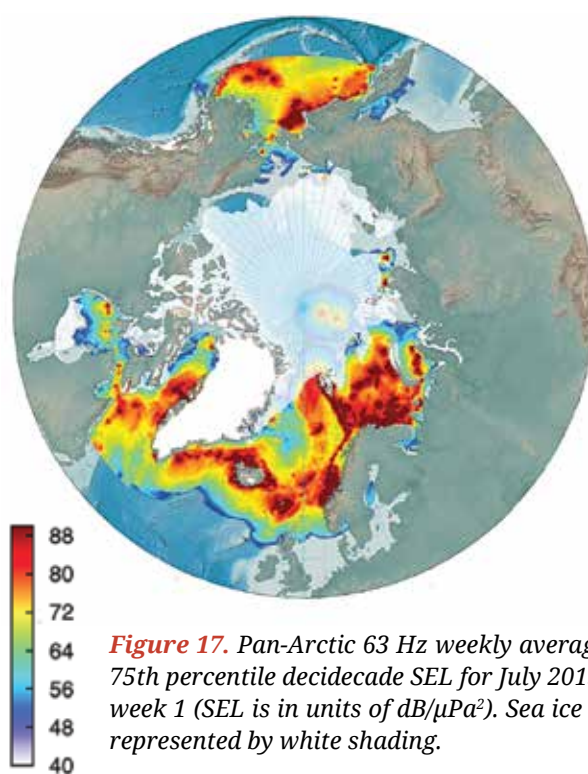


Figure 17. Pan-Arctic 63 Hz weekly average 75th percentile decedecade SEL for July 2015, week 1 (SEL is in units of dB/μPa²). Sea ice is represented by white shading.

We now show the Pan-Arctic, still in the ice-free summer, but for a different frequency, 63 Hz (Figures 16 – 18). Sixty-three Hz is heard by more marine mammals than 25 Hz (see section on acoustic overlap between marine mammals and noise), but it does not travel as far since it is a higher frequency. However, shallow water regions have higher sound levels at 63 Hz rather than 25 Hz (the higher frequency sound has smaller wavelengths and can thus propagate better in shallow water).

Similar to the 25 Hz results (Figures 13 - 15), we see that the sound is concentrated in the Bering Sea, Baffin Bay, the central Arctic Basin, and is highest in the Barents Sea (Figure 16). This pattern continues at the 75th and 95th percentile, with the ability to discern individual ship signals at the 95th percentile level. The fact that 63 Hz wavelengths can travel farther than 25 Hz in shallow water is quite evident in the eastern Bering Sea and the Kara Sea (Figure 17, 18).

Higher frequency underwater noise propagation

A set of one-week runs was completed at 125 Hz, 1 kHz, and 10 kHz to provide insight into the difference in sound propagation at higher frequencies. Here, we also compare propagation in March and September to illustrate spatial distribution in underwater noise in ice-covered versus largely ice-free seasons.

The spatial distribution of median shipping SEL at 125 Hz is shown below for a week in March and September 2019 (Figure 19). At this frequency, propagation loss is significant, and sound does not travel far. High noise levels in Baffin Bay, the Barents, and Bering are seen again. Sound at this and higher frequencies propagates

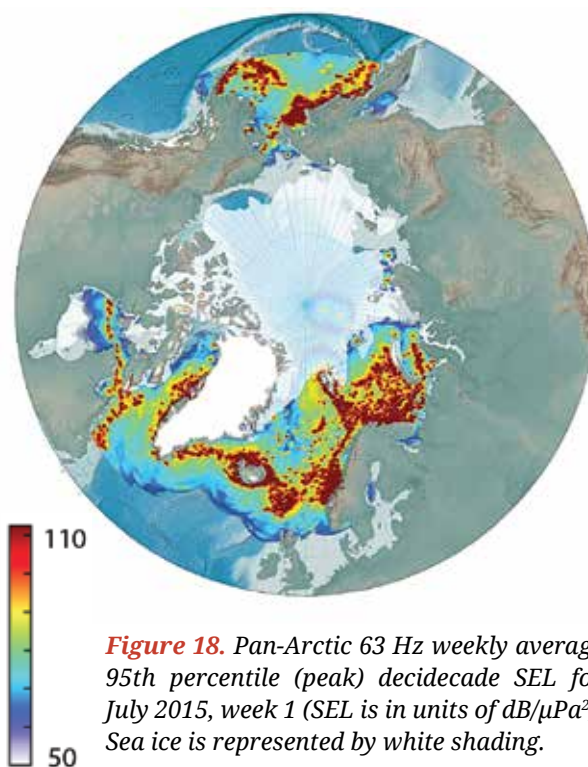


Figure 18. Pan-Arctic 63 Hz weekly average 95th percentile (peak) decedecade SEL for July 2015, week 1 (SEL is in units of dB/μPa²). Sea ice is represented by white shading.

relatively long distances in 50-100m of water, as seen in the Bering and Barents Seas (Figure 19).

The median 1 kHz decedecade SEL over a temporal and spatial ensemble of one week and 100 km, respectively, for March and September of 2019 are shown in Figure 20. The levels for the band-integrated energy are higher than at 25 and 63 Hz. This is despite the reduced source level and volume attenuation loss at 1 kHz compared to very low frequencies. The primary reason for this is that

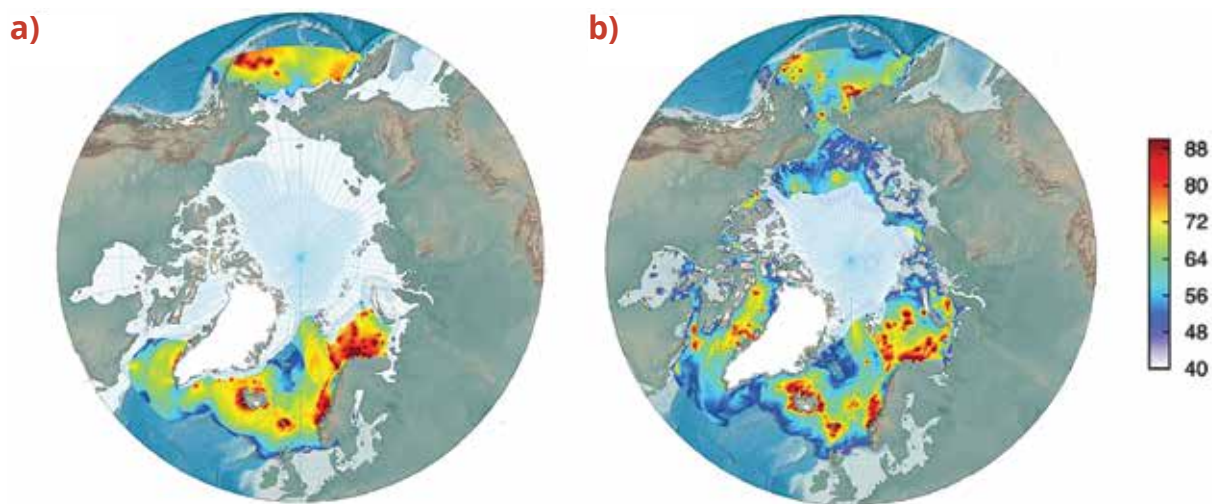


Figure 19. Pan-Arctic 125 Hz decidecade band weekly median levels for a) March 2019 and b) September 2019 (SEL is in units of $\text{dB}/\mu\text{Pa}^2$).

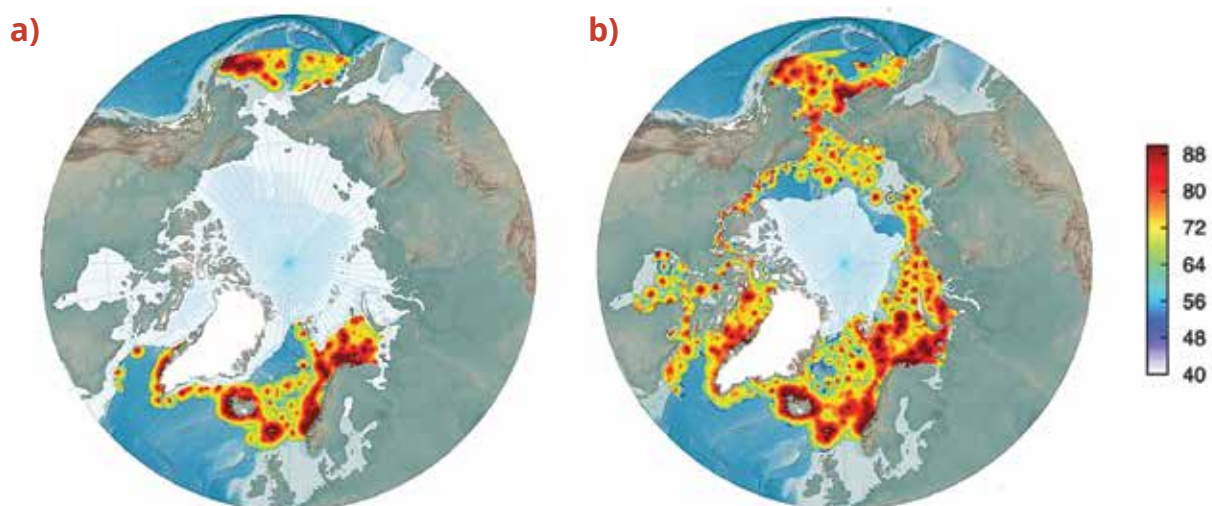


Figure 20. Pan-Arctic 1 kHz decidecade band weekly median levels for a) March 2019 and b) September 2019 (SEL is in units of $\text{dB}/\mu\text{Pa}^2$).

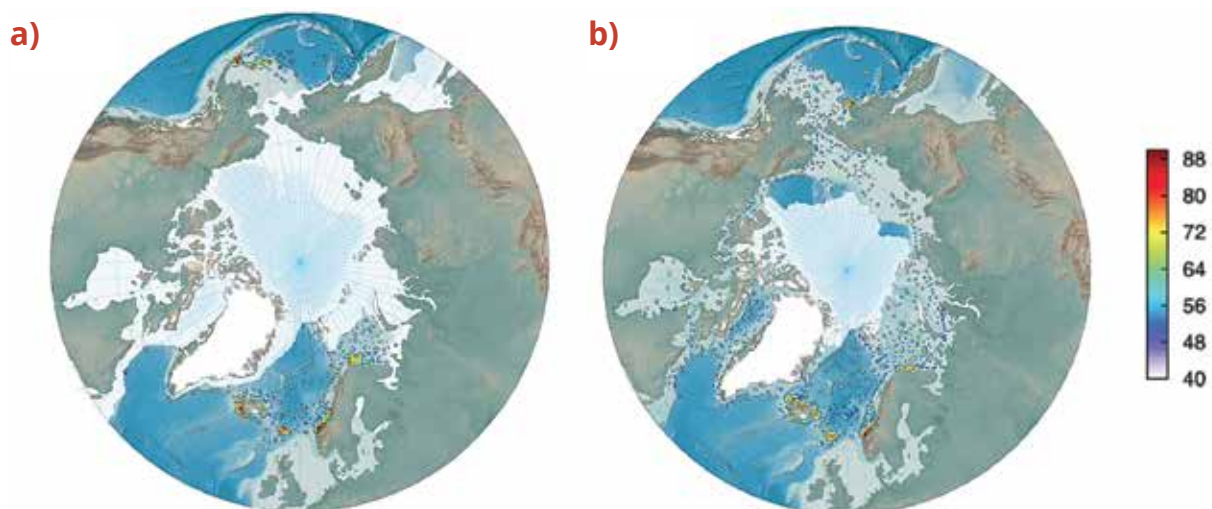


Figure 21. Pan-Arctic 10 kHz decidecade band weekly median levels for a) March 2019 and b) September 2019 (SEL is in units of $\text{dB}/\mu\text{Pa}^2$).

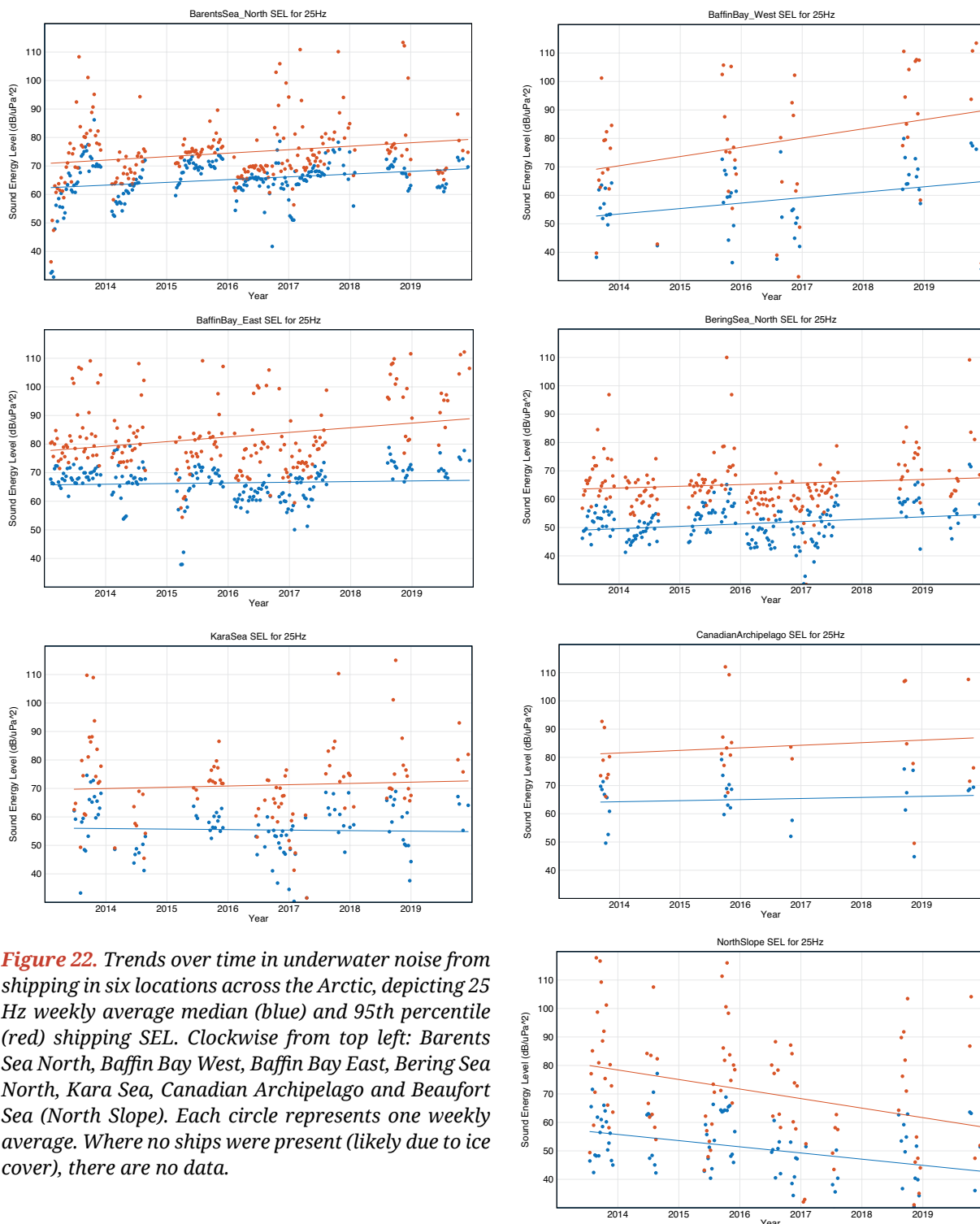


Figure 22. Trends over time in underwater noise from shipping in six locations across the Arctic, depicting 25 Hz weekly average median (blue) and 95th percentile (red) shipping SEL. Clockwise from top left: Barents Sea North, Baffin Bay West, Baffin Bay East, Bering Sea North, Kara Sea, Canadian Archipelago and Beaufort Sea (North Slope). Each circle represents one weekly average. Where no ships were present (likely due to ice cover), there are no data.

the bandwidth for the decade band at 1 kHz is 22 dB larger than that at 63 Hz. Individual ships are more apparent in the 1 kHz field relative to 63 Hz and noise levels attenuate quickly where there are only single ships. In the summer there are high noise levels in the Bering, Barents, Kara, Laptev, and Chukchi Seas, as well as Baffin Bay and the Canadian Archipelago (Figure 20b).

The 10 kHz acoustic runs were completed out to 150 km, although with a factor of 10 in increased frequency there is a factor of 17 in increased volume attenuation. The reduced ability of sound to travel far is evident

in the median SEL (Figure 21). Each ship contributes noise to the region but only to distances of a few tens of kilometres, so the impact on the marine environment will be within the vicinity of ships as they pass over individual sites or animals.

3. TRENDS OVER TIME IN UNDERWATER NOISE FROM SHIPPING

To evaluate the extent to which shipping noise levels have changed from 2013 to 2019, the modeled

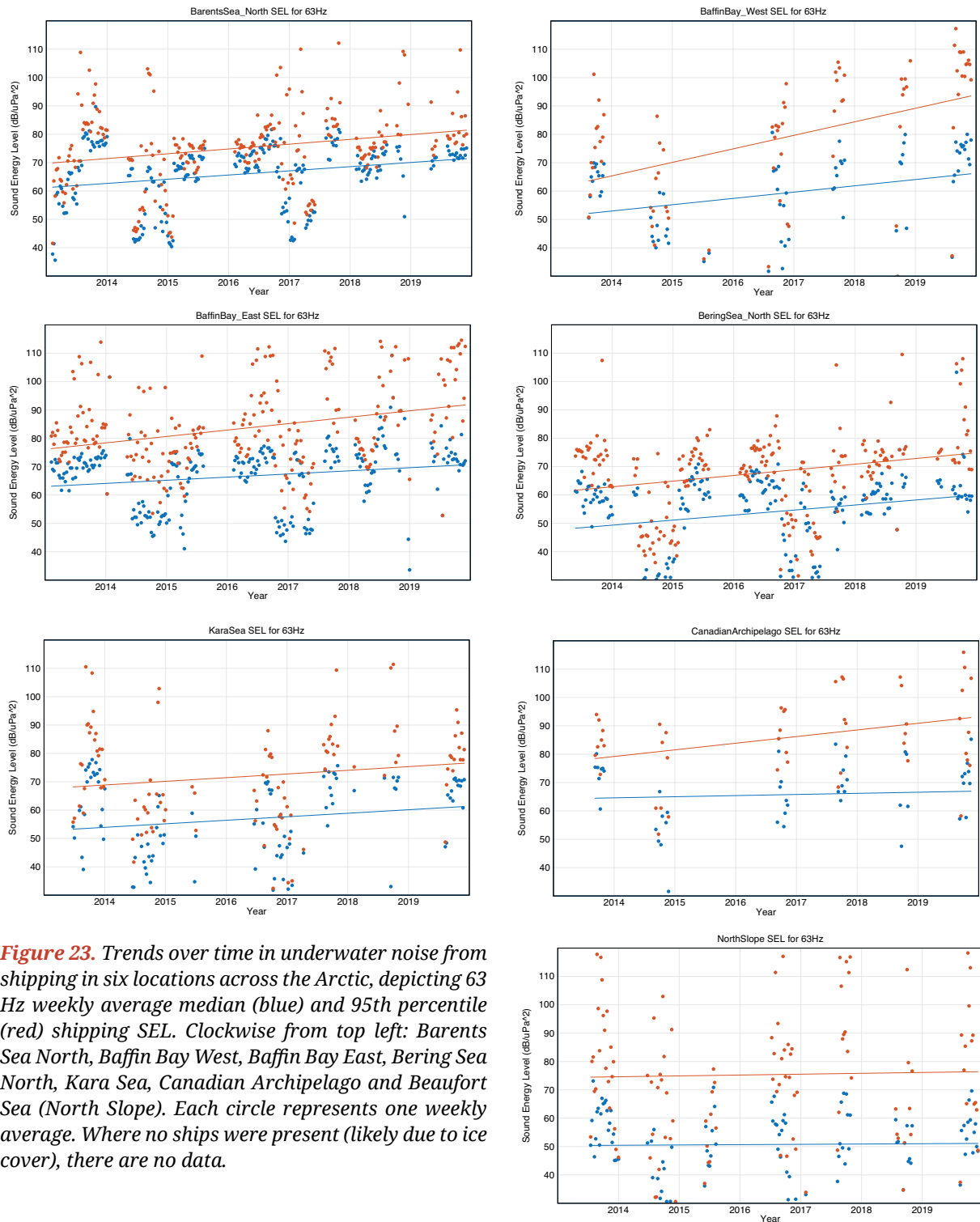


Figure 23. Trends over time in underwater noise from shipping in six locations across the Arctic, depicting 63 Hz weekly average median (blue) and 95th percentile (red) shipping SEL. Clockwise from top left: Barents Sea North, Baffin Bay West, Baffin Bay East, Bering Sea North, Kara Sea, Canadian Archipelago and Beaufort Sea (North Slope). Each circle represents one weekly average. Where no ships were present (likely due to ice cover), there are no data.

decade band SELs were extracted at seven locations and plotted as a function of time. These long-term time series show both the intra- and interannual variability in underwater noise from shipping across these seven sites in the Arctic Ocean, selected to represent regional seas as well as sensitive environments for marine mammals (Figure 22, 23).

The western portion of Baffin Bay shows a consistent increase in 25 Hz noise level of 15 – 25 dB SEL from 2013 to 2019. This region is covered in ice for much

of the year and is very quiet, thus it is more sensitive to ship noise when ships are present. The northern Barents Sea, however, shows a significant seasonal rhythm, with sound levels annually going from 50 to greater than 80 dB in the median, but no strong yearly increase in levels. The same general patterns for the Beaufort Sea and Kara and Laptev Seas are evident. In these regions, the number of ships is currently quite small, so the increase in sound level is driven by the new presence of ships, rather than the increase in the number of ships.

Figure 24. Acoustic overlap between marine mammals and natural and anthropogenic soundscape. Marine mammals separated into baleen whales (*Balaenidae*), toothed whales (*Odontoceti*), seals and sea lions (*Pinnipedia*), and other (one bear (*Ursidae*) and one otter (*Mustelidae*)). Black bars = species found in all three regions (Bering, Barents, Baffin). (Bering is the shortened label for the Pacific Arctic Corridor which includes the Bering, Chukchi, and Beaufort Seas.) Blue bars = species found in Baffin Bay and Barents Sea. Red bars = species found in the Bering and Baffin Bay. Orange bars = species found only in the Bering. Green bars = species found only in Baffin Bay. Purple bars = species found only in the Barents Sea. Arrows mean animals could call higher (or lower), but sampling rates of studies done were not high enough to capture actual highest possible frequency. An asterisk (*) means that the species has either been acoustically or visually documented in that region, but no secondary observations exist to validate the acoustic or visual method, so ranges can be considered extralimital. A review of these four species can be found in Seger & Miksis-Olds (2019)¹¹. A grayed out arrow indicates the range of an audiogram, not vocalizations. A carrot (^) represents sensitivity in air, not in water. Thick navy bars = ships. Thin blue bars = ice and wind from the Wenz curves. All citations for the figure are in Appendix C.

4. IMPLICATIONS OF UNDERWATER NOISE FROM SHIPPING FOR ARCTIC MARINE MAMMALS

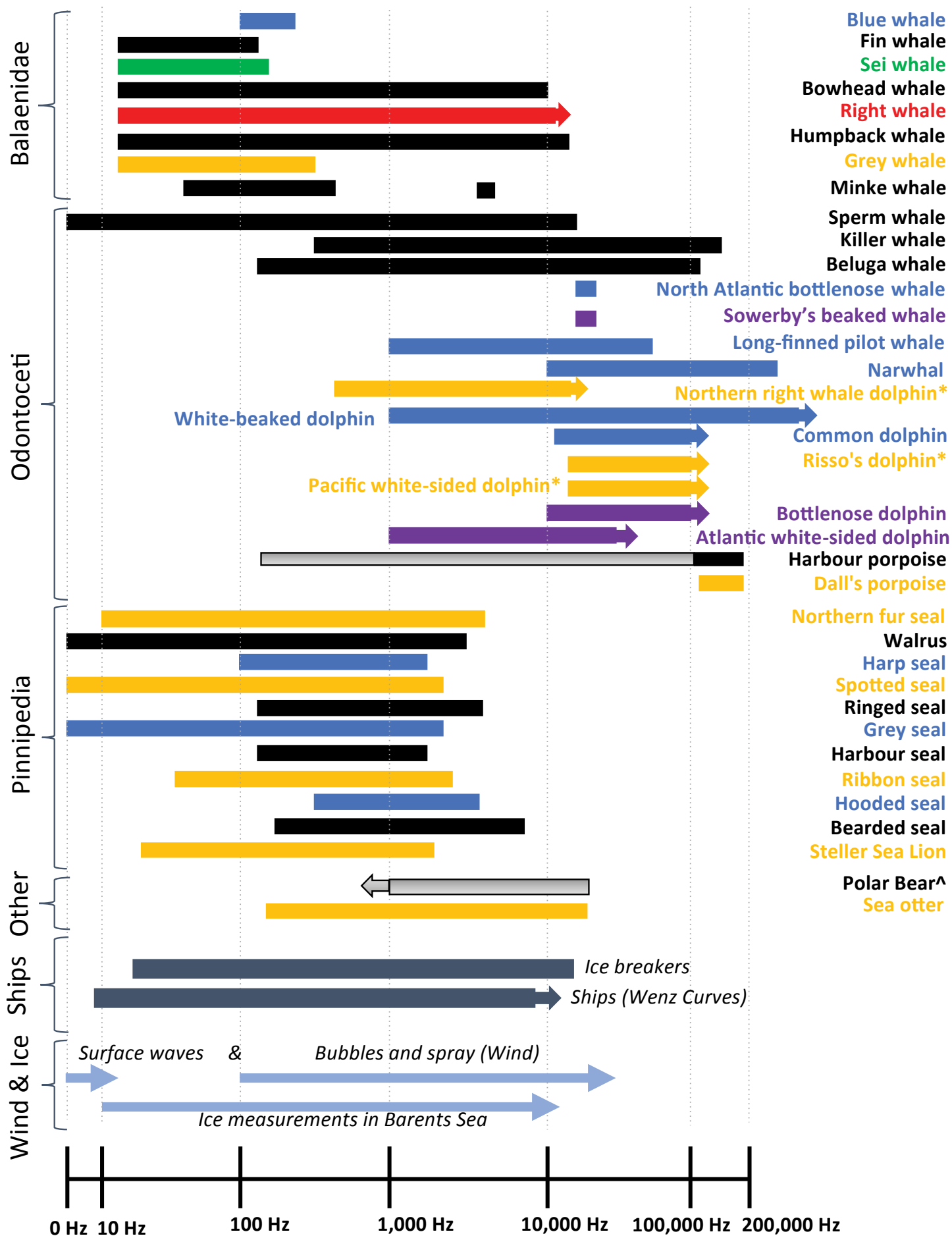
Acoustic overlap between mammal and ship noise

There is substantial overlap in acoustic frequencies used by marine mammals that spend part or all their lives in Arctic waters and underwater noise produced by ships (Figure 24). This includes species present in three regions of the Arctic Ocean with high levels of shipping and high densities of marine mammals: the Bering Sea, Barents Sea and Baffin Bay/Davis Strait. These marine mammals utilise acoustic frequencies over a wide range, from 0 Hz to >200 kHz, that overlap with the natural Arctic soundscape sources of wind

and ice, ranging from 0 Hz to >10 kHz (Figure 24). All *Balaenidae* whale species and nearly half of the Arctic *Odontoceti* species vocalise (and would therefore be acoustically sensitive) in frequency bands dominated by shipping noise. Here, underwater noise from shipping was characterised as having source levels extending from < 10 Hz to greater than 10 kHz (when icebreakers are considered, Figure 24, Appendix D, E).

Excess underwater noise in three regions important for marine mammals

For three regions of the Arctic Ocean with high levels of shipping and high densities of marine mammals: the Bering Sea, Barents Sea and Baffin Bay/Davis Strait, we assessed excess noise levels (median, 95th percentile (peak) and interquartile distance) at a frequency of 63 Hz in September 2019. Excess noise is defined here as the sound energy level above 68 dB/ μPa^2 and is considered the amount of noise above the expected background level on a moderately quiet day.



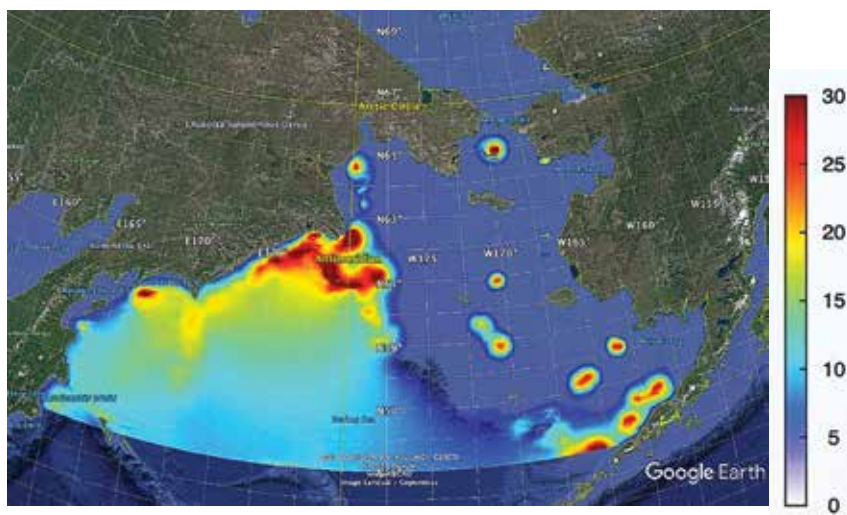


Figure 25. Bering Sea 63 Hz daily average median decade excess noise for September 5, 2019 (Excess noise is the sound energy level above 68 dB/μPa²).

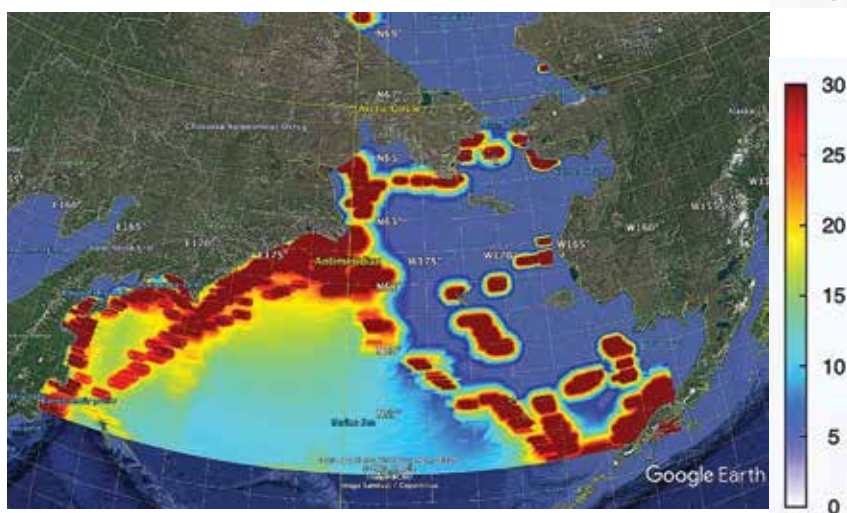


Figure 26. Bering Sea 63 Hz daily average peak (95th percentile) decade excess noise for September 5, 2019 (Excess noise is the sound energy level above 68 dB/μPa²).

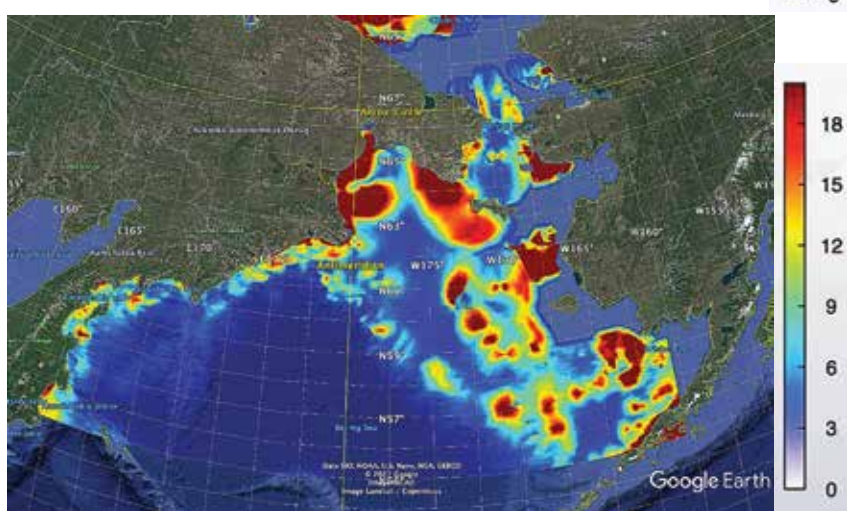


Figure 27. Bering Sea 63 Hz daily average interquartile distance for September 5, 2019 (Excess noise is the sound energy level above 68 dB/μPa²).

In the Bering Sea, the primary shipping was along the shelf and the region was ice free in September 2019 (Figure 25). The locations of individual ships are apparent (Figure 25). The eastern Bering Sea is quite shallow and sound travels poorly there, whereas in the deeper western Bering Sea, sound travels well and the area is dominated by shipping noise along the Russian east coast. Median excess noise levels are mostly between 10 and 20 dB. Maximum excess noise levels (95th percentile) of 30 dB or greater is widespread, including along the entire Russian east coast, in the

southern Bering sea, through the Bering Strait, and far north in the western Chukchi Sea and the eastern Siberian Sea (Figure 26). Finally, the interquartile range (IQR) (i.e., 75h percentile – 25th percentile) of excess noise shows areas of high variability, where just a few ships can dominate the soundscape (Figure 27). The western Chukchi Sea/eastern Siberian Sea is one of those places, with an IQR of 18 dB or more. Similarly, the northwestern Bering Sea has a high IQR, thus it is probably an area dominated by just a few ships. In contrast, the low IQR of the Russian east coast of the

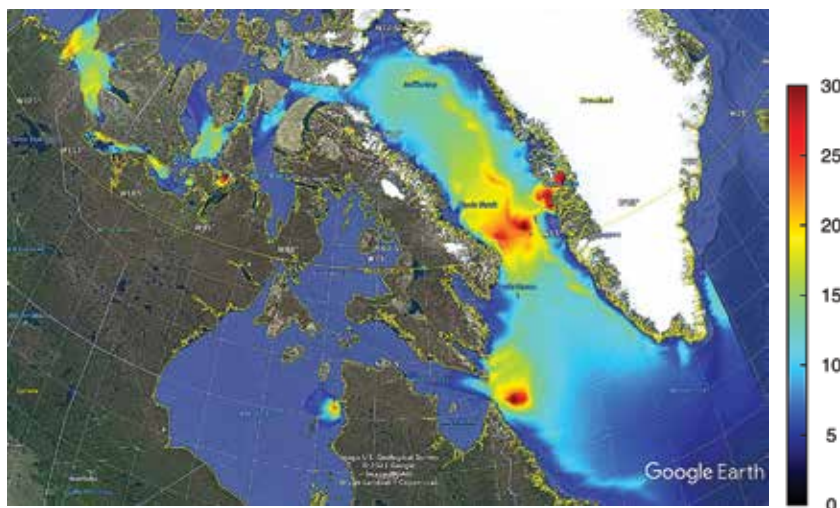


Figure 28. Davis Strait 25 Hz weekly average median decade excess noise for September 2019, week 1 (Excess noise is the sound energy level above 68 dB/μPa²).

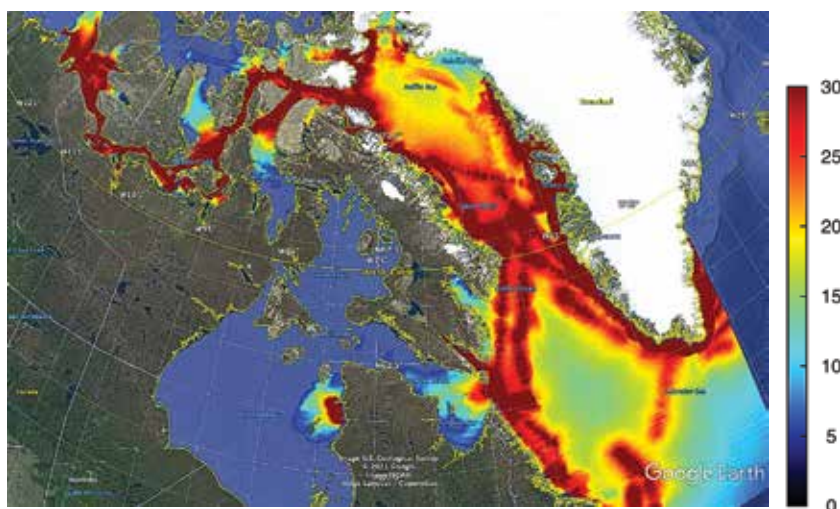


Figure 29. Davis Strait 25 Hz weekly 95th percentile decade excess noise for September 2019, week 1 (Excess noise is the sound energy level above 68 dB/μPa²).

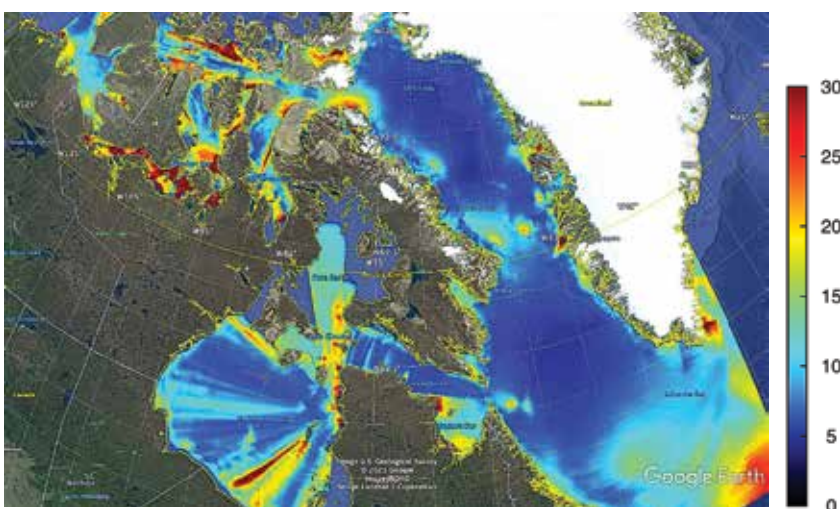


Figure 30. Davis Strait 25 Hz weekly interquartile distance for September 2019, week 1 (Excess noise is the sound energy level above 68 dB/μPa²).

Bering Sea indicates that there are consistently loud ships in that area.

Like the Bering Sea, Baffin Bay/Davis Strait was also ice-free in September 2019. Median excess noise levels were above 25 dB in just a few locations, including in Disko Bay, Greenland and off the coast of Baffin Island in the narrowest part of Davis Strait (Figure 28). There was also a hotspot of excess noise at the mouth of Hudson Strait, offshore of Killiniq, Nunavut, Canada. Based on the 95th percentile (peak) excess noise, ship positions become

visible as they pass through the Canadian Archipelago and transit Baffin Bay (Figure 29). Much of Baffin Bay has an excess noise level of 30 dB or more, as well as throughout the Canadian Archipelago and in Hudson Bay (Figure 29). Finally, throughout Baffin Bay and Davis Strait, there is less variability in excess noise, due to more consistent ship traffic. In contrast, throughout the Canadian Archipelago, especially the far western waters of the archipelago region, excess noise levels are more variable and likely affected by the presence of every ship that passes through (Figure 30).

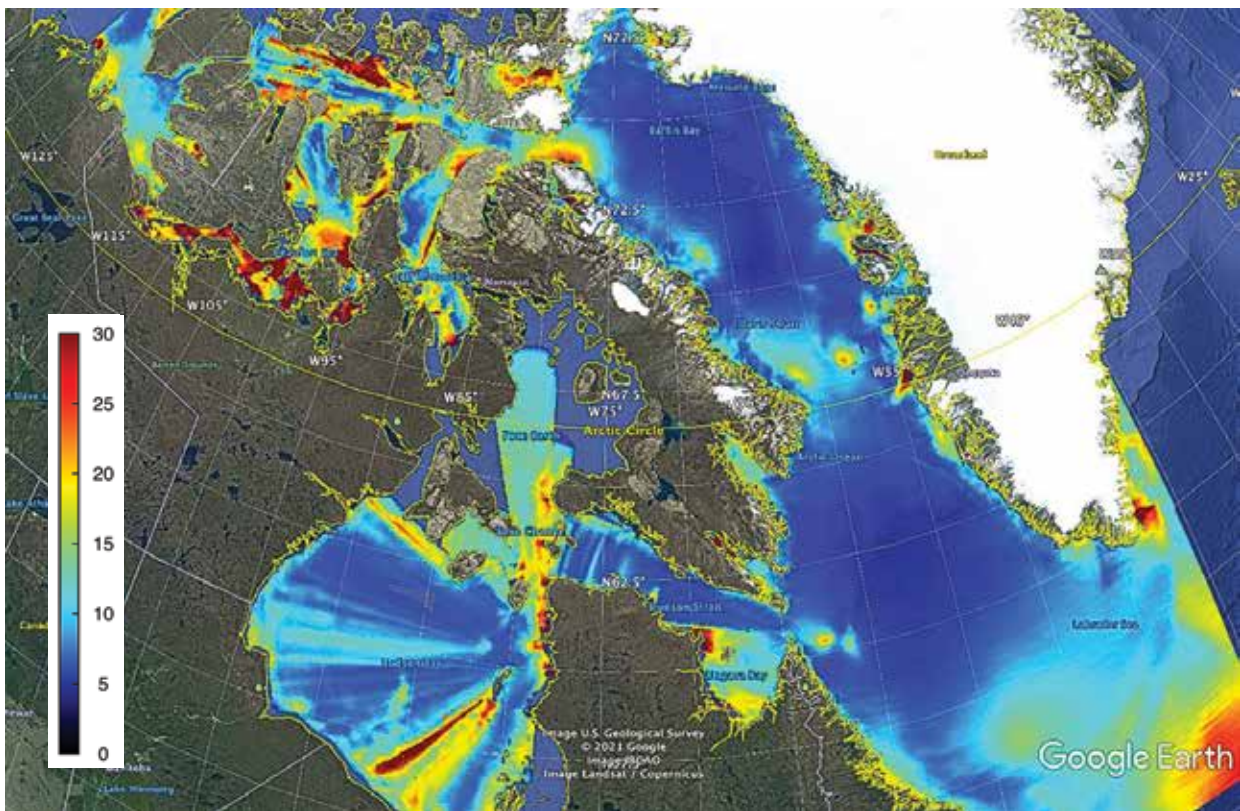


Figure 31. Barents Sea 63 Hz weekly average median excess noise for September 2019, week 1 (Excess noise is the sound energy level above 68 dB/μPa²).

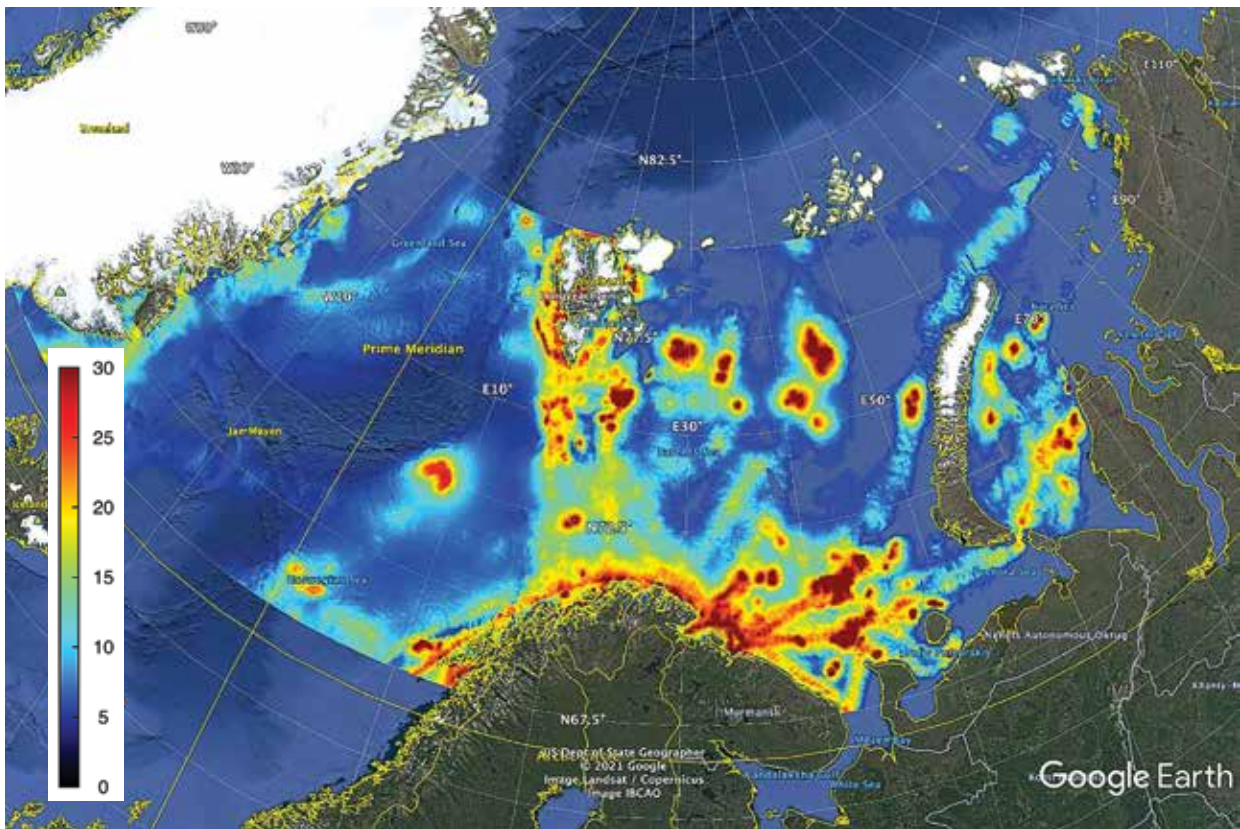


Figure 32. Barents Sea 63 Hz weekly 95th percentile decadal excess noise for September 2019, week 1 (Excess noise is the sound energy level above 68 dB/μPa²).

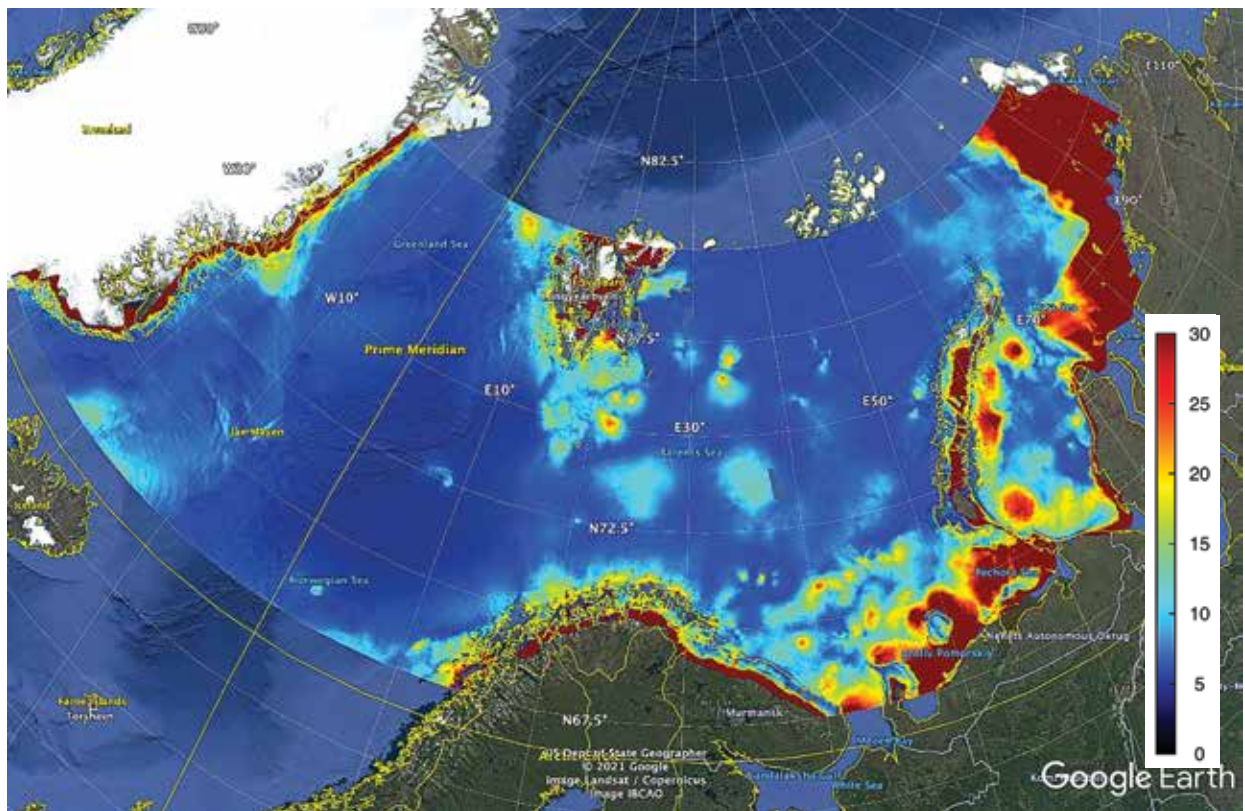


Figure 33. Barents Sea 63 Hz weekly interquartile distance for September 2019, week 1 (Excess noise is the sound energy level above 68 dB/μPa²).

Finally, excess noise in the Barents Sea was assessed. It is clear that there are underwater noise hotspots throughout the Barents Sea, including along the northern coast of Scandinavia and the northwesternmost coast of Russia, with the primary shipping lanes driving underwater soundscapes.

In summary, across three regions of the Arctic with ship traffic and high densities of marine mammals, excess noise levels reached up to 30 dB in the peak of the open water season in 2019. Excess noise above 3 – 6 dB can result in masking of communication in marine mammals, so these results warrant further consideration.

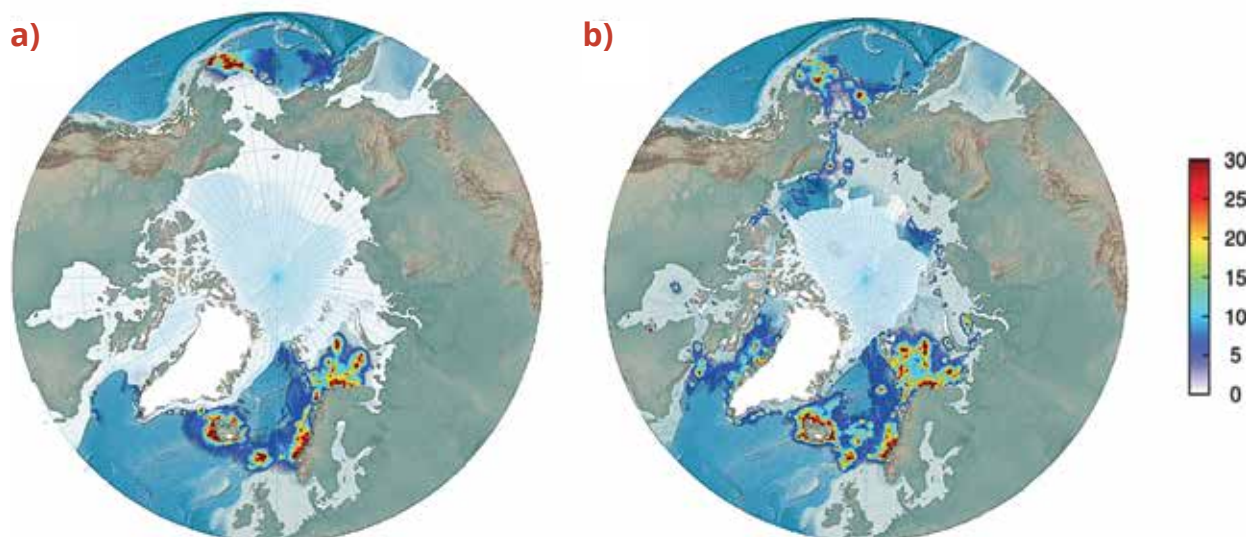


Figure 34. Pan-Arctic 25Hz decidecade band weekly 75th percentile excess noise for a) March 2015 and b) September 2015 (in units of dB/μPa²). Sea ice is represented by white shading.

Excess underwater noise across the Arctic

In addition to the three regions above, we present a selection of Pan-Arctic estimates of excess noise at the 75th percentile during ice-covered (March) and relatively ice-free (September) months. The 75th percentile is relevant to the discussion of impacts on

noise-sensitive species because it can be 10-20 dB higher than the median of excess noise and can persist for at least six hours of every day. In the maps below, it is obvious that excess noise at the 75th percentile only reaches small areas in ice-covered months but is more widespread throughout the Arctic in ice-free September (Figures 34 – 37).

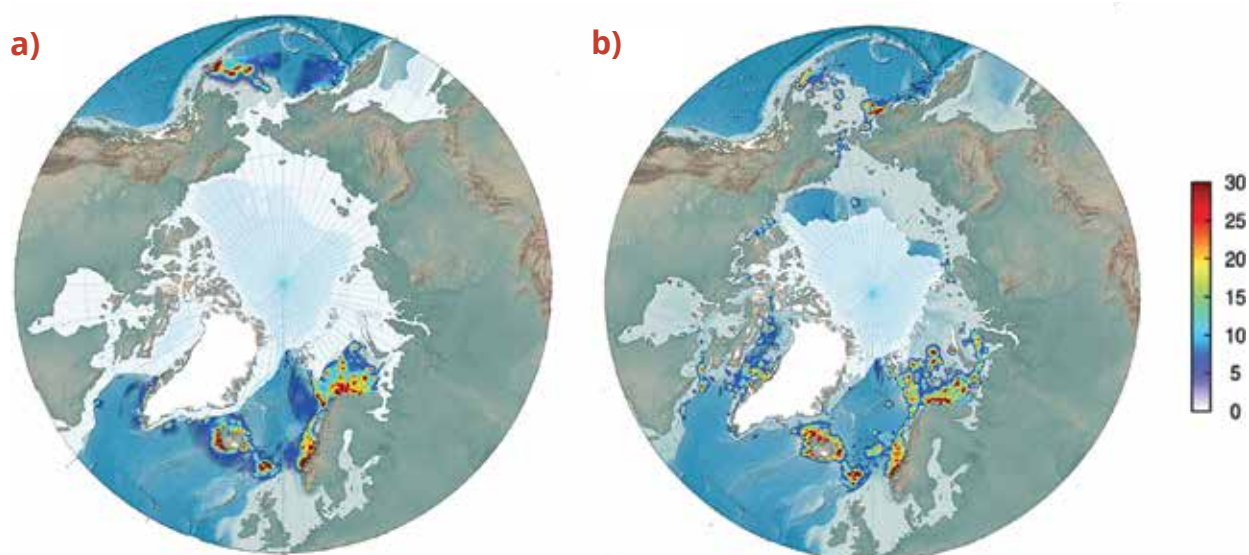


Figure 35. Pan-Arctic 125 Hz decidecade band weekly 75th percentile excess noise levels for a) March 2019 and b) September 2019 (SEL is in units of dB/μPa²).

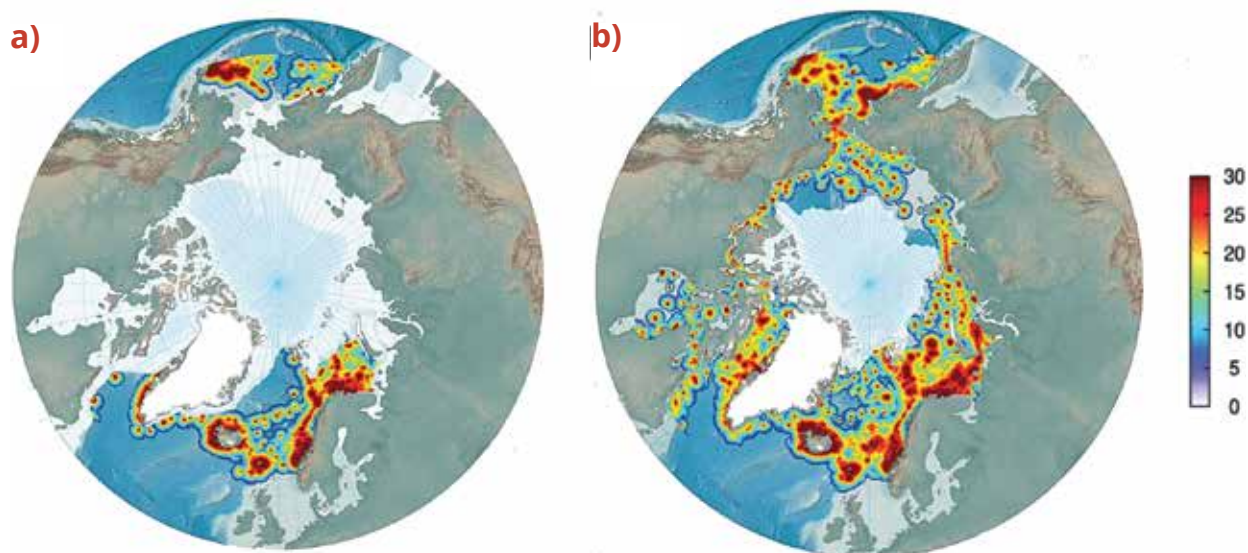


Figure 36. Pan-Arctic 1 kHz decidecade band weekly 75th percentile excess noise for a) March 2019 and b) September 2019 (SEL is in units of $\text{dB}/\mu\text{Pa}^2$).

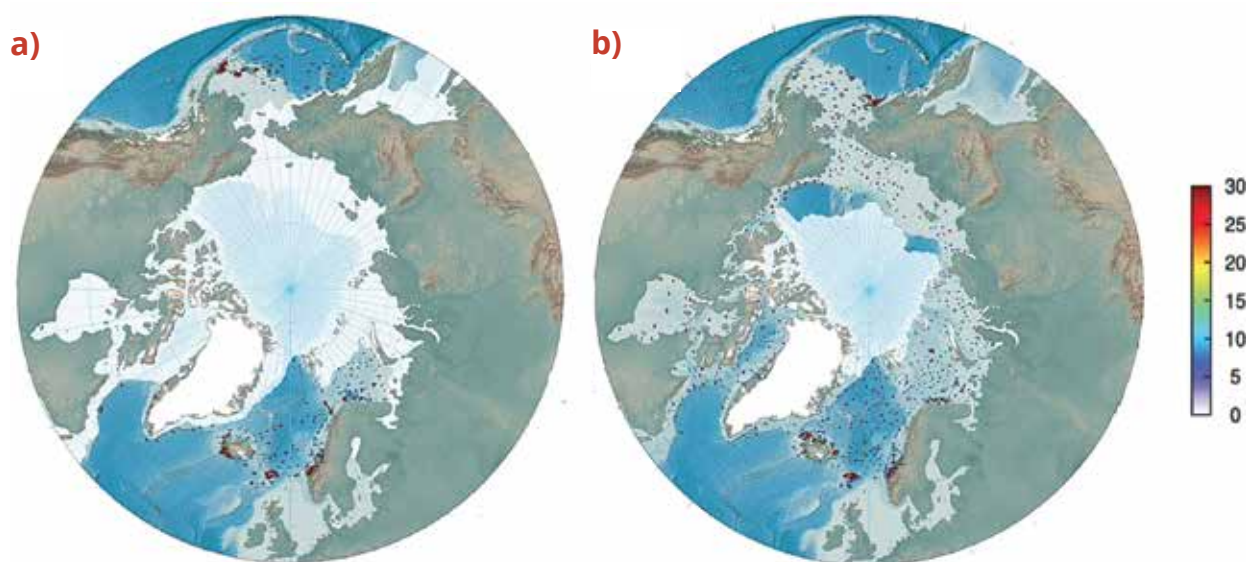


Figure 37. Pan-Arctic 10 kHz decidecade band weekly 75th percentile excess noise for a) March 2019 and b) September 2019 (SEL is in units of $\text{dB}/\mu\text{Pa}^2$).





DISCUSSION

The Arctic is a unique ecosystem, characterised by near-complete ice cover in the winter and large areas of open water in the summer. When there is ice present, marine species experience a relatively quiet ambient soundscape, as ice scatters and attenuates the sound of wind, ships, and local human activity. But when the ice retreats and boreal summer comes, the Arctic Basin's shallow bathymetry does just the opposite, allowing the sound of just a few ships to be magnified throughout the Basin. And this excessively loud soundscape may occur more in the future, as sea ice is melting at an alarming rate. More months of an open water Arctic, and the potential of a completely ice-free boreal summer by the 2030s, means that marine mammals may have to adapt to louder soundscapes dominated by anthropogenic noise.

Analysis of underwater noise produced by ships and noise propagation across the Arctic from 2013 – 2019 revealed hotspots of underwater noise in multiple regions. Across several locations, underwater noise from shipping has increased, in the order of 5-15 dB, over the past seven years. This finding is consistent with PAME's Arctic Shipping Status Reports in 2020 that also note increases in shipping activity. However, several properties of the Arctic Ocean make it a special case for underwater noise and this report concludes that even a small increase in the number of ships can greatly change the underwater soundscape and increase levels of ambient noise through long-range propagation.

This 5 to 15 dB increase at 25 Hz and 63 Hz in only seven years effectively represents a doubling in noise levels – some parts of the Arctic are twice as loud as they were in 2013. This is likely a change in marine soundscapes never experienced before. Rates of change in soundscapes in other parts of the world, for example, the Northeast Pacific Ocean, are at 2 – 3 dB per decade²⁷ and have taken 30 – 40 years to reach increases of the same magnitude reported here. Given the long lifespans of many species of Arctic marine mammals (> 200 years for bowhead whales), these rapid changes in underwater noise levels will be experienced within the lifetimes of individual animals and will require a level of plasticity and/or adaptation that may not be possible.

Estimation of excess noise levels, i.e., the additive contribution of underwater noise from shipping to the ambient soundscape, indicated that ship noise in some locations at particular times of the year is likely to affect noise-sensitive species in the Arctic. The excess noise in the Bering, Barents, Kara, Laptev, Chukchi, the Canadian Archipelago and Baffin Bay can be as high as 30 dB/ μPa^2 . As well as regional spatial overlap between marine mammals and underwater noise from shipping, there is substantial overlap between the

sound frequencies used by marine mammals with those produced by ships operating in the Arctic. The unique properties of the Arctic Ocean further exacerbate potential impacts: surface ducting caused by cold surface water temperatures allows noise generated at shallow depths (e.g., ship noise) to propagate great distances in the top layer of the ocean. Because marine mammals must breathe air, and many species swim and dive at relatively shallow depths, waters within this surface duct constitute their primary habitat.

Specific impacts of underwater noise from shipping in the Arctic on marine species are sparsely reported. Studies outside the Arctic have found that anthropogenic underwater noise pollution can lead to increased stress in marine mammal populations, as indicated by levels of hormones such as cortisone and aldosterone. Observations of the hormones of North Atlantic right whales showed a significant decrease in stress levels following a drop in the ambient noise levels directly after September 11th, 2001, when shipping traffic significantly quieted²⁸. A new study in the Eastern Canadian Arctic reported an up to 200 % increase in the amount of cortisol in narwhal blubber in the Eclipse Sound population, following an increase in shipping from 2006²⁹. Underwater noise from shipping can present additional challenges for conspecific communication, navigation, feeding, and calf protection³⁰. Certainly, high estimates of excess noise levels (up to 30 dB) from the current report suggest that masking of communications is a possibility for Arctic marine mammals in the vicinity of ship traffic.

There is a great need to continue to improve our understanding of the spatial and temporal changes of the Arctic soundscape, to put shipping noise in context of other natural sound sources, and to quantitatively measure increased sound exposure to animals and the negative biological and ecological impacts this could have.

AREAS OF UNCERTAINTY

Although this study is a significant step forward in understanding the contribution of underwater noise from shipping to the Arctic, several areas of uncertainty remain, which should be addressed in future work. A primary challenge is to understand the impact of ship noise on local ecosystems and marine mammal and fish health. To do this, an understanding of the background level of the ocean soundscape without ships must be determined. In ice-covered waters this can be loud due to ice cracking, or very quiet due to the lack of ships and wind and poor propagation conditions. For shallow seas with little ice cover, shipping and wind can dominate. There is a need to develop and apply regional statistics for “average” ambient sound levels

based upon measurements and the presence/absence of sea ice. In this study, a single number per frequency band has been chosen and this can be improved, which will lead to more accurate estimates of noise exposure to marine species.

The Arctic is a poorly sampled environment. The impact of oceanographic, bathymetric, and seafloor type uncertainty on the shipping noise model must be addressed. Although the results are presented in a statistical manner, they represent only statistical variability due to ship motion, and have not included uncertainty in the ocean temperature structure, the ice parameters and position, the seafloor topology, or seafloor type. Inclusion of these uncertainties will lead to a broader and more accurate assessment of the likelihood of negative impacts of increased shipping.

There are many environmentally and culturally sensitive regions of the Arctic. These require finer-scale measurements to understand the contribution of underwater noise from shipping. High-resolution spatial modeling of the soundscape in these regions that includes multiple years and anthropogenic sources of noise – similar to the snapshot examples of the Barents Sea, Baffin Bay and Bering Sea analyses presented here – would be useful.

Finally, there is a continued need to validate ocean noise models with observations of ambient sound through a spatially and temporally diverse sampling of the Arctic Ocean soundscape. This information can contribute to further development and validation of models to account for sea ice noise, the marginal ice zone and the effect of wind on the Arctic soundscape.

POTENTIAL NEXT STEPS

The management of anthropogenic noise towards healthy marine ecosystems is an ongoing focus of governments around the world and across several international fora. There are multiple research and policy workstreams PAME could undertake in the future, including:

1. Improving understanding of underwater noise from shipping in the Arctic

- Further explore noise propagation models from Phase I of this project to extract information on regional soundscapes, higher frequency effects, and dominant noise sources (i.e., vessel characteristics).
- Validate and calibrate noise propagation models from Phase I of this project using existing measurements from multiple locations in the Arctic Ocean.
- Compare the intra- and interannual temporal

changes in soundscapes between regions.

- Expand regional soundscape analysis to areas covered in ice most of the year, as well as areas of high shipping traffic.
- Explore implications of underwater noise (spatially, seasonally and related to excess noise contribution at frequencies important to noise-sensitive species) for populations of noise-sensitive species with input from CAFF's CBMP marine mammal expert network.
- Expand models to include natural activities such as biophony (whale calls, walrus knocking) and geophony (ice cracking, rain, wind) to provide a more complete picture of the Arctic Ocean soundscape and the contribution of shipping.
- Expand models to include underwater noise from icebreakers while breaking ice.
- Gather and include culturally important spatial data in further analyses to understand and mitigate potential impacts of increased shipping on coastal Indigenous communities.

2. Develop monitoring plans and explore policy measures

- Develop a monitoring plan that outlines a strategic and systematic approach for measuring underwater soundscapes in the Arctic Ocean (an acoustic monitoring network), based on existing monitoring programmes and noise propagation maps from this project.
- Build scenarios consisting of operational and technological measures to reduce or manage the contribution of underwater noise from shipping in key Arctic areas, including important Indigenous use and protected areas. Evaluate the effectiveness of these measurements using combined ship source and noise propagation modelling.
- Project future growth in vessel traffic and its related underwater noise pollution impacts, taking into account sea ice loss and climate change.
- Research anthropogenic underwater noise sources other than shipping, such as mineral exploration (through seismic survey) and extraction, military sonar and construction.
- Measure the contributions to the soundscapes from different types of vessels and vessels sailing under different flags. This could create a “noise footprint” map per country and lead to future policy recommendations.

3. Share findings of this project to relevant international fora and regulators

- Given its mandate to address marine policy measures, PAME has a valuable role to play in providing insight and information to international fora. Major findings and conclusions

from PAME's work should be presented to key international and regional organisations and initiatives, for comparison and cross-learning. Of immediate relevance will be to bring an Arctic

perspective to the proposed new work item at the International Maritime Organization (IMO) focused on updating the current voluntary underwater noise pollution guidelines.

WEB PRODUCTS THAT ACCOMPANY THIS REPORT

Hosted on the PAME website, to accompany this report, are all the acoustic runs for every region and year. This includes:

- All 270 daily medians for September 2019 for the Bering Sea, plus 1,080 files for the 5th, 25th, 75th, and 95th percentiles
- All 270 daily medians for September 2019 for the Barents Sea, plus 1,080 files for the 5th, 25th, 75th, and 95th percentiles
- All 270 daily medians for September 2019 for Baffin Bay/Davis Strait, plus 1,080 files for the 5th, 25th, 75th, and 95th percentiles
- All 3,276 weekly medians for the Pan-Arctic Basin, for every frequency and from every month from 2013-2019, plus 13,104 files for the 5th, 25th, 75th, and 95th percentiles

These are available for download from the PAME website in KMZ, KML, ESRI maps, netcdf, and GeoTiff formats through an opendapp server. The link to these files is here: [final PAME URL when available]. Also on the PAME website there is a jupyter notebook outlining the process that AOS used to model the acoustic maps, linked here: [final PAME URL when available].

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APPENDIX A:

KEY CONTRIBUTORS TO THIS REPORT

PAME:

PAME (Protection of the Arctic Marine Environment) is one of six Arctic Council working groups. PAME was first established under the 1991 Arctic Environmental Protection Strategy and was continued by the 1996 Ottawa Charter that established the Arctic Council.

PAME is the focal point of the Arctic Council's activities related to the protection and sustainable use of the Arctic marine environment and provides a unique forum for collaboration on a wide range of activities in this regard.

PAME's mandate is "To address marine policy measures and other measures related to the conservation and sustainable use of the Arctic marine and coastal environment in response to environmental change and from both land and sea-based activities, including non-emergency pollution prevention control measures such as coordinated strategic plans as well as developing programs, assessments and guidelines, all of which aim to complement or supplement efforts and existing arrangements for the for the protection and sustainable development of the Arctic marine environment."

PAME operates largely within these themes:

- Arctic Shipping
- Marine Protected Areas
- Resource Exploration and Development
- Ecosystem Approach to Management
- Arctic Marine Strategic Plan 2015-2025
- Arctic Marine Pollution

PAME carries out activities as set out in bi-annual work plans approved by the Arctic Council on the recommendation of the Senior Arctic Officials. These activities led by PAME include circumpolar and regional action programmes and guidelines complementing existing legal arrangements aimed at protection of the Arctic marine environment from both land and sea-based activities. PAME works in close collaboration with the other five Arctic Council Working Groups.

The PAME Working Group consists of National

Representatives responsible for its work in their respective countries. Permanent Participants, representing Arctic indigenous groups, also participate in PAME, as well as representatives of several observer countries and interested organisations. PAME provides a unique forum for collaboration on a wide range of Arctic marine environmental issues.

The PAME Working Group generally meets twice a year to assess progress of work, discuss program priorities and develop its biennial work plans. The PAME Working Group is headed by a chair and vice-chair, which rotate among the Arctic countries and is supported by an International Secretariat, based in Akureyri, Iceland. PAME reports to the Senior Arctic Officials, and through them, to the Ministers of the Arctic Council that meets every two years.

WWF:

WWF stops the degradation of the planet's natural environment to build a future in which people live in harmony with nature. WWF is a network of national WWF offices and global teams which focus on regions or thematic areas. Both WWF-Canada and WWF's global Arctic Programme participated in this project. WWF's vision for the Arctic is a well-managed, biodiverse and resilient region that supports healthy populations of wild species and benefits the well-being of people in the Arctic and beyond.

WWF actively engages with numerous local, national, and regional institutions responsible for governing various activities in the Arctic. This work includes the Arctic Council, the high-level intergovernmental forum on Arctic conservation and sustainable development. WWF has been an Observer since 1998.

In the Arctic, WWF works directly with Indigenous Peoples and Arctic communities to ensure conservation priorities are in line with community interests. WWF participates in projects that cover a wide range of topics, from funding groundbreaking wildlife research and advocating for habitat protection of Arctic species,

to mitigating the impacts of Arctic shipping and supporting community renewable-energy initiatives.

In 2017, WWF completed the first-ever assessment of the implementation of Arctic Council conservation-related direction, the WWF Arctic Council Conservation Scorecard. This project will continue to assess the implementation of Council direction together with national governments, encouraging them to provide reporting and advocating for a more effective and transparent Council.

UBA:

UBA (Umweltbundesamt) is the German Environment Agency and was founded in 1974. As Germany's main environmental protection agency, their task is to ensure that their fellow citizens have a healthy environment with clean air and water, free of pollutants to the greatest extent possible. They deal with an extremely broad spectrum of issues, including waste avoidance, climate protection, and pesticide approvals.

Their work centers around gathering data concerning the state of the environment, investigating the relevant interrelationships and making projections – and then, based on these findings, providing federal bodies such as the Ministry of the Environment with policy advice. They also provide the general public with information. Apart from these activities, they implement environmental law by making sure that it is applied in areas such as CO2 trading and approval processes for chemicals, pharmaceutical drugs and pesticides.

Their overarching mission is early detection of environmental risks and threats so that they can assess them and find viable solutions for them in a timely manner. They do this by conducting research in their own labs and by outsourcing research to scientific institutions in Germany and abroad. They are also the German point of contact for numerous international organizations such as the World Health Organization. UBA is also the National Competent Authority for all activities in the Antarctic which are organised in Germany or proceed from its territory.

Transport Canada:

Transport Canada is a federal institution, leading the Transport Canada portfolio, including marine transportation, and working with their partners. Transport Canada is responsible for transportation policies and programs. They promote safe, secure, efficient, and environmentally responsible transportation.

The Arctic Shipping division of Transport Canada works on developing and maintaining regulations, standards, and guidelines concerning shipping operations in

Canadian Arctic ice-covered waters; north of latitude 60° N.

This work includes:

- Interpreting transportation related acts and regulations applicable to the Canadian Arctic
- Interacting with International Maritime Organization (IMO) and The International Association of Classification Societies (IACS) in the development of the IMO Guidelines, and IACS Unified Requirements for the construction of Polar Class ships
- Participating in the Arctic Council through involvement in the Protection of the Arctic Marine Environment (PAME) working group, and the Arctic Marine Shipping Assessment
- Advising other government departments and industry stakeholders in matters concerning Arctic Class construction standards and ship operations in Canadian Arctic ice-covered waters
- Issuing Arctic Pollution Prevention Certificates for foreign and domestic vessels

NOAA:

NOAA is a federal agency of the United States government, whose mission is:

1. To understand and predict changes in climate, weather, oceans and coasts;
2. To share that knowledge and information with others; and
3. To conserve and manage coastal and marine ecosystems and resources.

NOAA's reach goes from the surface of the sun to the depths of the ocean floor as they work to keep the public informed of the changing environment around them. From daily weather forecasts, severe storm warnings, and climate monitoring to fisheries management, coastal restoration and supporting marine commerce, NOAA's products and services support economic vitality and affect more than one-third of America's gross domestic product. NOAA's dedicated scientists use cutting-edge research and high-tech instrumentation to provide citizens, planners, emergency managers and other decision makers with reliable information they need when they need it.

US Department of Transportation Maritime Administration:

As the DOT agency responsible for America's waterborne transportation system, the Maritime Administration (MARAD) is busy. At their core, they support the technical aspects of America's maritime transportation infrastructure – things like ships and shipping, port and vessel operations, national security, environment, and safety. They promote the

use of waterborne transportation, and ensure that its infrastructure integrates seamlessly with other methods of transportation. MARAD also maintains a fleet of cargo ships in reserve to provide surge sea-lift during war and national emergencies, and is responsible for disposing of ships in that fleet, as well as other non-combatant government ships as they become obsolete.

Beyond that, they work hard to maintain the overall health of the U.S. Merchant Marine. Commercial mariners, vessels, and intermodal facilities are vital for supporting national security, and so the agency provides support and information for current mariners, extensive support for educating future mariners, and programs to educate America's young people about the vital role of maritime operations in the lives of all Americans.

Applied Ocean Sciences:

Applied Ocean Sciences (AOS) was founded in 2019 in order to bring cutting-edge technology to the people who need it to do good things. AOS is an employee-owned company, a collective of ocean consultants, powered by their passion to do the highest caliber science, push

the boundaries of technology and innovation, and collaborate with academic, government, and nonprofit partners, all for the overarching goal of making the ocean safer, cleaner, and more resilient.

Applied Ocean Sciences has broad expertise in ocean acoustics, oceanography, biology, geospatial science, and science communication. AOS's collective capabilities can create state-of-the-art mapping products to evaluate ocean noise as a result of anthropogenic (and natural) sources, contextualize the maps to understand the effects of noise on the Arctic ecosystem, and communicate their importance to interested native councils.

DW-ShipConsult:

DW is a global acting consultant for the shipbuilding and shipping industry. With their team of 10 Naval architects they work every day to reduce unwanted noise on ships, in the oceans, and in ports. Dr. Dietrich Wittekind, who founded the company in 2004, gained his knowledge in over 20 years on shipyards where he was responsible for strength, shock, and acoustics of submarines.

APPENDIX B: DECIDECADE BAND INDEX, LOWEST, CENTER, HIGHEST FREQUENCIES, AND NOTIONAL FREQUENCIES USED IN THIS REPORT

Note that the higher frequencies have larger bands, so there is 3dB increase in decidecade SEL for each doubling in band center frequency for noise levels with the same spectral energy level (per Hz).

-22	5.623413	6.309573	7.079458	(6.3 Hz)
-21	7.079458	7.943282	8.912509	(8 Hz)
-20	8.912509	10	11.22018	(10 Hz)
-19	11.22018	12.58925	14.12538	(12.5 Hz)
-18	14.12538	15.84893	17.78279	(16 Hz)
-17	17.78279	19.95262	22.38721	(20 Hz)
-16	22.38721	25.11886	28.18383	(25 Hz)
-15	28.18383	31.62278	35.48134	(32 Hz)
-14	35.48134	39.81072	44.66836	(40 Hz)
-13	44.66836	50.11872	56.23413	(50 Hz)
-12	56.23413	63.09573	70.79458	(63 Hz)
-11	70.79458	79.43282	89.12509	(80 Hz)
-10	89.12509	100	112.2018	(100 Hz)
-9	112.2018	125.8925	141.2538	(125 Hz)
-8	141.2538	158.4893	177.8279	(160 Hz)
-7	177.8279	199.5262	223.8721	(200 Hz)
-6	223.8721	251.1886	281.8383	(250 Hz)
-5	281.8383	316.2278	354.8134	(320 Hz)
-4	354.8134	398.1072	446.6836	(400 Hz)
-3	446.6836	501.1872	562.3413	(500 Hz)
-2	562.3413	630.9573	707.9458	(630 Hz)
-1	707.9458	794.3282	891.2509	(800 Hz)
0	891.2509	1000	1122.018	(1 kHz)
1	1122.018	1258.925	1412.538	(1.25 kHz)
2	1412.538	1584.893	1778.279	(1.6 kHz)
3	1778.279	1995.262	2238.721	(2 kHz)
4	2238.721	2511.886	2818.383	(2.5 kHz)
5	2818.383	3162.278	3548.134	(3.2 kHz)
6	3548.134	3981.072	4466.836	(4 kHz)
7	4466.836	5011.872	5623.413	(5 kHz)
8	5623.413	6309.573	7079.458	(6.3 kHz)

APPENDIX C:

METHODS FOR CALCULATING UNDERWATER NOISE SOURCE LEVELS FROM SHIPS OPERATING IN THE ARCTIC

The quantity “ΔSL” was introduced to compare all models. It describes absolute value of the arithmetic mean of the difference between predicted and measured source level. All comparisons are presented for different versions of the Wittekind Model which are further described in the following chapter.

- V0: Initial version as presented in the publication
- V1: Updated engine coefficients
- V2: Updated coefficients based on more measured source levels
- V3: New input parameters for large vessels

With reference to Figure F5 we conclude

- The statistical error “ΔSL” of all available models is higher than 5 dB for the majority of all models.
- Wittekind Model V3 and SONIC model fit best for general cargo vessels
- Wittekind Model V2 and V3 fit best for bulk carriers
- Wittekind Model V2 and V3 fit best for container ships

The Wittekind model is chosen for further modelling of ship source levels in the project project for mapping of ship noise in Arctic waters.

Table 1: Overview of additional parameters considered in the Wittekind model

Version	F_4	$40 \log \frac{V_{STW}}{V_{ref}}$	m_{aux}	c_B	$L_{oa} \cdot B_s$	$\frac{V_{STW}}{V_{CIS}} > 1, L_{oa} > 120 m$	C_{new}
V 0	×	×	×	×	×	×	×
V 1	✓	✓	✓	✓	×	×	×
V 2	✓	✓	✓	×	✓	×	✓
V 3	✓	✓	✓	×	✓	✓	✓

The coefficients describe:

- F_4 : Factor to describe contribution of two-stroke engines on large merchant ships
- $40 \log (v_{STW} / v_{ref})$: Speed dependence of noise from four-stroke main engines
- m_{aux} : size of auxiliary engines
- c_B : Block coefficient of the hull (requires knowledge of displacement)
- $L_{oa} \cdot B_s$: Simplification to avoid requirement of knowledge of displacement

A detailed description and discussion of how to take into account different design parameters on the estimated underwater source level of the individual ship can be found in the initial publication of the Wittekind model¹ and in a published master thesis in which the model was developed further². In the context of source level calculation for modelling of the Arctic, all recent versions of the model are taken into account according to the selection process shown in Figure F1.

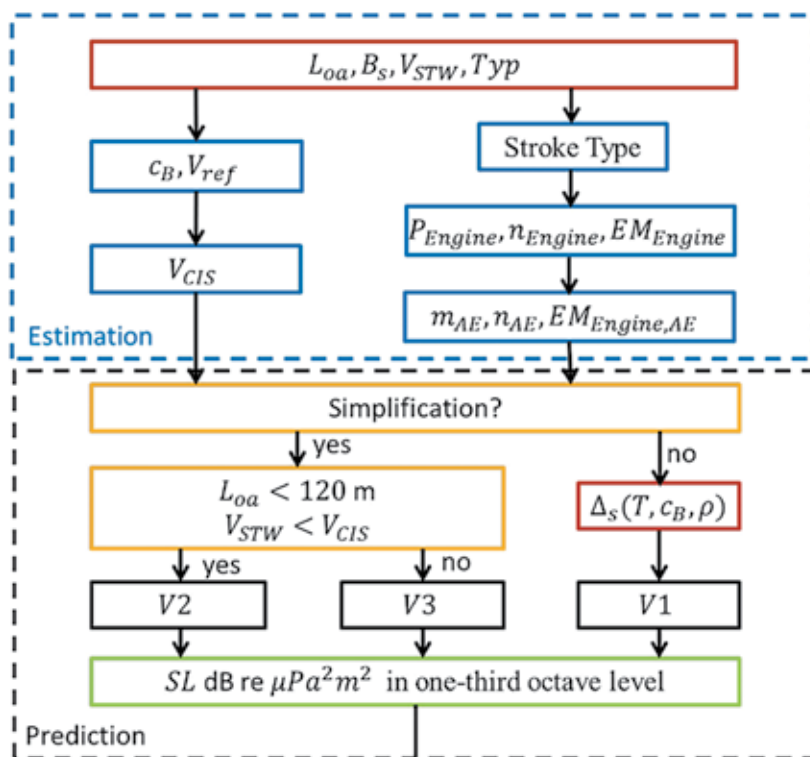


Figure 1. Flow chart for selection of suitable prediction model

1 Wittekind, Dietrich. A Simple Model for the Underwater Noise Source Level of Ships. Journal of Ship Production and Design. 2014.

2 Daniel, J. M. Development of a Model for Underwater, Master Thesis Hamburg University . Hamburg : s.n., 2020.

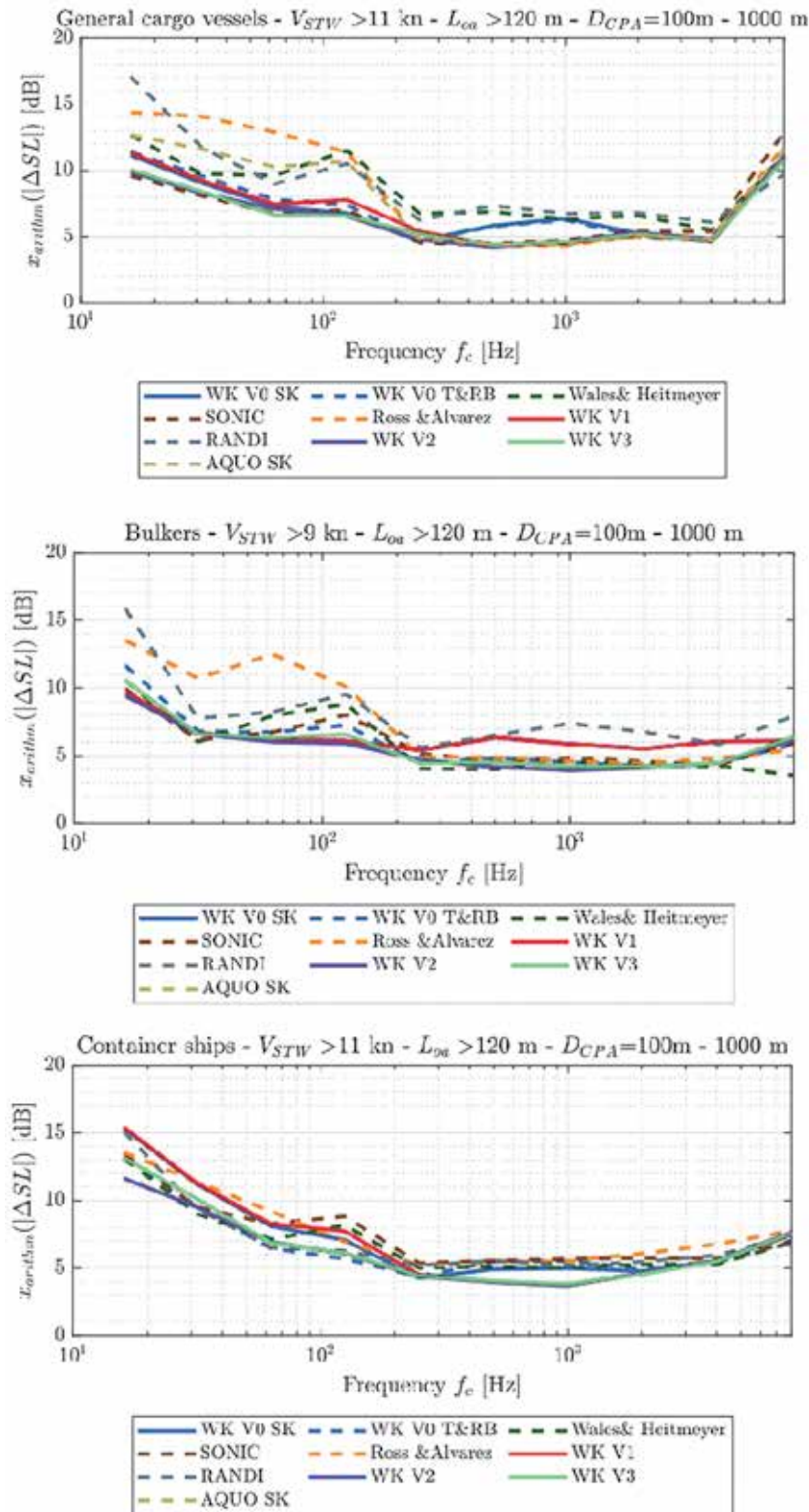


Figure 2. Comparison of statistics for predicted and measured source level, presented in octave bandwidth (source: master thesis on further development of the acoustic ship model3)

For ships with only few information available different procedures were developed to obtain most precise assumption possible. (see description B,C,D in chapter Description of Procedures A, B, C, D)

Table 2: Available data and required input data of the Wittekind model

ASTD-DATA:	USABLE IHS-DATA	DW MODEL
LAT/LON	IMO	L
UTC	LLcat5	B
IMO/MMSI	GT	m (weight main engine)
LLcat5	Power main engine	n (number of main engines)
GT group	L,B,T,Displ.	Type of engine
	v_service	v_stw (Speed trough water)
		v_cis (cavitation inception speed)
		V_serv (service/design Speed)
		Displ./cb
		Mounting type of main engine
		m_aux (auxiliary engine)
		n_aux (auxiliary engine)

Note that both ASTD and IHS data contain incomplete data sets.

The estimation of ship parameters necessary for the DW model depends on the availability of ship data for each considered ship. If the IMO-No is contained in List1 or List2 necessary parameters are available from IHS data. Estimating ship parameters of ships that are not contained in List1 or List2 is based on the evaluation of the IHS data set and the use of average values for different combinations of ship size and type. If no information is available “dummy values” are used.

Table 33: Summary of modelling procedures according to availability of data

LIST NO.	DATA AVAILABILITY	PROCEDURE TO ESTIMATE SHIP PARAMETERS
1	complete IHS-Data (L,B,T,P,Displ.,v)	Not necessary
2	incomplete IHS-Data,	A (statistic approach based on correlations inside IHS data)
3	only GT group and LLcat5	B (average values for LLcat5 and GT group from IHS)
	only GT group or LLcat5	C (median of category)
	only speed* (always available if time & position mentioned)	D (Dummy values „ghostship“ in correlation to v*)

Description of Procedures A, B, C, D

Linear regression is used to estimate missing data. Regression parameters come from complete data set. (see IHS data description)

For every combination of GT group and LLcat5 category Parameters are estimated. If >50 ships of a LLcat5 category are available in IHS data parameters are described in relation to GT for each GT group. Otherwise Parameters are estimated by averaging information of available similar ships.

number of GT groups: 7; number of LLcat5 types: 125

Median parameters for each GT group and LLcat5 category. Dummy values „ghostship“ in correlation to v*).

APPENDIX D:

MARINE MAMMAL AND OTHER NOISE SOURCES' ACOUSTIC FREQUENCIES AND LITERATURE SOURCES

MARINE MAMMAL	ACOUSTIC FREQUENCY	SOURCE
Beluga whale	200 Hz to 20kHz; echolocation clicks extending upward of 120 kHz	Au et al. (1985). JASA. 77(2), 726-730. Sjare, B.L. & Smith, T.G. (1986). Can J of Zoology. 64(12), 2824-2831.
Killer whale/orca	<500 Hz to 1500 Hz for pulsed calls and whistles; clicks up to 150 kHz at least	Filatova et al. (2015). JASA. 138(1), 251-257. Wladichuk et al. (2020). 148, 2632
Sperm whale	0 to 24 kHz	Goold, J.C. & Jones, S.E. (1995). JASA. 98(3), 1279-1291.
Bowhead whale	20 Hz to 10 kHz	DOSITS.org
Humpback whale	20 Hz to 20 kHz	Catalogue of the Humpback Whale Social Call Working Group (managed by Dr. K.D. Seger). Perazio et al. (2018). JASA. 144(3), 1953.
Right whale	20 Hz to >16 kHz	Parks et al. (2011). Endangered Species Research. 15(1), 63-76.
Fin whale	20 Hz to 131 Hz	De Vreese et al. (2018). Sci Reports. 8(1), 1-14.
Minke whale	5 to 6 kHz clicks 80 to 118 Hz downsweeps 58 Hz – 500 Hz	Beamish, P., & Mitchell, E. (1973). Deep Sea Research and Ocean. Abstracts. 20(4), 375-386. Edds-Walton, P.L. (2000). Bioacoustics. 11(1), 31-50. Risch, et al. (2013). MEPS. 489, 279-295.
Blue whale	100 Hz to 300 Hz	De Vreese et al. (2018). Sci Reports. 8(1), 1-14.

MARINE MAMMAL	ACOUSTIC FREQUENCY	SOURCE
Sei whale	21 Hz to 100 Hz	Rankin, S., & Barlow, J. (2007). Bioacoustics. 16(2), 137-145.
	35 Hz to 129 Hz	Español-Jiménez et al. (2019). Ocean Science. 15(1), 75-82.
Narwhal	clicks 10 kHz to 240 kHz	Rasmussen et al. (2015). Aquatic Mammals. 41(3).
Grey whale		Dahlheim, M.E. (1987). Doctoral dissertation, UBC.
	20 Hz to 2 kHz	Crane, N.L., & Lashkari, K. (1996). JASA. 100(3), 1878-1886.
	45 Hz to 4.520 kHz	Burnham et al. (2018). Frontiers in Marine Science. 5, 329.
Risso's dolphin	20 kHz to about 100 kHz	Soldevilla, M.S. (2008). Doctoral dissertation, UC San Diego.
Northern right whale dolphin	6 kHz to >22 kHz	Rankin et al. (2007). JASA. 121(2), 1213-1218.
Pacific white-sided dolphin	20 kHz to about 100 kHz	Soldevilla, M.S. (2008). Doctoral dissertation, UC San Diego.
North Atlantic bottlenose whale*	31 to 39 kHz	De Vreese et al. (2018). Sci Reports. 8(1), 1-14.
Sowerby's beaked whale*	31 to 39 kHz	De Vreese et al. (2018). Sci Reports. 8(1), 1-14.
Long-finned pilot whale	1 kHz to 15 kHz	Alves et al. (2014). Marine Mammal Science. 1-17.
	2.5 kHz to 75 kHz	Foskolos et al. (2019). Scientific reports. 9(1), 1-9.
White-beaked dolphin	whistles 3 kHz to 35 kHz	Rasmussen, M.H. & Miller, L.A. (2002). Aquatic Mammals. 28(1), 78-89.
	clicks 1 kHz to >300 kHz	
Common dolphin	15 kHz to >100 kHz	Soldevilla, M.S. (2008). Doctoral dissertation, UC San Diego.
Bottlenose dolphin	10 kHz to about 100 kHz	Soldevilla, M.S. (2008). Doctoral dissertation, UC San Diego.
Atlantic white-sided dolphin	1 kHz to >48 kHz	Simard, P. et al. (2008). JASA. 34(4), 464-470.
Harbour porpoise	110 kHz to 180 kHz	Villadsgaard et al. (2007). Journal Experimental Bio. 210(1), 56-64.
	125 Hz-150 kHz*	Kastelein et al. (2015). SEAMARCO.
Dall's porpoise	130 kHz to 180 kHz	Kyhn et al. (2013). PloS one. 8(5), e63763.
Walrus	0 to 5 kHz	Mouy et al. (2012). JASA. 131(2), 1349-1358.
Steller sea lion	30 Hz to 3 kHz (females)	Campbell et al. (2002). JASA. 111, 2920.
Harp seal	100 Hz to 2500 Hz	Watkins, W.A. & Schevill, W.E. (1979). JASA. 66(4), 983-988.

MARINE MAMMAL	ACOUSTIC FREQUENCY	SOURCE
Bearded seal	1 to 8 kHz	De Vreese et al. (2018). Sci Reports. 8(1), 1-14.
	300 Hz to 2500 Hz	Jones et al. (2014). Arctic. 203-222.
Ribbon seal	50 Hz to 4000 Hz	Jones et al. (2014). Arctic. 203-222.
Ringed seal	200 Hz to 1,600 Hz	Jones et al. (2014). Arctic. 203-222.
Harbour seal	200 Hz to 2000 Hz	Nikolich et al. (2016). JASA. 140(2), 1300-1308.
Spotted seal	0 to 3 kHz	Yang et al. (2017). JASA. 141(3), 2256-2262.
Hooded seal	0.5 kHz to 6 kHz	Ballard, K.A., & Kovacs, K.M. (1995). Canadian J. of Zoology. 73(7), 1362-1374.
Grey seal	0 to 3.5 kHz	McCulloch, S. (2000). Doctoral dissertation, University of St Andrews.
Polar bear	1 to 30 kHz* IN AIR	Nachtigall et al. (2007). J. of Experimental Biology. 210(7), 1116-1122.
Sea Otter	270 Hz to 13 kHz	McShane et al. (1995). Journal of Mammalogy. 76(2), 414-427.
Northern Fur Seal	10 Hz to 6 kHz	Insley et al. (2001). Animal Behaviour. 61, 129-137.

*= audiograms, not vocalization ranges

OTHER SOUND SOURCES	ACOUSTIC FREQUENCY	SOURCE
Boat noise	8 Hz to 6 kHz	Wenz, G.M. (1962). JASA. 34(12), 1936-1956.
Ice breakers	20 Hz to 20 kHz	Roth et al. (2013). JASA. 133(4), 1971-1980.
Ice breaker propellers	50 to 100 Hz	Roth et al. (2013). JASA. 133(4), 1971-1980.
Peak ship noise	25 to 60 Hz	Wales, S.C., & Heitmeyer, R.M. (2002). JASA. 111(3), 1211-1231.
Seismics in the Barents	30 Hz to 500 Hz	De Vreese et al. (2018). Sci Reports. 8(1), 1-14.
Sonar off Greenland	6 to 7 kHz	De Vreese et al. (2018). Sci Reports. 8(1), 1-14.
Ice in Barents	1 to 20 kHz	De Vreese et al. (2018). Sci Reports. 8(1), 1-14.
Wind	100 Hz to >10 kHz	Wenz, G.M. (1962). JASA. 34(12), 1936-1956.

APPENDIX E:

LITERATURE REVIEW OF UNDERWATER NOISE SOURCE LEVELS OF SHIPS

Shipping source levels have been studied extensively for the past 15 years, with a recent advancement in field measurements. The best model to date, prior to the individual mechanical engineering ship analysis, was performed by Wales and Heitmeyer (2002)⁴. Their data and model for ship noise peaks in the 25-60 Hz and drop off significantly beyond 500 Hz, but so does the average background noise due to increased propagation loss for the higher frequencies. Literature values for frequency ranges of shipping noise vary dramatically. The traditional Wenz curves described previously in this document illustrate ship noise ranging from 8 Hz to approximately 6,000 Hz (6 kHz)²⁶.

For a specific region, the anthropogenic soundscape from vessels depends greatly on environmental acoustic propagation conditions including oceanographic, bathymetric, and geomorphic considerations, and on the specific vessels being considered including factors such as size, propeller type, shaft rotation rate, and other machinery onboard. As a general rule, larger vessels such as tankers and container ships produce lower frequency acoustic energy than smaller fishing or pleasure craft; but this difference narrows between 1 kHz and 10 kHz with most vessels producing approximately equivalent acoustic energy above 10 kHz (which is lower in intensity than lower bandwidths). It is commonly reported in the literature that vessel noise is confined to lower frequency bands, under 1 kHz, and while it is true that ship noise usually has peak frequencies below 100 Hz, and that higher frequency

sound does not travel as far due to attenuation, ships do produce noise over 10 kHz. This higher frequency noise contribution is particularly relevant in the Arctic because the surface-ducting propagation effects allow higher frequency sound to propagate further than in warmer regions. Added to that is the high concentration of marine mammals sensitive to these higher bands present in the region. Finally, there are certain types of vessels such as icebreakers that are present more in the Arctic than in other oceans, which produce very different sounds than the typical engine and propeller noise of commercial shipping traffic. Icebreakers have onboard systems that inject bubbles into the water around the hull to reduce friction with the ice, and this action produces a broadband sound up to 5 kHz with source levels up to 194 dB⁵. The source levels of cavitation from propellers on the U.S. Icebreaker Healy while it is breaking ice have been reported at 190-200 dB. This is 10 dB louder compared to when it is doing open water operations (not breaking ice) in the 20 Hz and 20 kHz band³² (which also happens to be the entire range of human hearing, for reference to the reader). Noises from impact of the breaker with the ice itself can also exceed 200 dB across a broad band of frequencies. These breaking noises are in addition to the engine noises. Finally, there are notable differences between vessels with differing propulsion plants that will require future research. For example, the ten nuclear icebreakers currently in operation likely have different emission spectra than current non-nuclear ones, although this is not well characterised in the literature.

4 Wales, S. C., & Heitmeyer, R. M. (2002). An ensemble source spectra model for merchant ship-radiated noise. *The Journal of the Acoustical Society of America*, 111(3), 1211-1231.

5 Roth, E. H., Schmidt, V., Hildebrand, J. A., & Wiggins, S. M. (2013). Underwater radiated noise levels of a research icebreaker in the central Arctic Ocean. *The Journal of the Acoustical Society of America*, 133(4), 1971-1980.

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