UNDERWATER NOISE IN THE ARCTIC

Understanding impacts and defining management solutions

PHASE II

MAY 2025

ARCTIC COUNCIL

PAME

Protection of the Arctic Marine Environment

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UNDERSTANDING IMPACTS AND DEFINING MANAGEMENT SOLUTIONS

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This report is under editorial review, formating and and final layout

PAME
Protection of the Arctic Marine Environment

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Contents

Executive summary

Underwater noise from shipping is recognised as a serious environmental problem that has impacts on Arctic species, ecosystems and ecosystem services. The goal of this report is to improve understanding of underwater noise and identify possible actions that may help address this issue in the Arctic by assessing contributions of underwater noise from shipping under various economic and environmental scenarios.

This report explores current and future Arctic shipping and associated underwater noise at two timepoints: 2019 to represent the present and 2030, to present the near future based on a modelled shipping scenario reflecting growth in shipping sectors. The report focuses across the whole Arctic Ocean, as well as three sub-regions where there is a high overlap of ship traffic with habitats of noise-sensitive species (whales and other marine mammals). It also evaluates noise implications of several ship traffic management measures and presents the results of these in each sub-region.

The following summarises the main findings of this report:

- The Arctic is a special case when it comes to underwater sound. The addition of a relatively small number of vessels can have a large impact in historically less trafficked Arctic waters.

- Regional knowledge gaps for characteristics that affect how sound travels underwater, together with physical, chemical and biological changes to the ocean resulting from climate change, make it challenging to assess underwater noise in the Arctic.

- Models such as those used in this project enable testing of scenarios, including vessel management measures, that have the potential to affect underwater noise, in order to support decision- and policy-making.

- This modelling predicts that with no further policy action, by 2030, underwater noise from shipping will increase across the Arctic Ocean, including into the Central Arctic Ocean, as a result of more ship traffic and reductions in sea ice extent and thickness.

- Increases in noise levels will not be uniform. In sub-regions with less shipping (Chukchi Sea), changes will be large despite only modest increases in shipping. In sub-regions with heavy shipping (Barents Sea), overall changes will not be as marked but ship noise will be persistently higher than ambient levels across most of the sea.

- Measures with the potential to influence underwater noise (speed reduction, rerouting and technological changes at the source (the ship)) were tested using real-world and hypothetical scenarios that reflected vessel management decision-making in Baffin Bay, the Barents Sea and the Chukchi Sea.

- The implications of these measures were evaluated relative to both current and future traffic. The success of different measures at reducing underwater noise both now and in the future was context-specific, but generally not high, for several reasons, and underscored the importance of incorporating noise reduction goals directly into vessel management planning if URN reduction goals are to be achieved.

- A trade-off of re-routing vessels is a shift in underwater noise from one location to another. Because of this, direct goals for reducing underwater noise should be spatially defined and multiple spatial scales used to explore consequences of such measures on underwater sound propagation, as well as other consequences, such as to navigational safety.

- This is also true for regional, sub-regional and target biological area evaluations of benefits achieved through fleet or sector-specific technical changes in vessel design to reduce noise emissions: such changes may be considered ineffective at the scale of the region but highly beneficial locally or vice versa, depending on the scale of the goal and the composition of traffic affecting that goal.

- Spatial measures to manage underwater noise should consider the inclusion of buffer areas and be sufficiently dynamic to keep pace with rapid changes in the geographic distribution and movement patterns of Arctic species.

- The use of vessel speed limits to decrease noise from growing traffic in Arctic habitats of concern may not be effective if traffic is predominantly travelling slowly to begin with and/or if the decreases in speed do not correlate to significant decreases in vessel source level for the ship types affected.

- Next steps for this work could include applying lessons learned to build regional Arctic monitoring and management practices that form a common basis for decision-making to preserve the health of Arctic marine species and ecosystems.

Introduction

Underwater noise from ship traffic in the world's oceans has doubled approximately every decade since the 1960s, and this trend is predicted to continue (Jalkanen et al., 2022; McDonald et al., 2006). Underwater noise from ships is recognised by governments and international institutions as a rising environmental problem that has impacts on marine species and ecosystems and the services they provide (Harding and Cousins, 2022). Attempts to raise awareness about this issue and address it are taking place through national, regional and global initiatives (European Commission, 2008; International Maritime Organisation, 2023; Fisheries and Oceans Canada, 2024).

In the Arctic Ocean, expansion of shipping has been limited by sea ice until recently. Human-caused climate change is resulting in the Arctic warming almost four times faster than the rest of the world (Rantanen et al. 2022), and the subsequent reduction in extent and thickness of sea ice has created access to more open water for longer periods each year (Meredith et al., 2019). In the last decade, the number of ships entering Arctic waters as defined within the Polar Code has increased by 37 percent and the distance travelled has doubled (PAME, 2023). Consequently, underwater noise from shipping has increased rapidly across much of the Arctic at a rate higher than the global average (Jalkanen et al., 2022; PAME, 2021).

The large increase in underwater noise in the Arctic relative to other oceans is due partly to shipping noise emission baselines being low (Jalkanen et al., 2022). Very little noise energy is required to substantially degrade listening conditions when ambient sound levels underwater are very low, so the addition of a relatively small number of vessels can have a large impact (Hatch and Fristrup, 2009; Jalkanen et al., 2022). In addition, the Arctic Ocean has physical and chemical properties that affect how sound travels underwater, making it distinctive from other oceans. The naturally-occurring layer in the water column where low-frequency sound waves can travel over long distances – the sound fixing and ranging (SOFAR) channel – is located at a shallower depth in the Arctic than in other oceans (50 – 300 m *cf* 1000 m, Au and Hastings, 2008; Kutschale, 1969). While this polar extension of the SOFAR channel does not enable sound to travel as far as in temperate oceans, it enables relatively long-range sound propagation at shallow depths. Conversely, sea ice, particularly multi-year ice, can be an effective dampener of underwater sound. However, with climate change, sea ice cover is now thinner, younger and less prevalent, and together with warming of the ocean, underwater sound travels faster and further from the source (Munk, 2011; Poulson et al. 2016). For whales and other marine animals that use sound for critical life functions, loss of sea ice and further opening of the Arctic Ocean to commercial shipping brings potentially negative impacts. It should be noted as well that in some Arctic regions, such as the Northwest Passage, despite a reduction in overall sea ice coverage, the length of the shipping season is more variable and sometimes shorter due to higher risk associated with more mobile ice following breakup. This variability, however, has not led to a reduction in overall transits (Hedland et al., 2025)

Marine animals produce and rely on underwater sound for many critical life functions, including communication, navigation, foraging, reproduction and territorial interactions (Harding and Cousins, 2022). Effects of underwater noise on Arctic marine life can be direct, indirect and cumulative, and are most well studied in marine mammals. Although relatively few empirical studies document the specific effects of ship noise, examples in the literature are growing and are complemented by studies describing responses of marine life to shipping more generally (see also Halliday et al., 2021; Lancaster et al., 2021; PAME, 2019 and references within).

As Arctic marine species face pressure to adapt to rapidly changing conditions resulting from climate change, the increased maritime navigability of the Arctic Ocean has the potential to be a source of additional stress. Healthy marine ecosystems are essential for people both within and outside the region, and noise-sensitive species such as seals, whales and walruses are central to the cultures, livelihoods and food security of many coastal Indigenous communities. Understanding how shipping is affecting underwater noise levels and marine life is key to implementing management strategies in the Arctic. To prepare for and mitigate potential negative impacts, vessel management needs to be considered and understanding and anticipating the impacts of management and policy decisions is key to success.

In 2009 the Arctic Council's Working Group on the Protection of the Marine Environment (PAME) oversaw the Arctic Marine Shipping Assessment which, *inter alia*, identified underwater noise from shipping as having potential impacts on Arctic species and ecosystems and needing further research and action (PAME, 2009). The current project follows on from previous work on underwater noise by PAME. In 2019, PAME published a State of Knowledge report and in 2021 produced a report that mapped for the first time underwater noise across the Arctic in a six-year time series (Heaney et al., 2024; PAME, 2019; 2021).

This report summarises the second phase of that project: *Underwater Noise in the Arctic: Understanding Impacts and Defining Management Solutions, Phase II*. It explores current and future Arctic shipping and associated underwater noise across the whole Arctic Ocean, as well as in three sub-regions where there is high overlap of ship traffic with habitats of noise-sensitive species (whales and other marine mammals). It also evaluates sound reduction implications of several ship traffic management measures and presents the results of these in each sub-region.

Goals of this project

Build on previous PAME work to

1. Assess the current and projected contributions of underwater noise from shipping under various economic and environmental scenarios.
2. Explore the noise implications of a variety of vessel management measures.

Approach

Geographic and temporal scopes

To understand underwater noise from shipping in the present and future, we focused on two geographic scales: the whole Arctic Ocean (based on the CAFF boundary) and three sub-regions of the Arctic: Baffin Bay, the Barents Sea, and the Chukchi Sea. These three sub-regions were chosen because they have relatively high amounts of ship traffic overlapping with the geographic ranges of Arctic marine mammals (PAME 2021; Halliday 2020). PAME's delineation of Arctic Large Marine Ecosystems (LMEs) was used to represent these three sub-regions, i.e., the Barents Sea LME, the Northern Bering–Chukchi Sea LME, and the Canadian Eastern Arctic – West Greenland LME (which encompasses Baffin Bay (PAME, 2006, 2013)). The two years selected to represent present and future timepoints were 2019 and 2030, respectively. Although this project commenced in 2021, the Covid-19 pandemic reduced global shipping and subsequent underwater noise to levels that were not typical (Jalkanen et al., 2022). Thus, 2019 was chosen as the nearest year to the present to represent current shipping. Within these years, we focused on the month of September, when sea ice extent and thickness is at its minimum, and when there is the most open water throughout the Arctic Ocean.

Modelling the contribution of wind to the Arctic Ocean soundscape

To interpret the contribution of underwater noise from shipping in the Arctic Ocean, we need to understand natural, or ambient sound levels. These are affected by unique physical, biological and chemical properties which result in different propagation characteristics compared to other oceans, including sea ice, wind, and sound produced by marine life. While all these sources can have important influences on the Arctic soundscape, wind and ice are considered two key contributors to "chronic" or "ambient" sound levels as they are less episodic and less narrow in their pitch content (frequencies) than most animal vocalisations. Wind speed over the Arctic Ocean's surface was used to estimate ambient underwater sound levels in 2019 and 2030. While the movement, cracking, shearing and ridging of sea ice also produces sound underwater, a lack of standard modelling practice meant that sea ice was not included in the model as a source of ambient sound (for details and further explanation, see Appendix A). Given that all three sub-regions assessed were ice-free in September in 2019 and projected to be ice-free in 2030, and September falls outside the main months of the year when break-up and freeze-up occur and sea ice sounds can dominate the natural soundscape, the implications of not including sea ice as a sound source are lessened. However, analyses at other times of the year should consider the added contribution of sea ice to the ambient soundscape

Shipping datasets

Current Arctic shipping (2019)

Arctic ship traffic information from 2019 was sourced from PAME's Arctic Ship Traffic Data (ASTD) database. The raw data were processed to obtain a dataset of all vessel traffic in the Arctic during 2019 (full details on data processing in PAME, 2021 and Appendix A).

Projected Arctic shipping (2030)

Arctic shipping is projected to continue increasing in the future due to national and global political and socioeconomic drivers, together with changing sea ice conditions, which will contribute to the improvement of navigability of existing shipping routes and may eventually create access to new global transit routes (Meredith et al. 2019). There is currently no consensus on what shipping in the Arctic will look like in 2030, however, it is possible to describe multiple scenarios from trends in factors likely to affect vessel traffic and taking into account projected sea ice extent and thickness.

Using information sourced from scientific literature, grey literature and interviews with individuals with shipping or other sector-specific expertise, a 2030 Arctic shipping dataset was built. The dataset is grounded in region-specific projections of factors likely to affect vessel traffic in the Arctic (for full details, see Appendix B). The sectors considered in each region were fisheries, extractives (oil and gas, mining), cruise tourism and transit shipping. Levels and distribution of shipping in 2030 were estimated from existing plans for extractive projects, projected growth of the various sectors, northward movement of commercially important fish species, and additional shipping routes becoming available due to less ice-impeded conditions. We also considered factors such as the current size of the global icebreaker fleet, costs of compliance with mandatory requirements set by the International Maritime Organization (IMO) for vessels operating in polar waters (the International Code for Ships Operating in Polar Waters, or Polar Code) and the projected 2030 sea ice extent.

Underwater noise from shipping

The intensity and distribution of underwater shipping noise is determined by the amount of noise radiated by each ship, and the way that noise travels through the water column. The 2019 and 2030 Arctic shipping datasets were used to generate underwater shipping noise maps by first estimating each vessel's radiated source level based on type and operational condition (e.g., speed, see Appendix A for details). Noise maps were then calculated for all ships in 2019 and 2030 based on multiple factors that affected the spread of each ship's radiated noise in the water, such as water depth, bathymetry, seafloor type, temperature and salinity (for details, see Appendix A and PAME, 2021). We also included sea ice extent and the location of the ice edge (actual for 2019, forecast for 2030, Appendix A) in our analyses, because sea ice has a large effect on how sound propagates underwater. Sea ice isolates the water column from effects of natural sound sources, such as waves and wind, and can scatter sound waves, including those produced by ships, greatly reducing their spread. Resulting maps predict these components of the Arctic Ocean soundscape in 2019 and 2030, and can be examined for different frequencies, (measured in Hertz or Hz), depths, and for peak, average and median sound pressure. Maps include natural sound levels, plus underwater noise from ships, adjusted for sound dampening and reflecting qualities of sea ice.

Applying vessel management strategies

As well as exploring the Arctic underwater soundscape and the contribution of shipping to underwater noise levels now and in 2030, we sought to understand how different vessel management strategies might influence these noise levels. For the three sub-regions of interest, we simulated shipping management measures proposed or in place to reduce disturbance to important components of local ecosystems, such as sensitive populations of species and/or their habitats. Measures we selected included re-routing of ships (via areas to be avoided or recommended paths), speed reductions, and reduction of ship's radiated source level via technological solutions. Some measures are already in place (either voluntary or mandatory), while others were introduced as hypothetical measures. We simulated these in each sub-region relative to ship traffic both in 2019 and 2030 and assessed effects on the underwater soundscape locally and at the ecosystem scale (detailed further in section: *vessel management strategies for underwater noise*).

Reporting of results

Underwater sound levels are reported as median sound pressure levels over the month of September. September was selected for both years, as it is the month in the year when Arctic sea ice reaches its minimum extent and open water is at its greatest extent, thus allowing the highest shipping activity.

Units are decibels (dB), which are a measure of sound pressure, referenced to 1 microPascal. Decibels quantify sound pressure, or power of sound waves and are measured on a logarithmic scale. For example, a 3 dB increase represents a doubling of sound pressure/sound intensity, while a rise of 10 dB represents a tenfold increase in sound pressure/sound intensity.

Underwater sound is reported for a range of frequencies in a decidecade band centred at 125 Hz (spanning 112 to 141 Hz) for all results, with the exception of wind sound (reported at 400 Hz). Although a broader range of frequencies was modelled, the 125 Hz decidecade band is strongly influenced by underwater radiated noise from a range of vessel types and overlaps with frequencies used by marine animals, primarily mysticetes (baleen whales), in the Arctic to communicate. It also is a reference for chronic noise assessment in European waters (Borsani et al., 2024).

Underwater noise from current and future shipping

Natural wind sound in the Arctic Ocean

Natural sound from wind varies across the Arctic Ocean (Figure 1). In September, when there is the greatest extent of open water and the lowest extent of sea ice, the East Siberian Sea, Central Arctic Ocean and Canadian high Arctic and North Greenland ecosystems/LMEs are exposed to low levels of sound from wind, while the Bering Sea and Norwegian Sea LMEs are exposed to higher levels of wind-produced sound. One of the quietest areas is located north of Greenland and eastern Canada, in the so-called Last Ice Area, where the Arctic Ocean's reserve of multi-year sea ice is found and includes the Tuvaijuittuq Marine Protected Area (MPA). These ambient sound levels were used to calculate and understand the additional contribution of ship noise to the Arctic Ocean in 2019 and 2030.

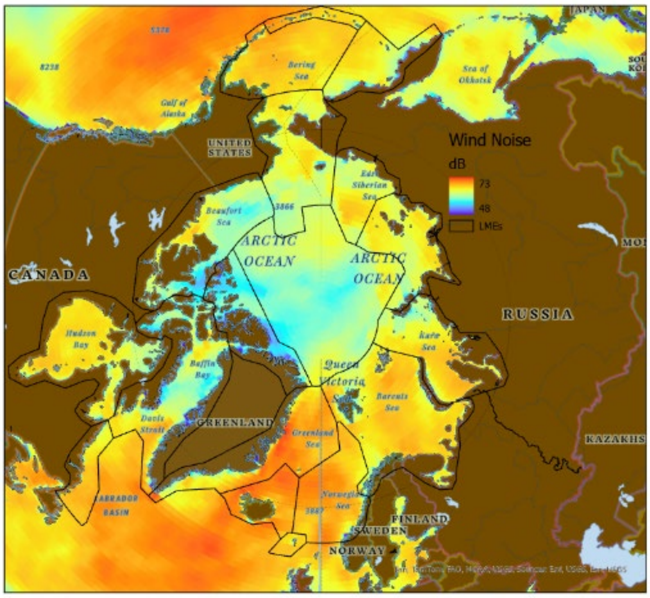


Figure 1: Median sound levels (400 Hz) from wind across the Arctic Ocean in September 2019. Cooler colours represent lower sound levels (<48 - 60 dB) and warmer colours represent higher sound levels (60 - >73 dB). Arctic Large Marine Ecosystem (LME) boundaries are delineated by black lines.

Pan-Arctic

Across the Arctic Ocean, the median difference between 2019 and 2030 underwater noise levels was 5 dB. Since an increase of 3 dB corresponds with a doubling of sound pressure, this denotes, on average, an almost quadrupling of sound pressure in the panarctic acoustic environment by 2030 due to a combination of predicted diminished sea ice and increased vessel traffic. However, this increase is not predicted to be uniform across the Arctic Ocean. Few areas experience a drop in noise, while much of the region would experience an increase, up to or exceeding 10 dB (Figure 2).

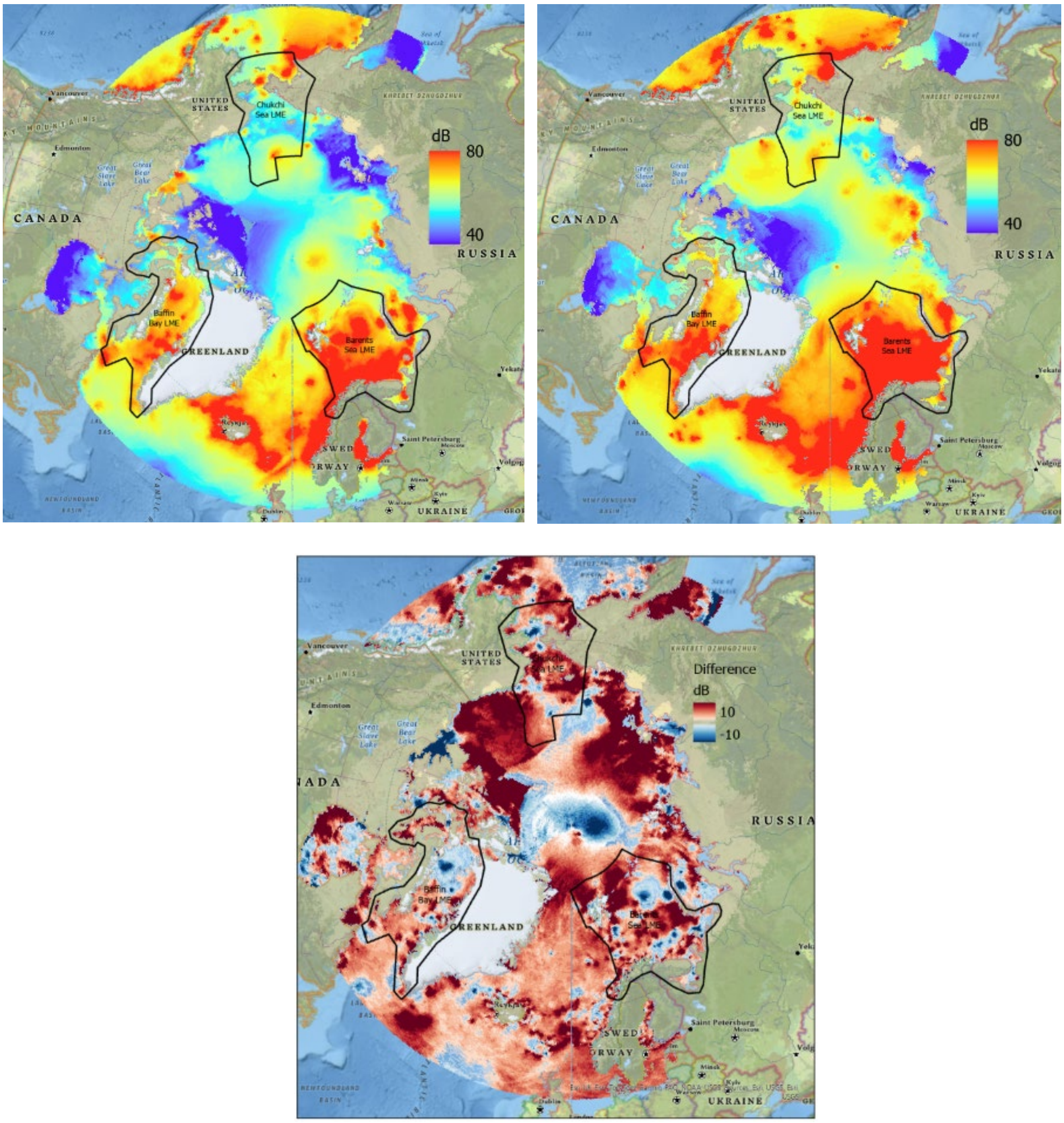


Figure 2: Median ship noise at 25 Hz over the month of September in 2019 (top left) and 2030 (top right). Black borders delineate the three sub-regions of interest in this report. Bright blue is 40 dB or less and bright red is 80 dB or more; in 2019, the maximum noise level is 111 dB; in 2030, it is 123 dB. For the difference in ship noise between 2030 and 2019 (bottom), dark red areas indicate a 10 dB or more increase in 2030 from 2019, and dark blue areas indicate a 10 dB or greater reduction in 2030 from 2019.

Sub-regions of interest

Baffin Bay

Baffin Bay is part of the Canadian Eastern Arctic – West Greenland LME. Baffin Bay is a large, elongated and deep (>2300 m maximum depth) basin that flanks the eastern opening of the Northwest Passage (NWP) and extends southward to the south-western shelf of Greenland and the northern part of the Labrador Sea. Its connections to the North Atlantic Ocean, the Pacific Ocean and the Central Arctic Ocean and influxes of terrestrial ice masses from calving glaciers in West Greenland make it ecologically dynamic and sensitive (PAME, 2006). Baffin Bay is an important sub-region for Arctic marine mammals, seabirds and fish, with 80% of the world's narwhal overwintering there (PAME, 2006). Healthy ocean ecosystems are relied on by Indigenous peoples in Nunavut and Greenland for food, culture and livelihoods. Shipping in the Canadian Eastern Arctic – West Greenland LME, where Baffin Bay is located, is primarily a combination of cargo (for community resupply and mining operations), fishing, and cruise/passenger traffic.

Sea ice and shipping activity

In the September 2019 and 2030 models, the entire Baffin Bay LME is ice-free, so changes in underwater noise are from changes in shipping rather than changes in the dampening/reflecting effects of sea ice.

Shipping datasets 2019 and 2030

In September 2019, 218 unique vessels were present in Baffin Bay; the smallest number for the three sub-regions studied in this report. Vessel traffic in September 2019 in Baffin Bay was dominated by cargo vessels (35%), fishing vessels (28%), and passenger vessels (9%), with cargo vessels largely servicing the Mary River mine and mines along the west coast of Greenland, as well as cargo vessels resupplying coastal communities.

The 2030 shipping scenario (344 unique vessels) included a projected 44% increase in fishing vessel traffic, but a 33% and 20% decrease in cargo and passenger vessel traffic, respectively (Figure 3). The decrease in cargo vessel traffic is due largely to a predicted rerouting by 2030 of ships transporting ore from the Mary River mine. In 2019, all over-sea transport of the ore took place within the Canadian Eastern Arctic – West Greenland LME. However, in the 2030 model, there are plans to consider rerouting all bulk carrier traffic associated with the mine into the neighbouring Hudson Bay complex LME. Ships would spend almost all transit time in the neighbouring LME and exit on the southern border of Baffin Bay, thus reducing the duration, or number of vessel hours, in Baffin Bay by 93% in 2030.

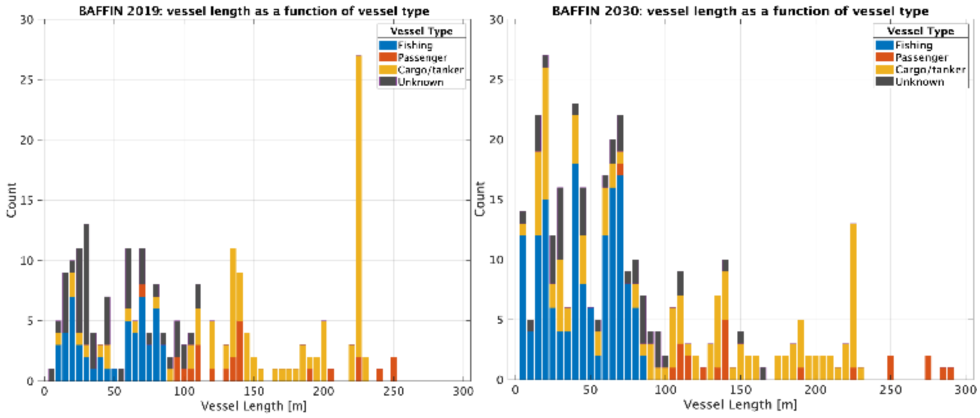


Figure 3: Number and distribution of vessel types in the 2019 (left) and 2030 (right) Arctic ship traffic datasets for the Eastern Canadian Arctic – West Greenland LME, in which Baffin Bay is situated.

Underwater noise maps 2019 and 2030

In Baffin Bay, wind creates sound levels mostly between 65 and 85 dB. For half the time in the month of September, the sound from wind was above 77 dB.

In 2019, most underwater noise from ship traffic was in the northern half of Baffin Bay, while the southern half was relatively free of vessel noise (Figure 4a). One notable area of higher noise intensity was on the Canadian side of the LME, just outside the entrance to Eclipse Sound. This is a mandatory milling (waiting) area for cargo vessels going into the Mary River mine. The other area of higher noise intensity is due to fishing vessels south and west of Disko Bay, off west Greenland (Figure 4a).

In 2030, modelling shows that Baffin Bay will experience increased levels of vessel noise. Underwater noise in the waiting area outside Eclipse Sound is lessened because cargo traffic to and from the Mary River mine has been rerouted (Figure 4b). The central part of Baffin Bay has higher levels of underwater noise due to greater fishing activity, as does the area off west Greenland, due to zinc and iron ore mining in Maarmorilik, as well as increased fishing. The portion of the Canadian Archipelago within the LME is also predicted to have more vessel noise in 2030, despite only a small increase in the number of vessels, as is the southern end of the Baffin Bay LME, due to a combination of fishing vessels moving further into Arctic waters and rerouted ship traffic from Mary River mine re-entering the LME via Hudson Strait (Figure 4c).

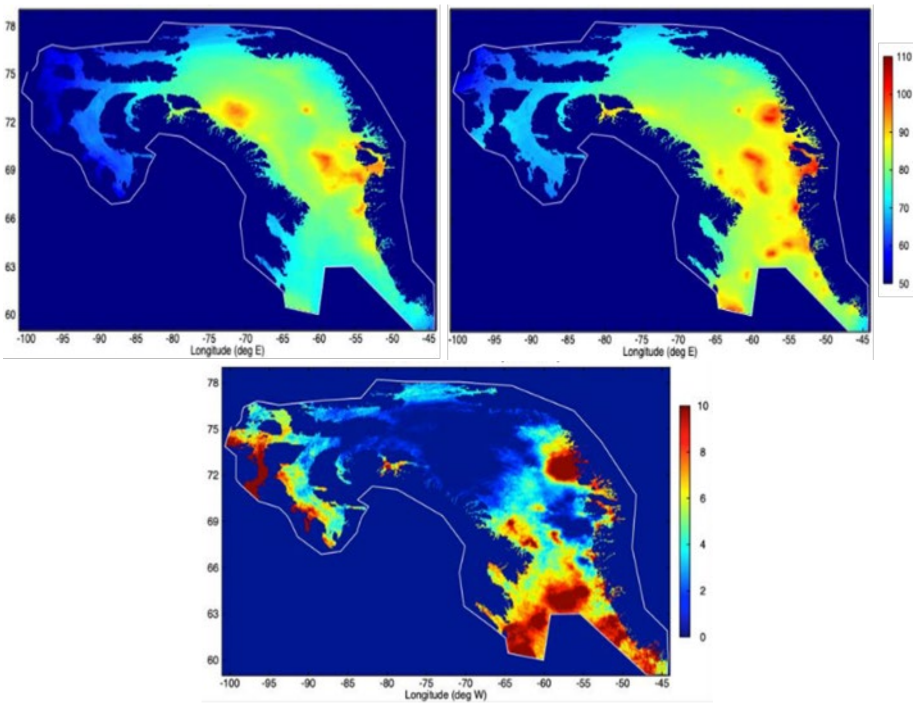


Figure 4: Natural wind sound and ship noise in the Eastern Canadian Arctic – West Greenland LME (including Baffin Bay) in September 2019 (a, top left), September 2030 (b, top right) and the difference between 2019 and 2030 (c, bottom, note the different magnitude of the scale bar). Red is louder and blue is quieter.

Noise from shipping 2019 and 2030

We identified where, by what intensity, and how much of the month of September underwater noise from shipping in Baffin Bay was higher than the natural wind levels in 2019 and 2030. This information is a first step to understanding how noise-sensitive marine life could be affected by ship traffic, as well as options for reducing risk from ship noise through implementation of mitigation measures.

In 2019, ship noise was higher than wind levels across almost half (40 %) of Baffin Bay (Figure 5a). On average, ships contributed an extra 6 dB of noise above wind sound, although in some parts of Baffin Bay, ship noise was up to 30 dB louder than ambient sound levels. In two areas of Baffin Bay, ship noise levels were consistently higher than ambient levels every day throughout September (Figure 5c). This was due to Mary River mine traffic milling outside Eclipse Sound, ships servicing the zinc and iron ore mine in Maarmorilik and fishing off Disko Bay in west Greenland.

In 2030, ship noise levels were higher than natural levels across more of LME (60%) and for more of the time, with ship noise constantly above wind levels throughout most of Baffin Bay in September (Figure 5b, d). On average, ships contributed an extra 8 dB of noise above natural sound levels, although similar to 2019, this was highly variable.

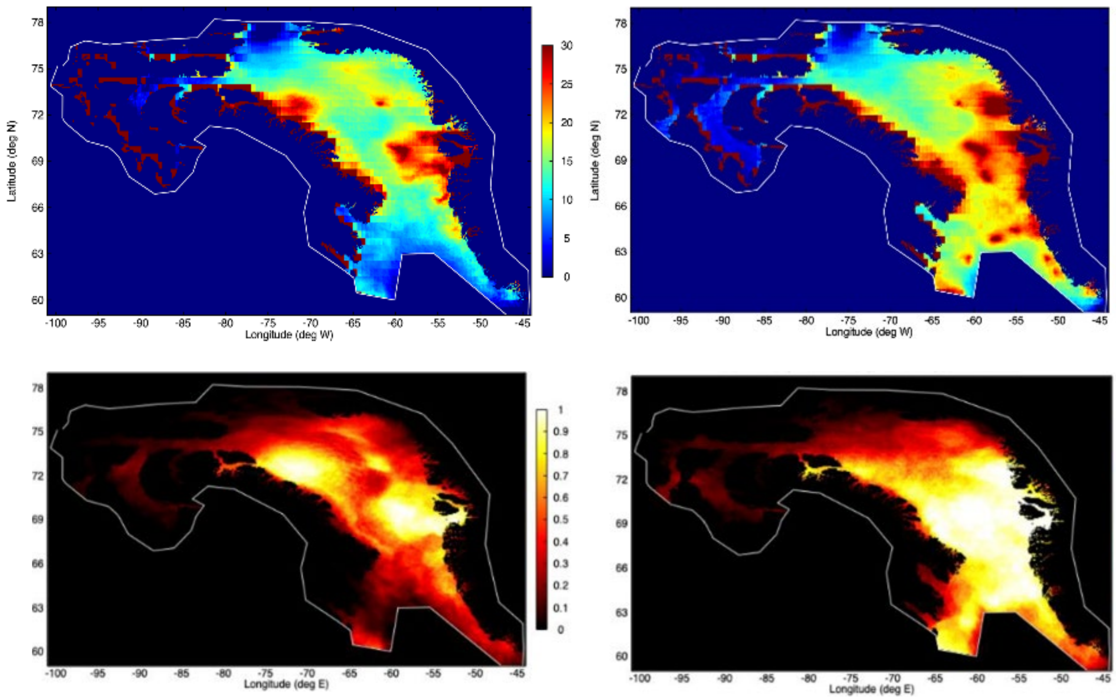


Figure 5: The intensity of ship noise above ambient levels in the Eastern Canadian Arctic – West Greenland LME (including Baffin Bay) in September 2019 (a, top left) and 2030 (b, top right) and the proportion of time ship noise was louder than ambient levels in September 2019 (c, bottom left) and 2030 (d, bottom right, scale 0 – 1, where white is proportionally more time and black is less time).

Barents Sea

The Barents Sea LME is a large, high latitude shelf area to the north of Norway and Russia. It has mean and maximum depths around 230 m and 500 m respectively, and has complex bottom topography (PAME, 2006). The Svalbard and Franz Josef Land archipelagos are located in the northwestern and northeastern corners of the Barents Sea. The Barents Sea is an important sub-region for marine mammals, with about 25 species recorded, including those migrating seasonally from lower latitudes (PAME, 2006). The majority of Arctic shipping is concentrated in the Barents Sea and neighbouring Norwegian Seas (Eguíluz et al. 2016). Fishing is a significant economic sector, with around 10 commercially exploited fish species and some of the world's largest fish stocks (PAME, 2006, ICES, 2020). There are currently 12 nations with fisheries targeting the stocks in this ecoregion (ICES, 2020).

Sea ice and shipping

In September 2019 the Barents Sea was ice-free and sea ice models predicted that it will remain ice-free in September 2030.Therefore, changes in underwater noise are from changes in shipping rather than changes in the dampening/reflecting of sea ice.

Shipping datasets 2019 and 2030

The Barents Sea is a heavily trafficked sub-region of the Arctic. In 2019, there were 1829 unique vessels observed, consisting of fishing vessels (32%), transport vessels (30%), and passenger vessels (7%). Remaining vessel classes (31%) were of “other” or unknown classification, with most 50 m or less in length. Most vessel traffic was along the coastline of Norway and Russia, but there was also substantial traffic to and from Svalbard, dominated by fishing vessels.

The 2030 shipping scenario for the Barents Sea estimates 3431 unique vessels in the LME in the month of September, driven by a substantial increase in the three vessel classes that were dominant in 2019 and a larger number of smaller sized ships in the 2030 dataset (Figure 6). A projected 140% increase in fishing vessel hours was attributed to the Norwegian snow crab fishery, which is developing due to the westward movement of snow crabs in the Barents Sea (ICES, 2020). There was an increase in small- to medium-sized tourist vessel traffic and a decrease in ocean liners around Svalbard to reflect recent regulatory changes to the number of passengers permitted in Svalbard’s protected areas. Finally, growth in transport vessels (container ships, bulk carriers and tankers) followed economic projections for raw materials and goods expected to be shipped along routes in the Barents Sea (see Appendix B for details).

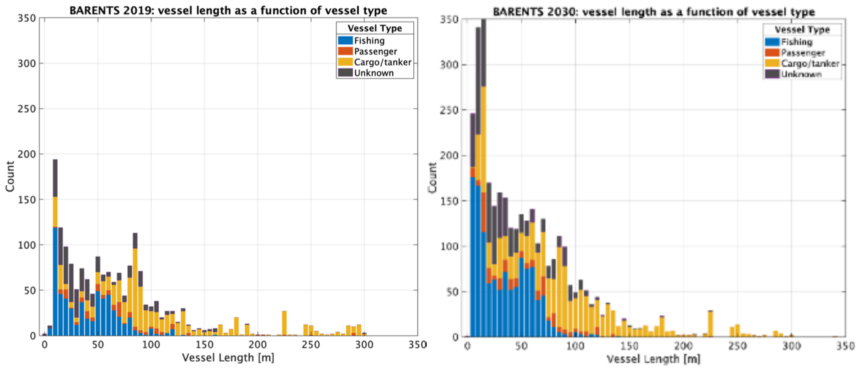


Figure 6: Number and distribution of vessel types in the 2019 (left) and 2030 (right) Arctic ship traffic datasets for the Barents Sea LME.

Underwater noise maps 2019 and 2030

The Barents Sea has more wind than Baffin Bay and the Chukchi Sea, which results in naturally louder ambient sound levels. Sound levels from wind are mostly between 75 and 83 dB, and above 80 dB for half the time in the month of September.

In 2019, most areas in the Barents Sea were exposed to noise from vessels and many areas exceeded sound levels of 100 dB (Figure 7a). Exceptions were the northeastern part of the Barents Sea around Franz Josef Land and the northeastern coast of Svalbard. Underwater noise from cargo and fishing vessels was concentrated both along the Norwegian and Russian coastlines and in the central Barents Sea.

In 2030, expansion in multiple industry sectors is projected to result in more shipping and a louder Barents Sea (Figure 7b). While much of the noise is concentrated in the same areas as in 2019, a substantial increase is projected in noise levels around the Svalbard archipelago, driven by a combination of the ice edge receding and northward growth in fishing and cargo vessel traffic circumnavigating Svalbard. This increase in traffic also results in an expansion of underwater noise into the central Arctic Ocean and towards the North Pole (Figure 7c).

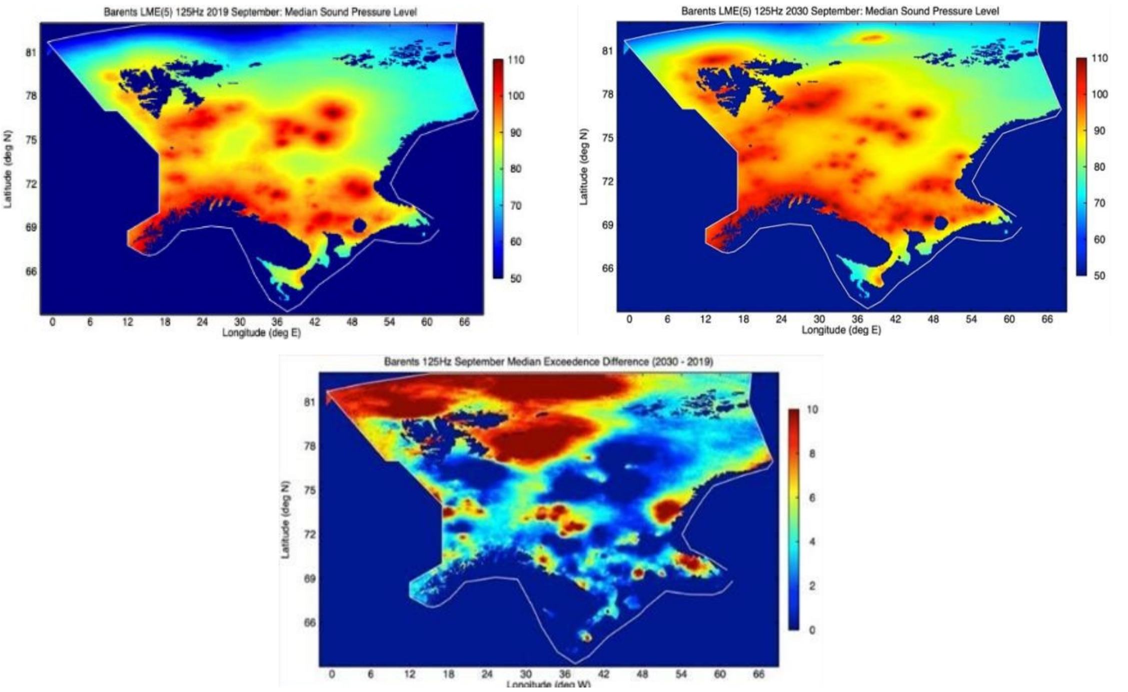
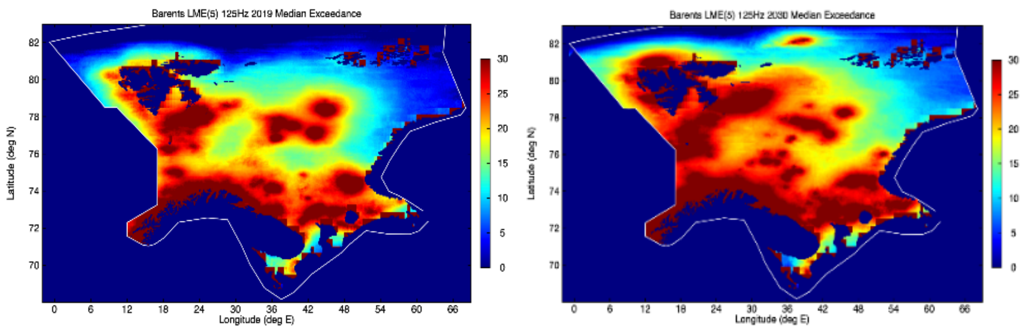


Figure 7: Natural wind sound and ship noise in the Barents Sea LME in September 2019 (a, top left), September 2030 (b, top right) and the difference between 2019 and 2030 (c, bottom, note different magnitude of the scale bar).

Noise from shipping 2019 and 2030

In 2019, ship noise was louder than sound from wind across half of the Barents Sea LME (Figure 8a). While this seems low given the amount of ship traffic, the Barents Sea is naturally windy, which means that more ship noise is needed relative to other locations to exceed this source of natural ambient sound. On average, ships contributed an extra 16 dB of noise on top of natural sound levels; much more than in Baffin Bay (6 dB). Across almost the entire Barents Sea LME, ship noise was higher than wind levels for all days in September (Figure 8c). Only in small areas, including northeast Svalbard, Franz Josef Land and part of the White Sea, ship noise did not exceed wind levels for at least half the month.

In modelling results for 2030, ship noise was above wind levels across almost three-quarters (70%) of the Barents Sea (Figure 8b). On average, shipping is predicted to contribute an extra 20 dB of noise to the natural soundscape. Zooming into the northern part of the Barents Sea, more ship noise would cause that area to become louder more consistently, up to every day of September, compared with only around half the month in 2019. This is particularly noticeable west and north of Svalbard (Figure 8d).



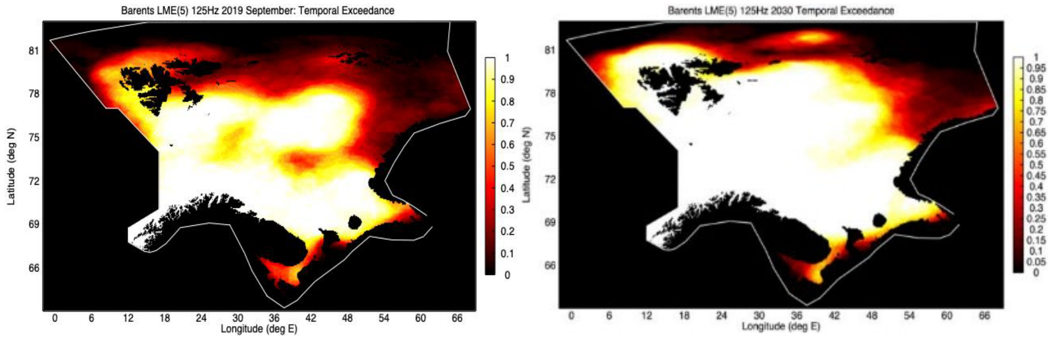


Figure 8: The intensity of ship noise above wind levels in the Barents Sea LME in September 2019 (a, top left) and 2030 (b, top right), and the proportion of time ship noise was louder than wind levels in September 2019 (c, bottom left) and 2030 (d, bottom right, scale 0 – 1, where white is proportionally more time and black is proportionally less time).

Chukchi Sea

The Chukchi Sea lies within the Northern Bering-Chukchi Sea LME. It is a shallow Arctic shelf sea, half of which is less than 50 m in depth. It has soft sediment seafloor, which may contribute to dampening underwater sound in the sub-region. The Chukchi Sea borders the East Siberian Sea on the west and the Beaufort Sea on the east (PAME, 2006). It also extends south through the Bering Strait and to the top of the Bering Sea, from where it receives bountiful food sources and water currents that support tens of thousands of marine mammals (PAME, 2006). Further into the future, this sub-region is likely to attract more vessel traffic as fish stocks move northwards, and the Northern Sea Route and other trans-polar routes become increasingly navigable, being the only connection point between the Pacific and Arctic Oceans.

Sea ice and shipping activity

In summer 2019, the entire Chukchi Sea was ice-free, so changes in the 2030 underwater soundscape are due to a greater amount of modelled shipping, rather than less sea ice to dampen noise.

Shipping datasets 2019 and 2030

In September 2019, 414 unique vessels were present in the Chukchi Sea. Shipping activity was generally limited to vessels servicing the North Slope of Alaska and western Canada as well as those making their way along the Russian coastline towards the Kara Sea. Projections for shipping in 2030 (681 unique vessels in September) show an increase in commercial transits, exploratory oil and gas surveying, and fishing off the eastern coast of Russia. More vessel traffic was projected on routes coming north from the Kamchatka Peninsula, where the Uelkal port is located.

Underwater noise maps 2019 and 2030

In the Northern Bering-Chukchi Sea LME, wind generates sound levels mostly between 50 and 85 dB, and above 76 dB for half the time in September.

In 2019, the contributions of wind and ships to the underwater soundscape was highest through the Bering Strait and north and south of the Strait along the Russian coastline. The eastern side of the Chukchi Sea was undisturbed by ship noise, likely due to low sound propagation in the Chukchi Sea's shallow waters (Figure 9a). Across the eastern side, wind and ship contributions were at or below 55 dB for half of September.

In 2030, the soundscape was projected to be 15 dB louder (median of 70 dB for September), although still quieter overall than Baffin Bay and the Barents Sea. Higher numbers of ships resulted in an increase by 10 dB or more across most of the LME, including the spreading of noise poleward from along the Russian coastline associated with more liquified natural gas (LNG) tanker traffic on the Northern Sea Route, and an increase in vessel noise in coastal waters on the US side of the Chukchi Sea (Figure 9b). Some areas that were very quiet (less than 60 dB) in 2019 increased by 40 dB or even more in 2030, underscoring the particular vulnerability of the Arctic's quieter areas to the addition of noise sources (Figure 9c).

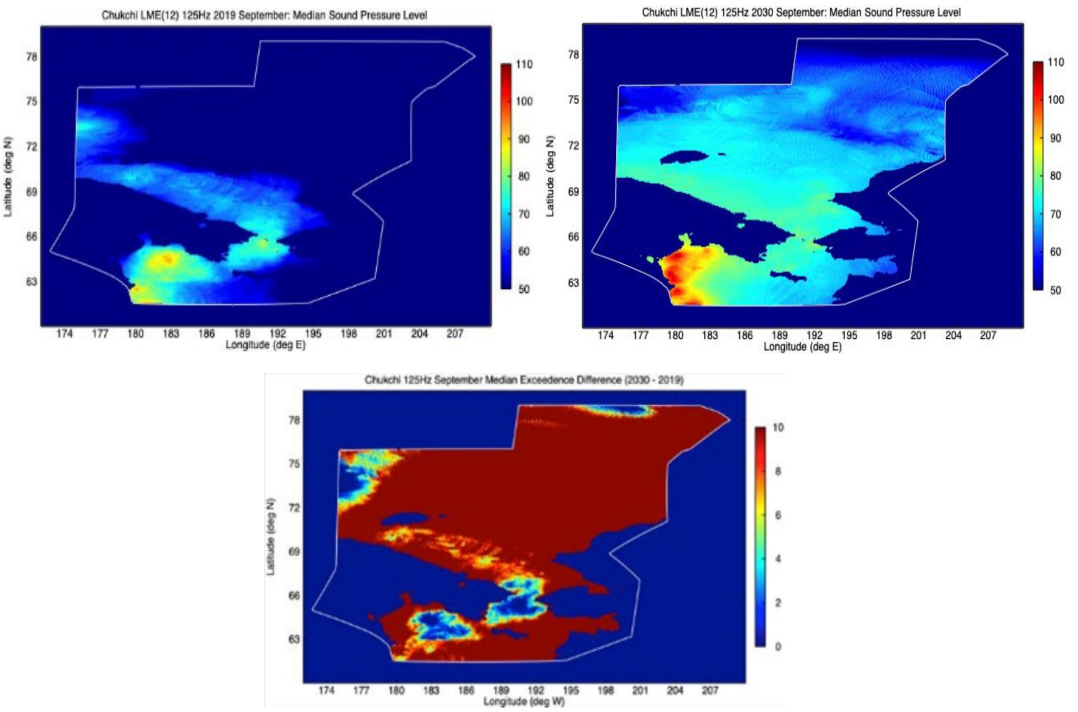


Figure 9: Natural wind sound and ship noise in the Northern Bering-Chukchi Sea LME in September 2019 (a, top left), September 2030 (b, top right) and the difference between 2019 and 2030 (c, bottom, note different magnitude of the scale bar).

Noise from shipping 2019 and 2030

Ship noise exceeded wind levels across 15% of the Chukchi Sea in 2019, leaving most of the sub-region influenced by natural sound rather than shipping-driven noise (Figure 10a). There were several areas where ship noise was louder than wind levels for one quarter of the month of September: the northern Bering Sea, the Bering Strait, the Russian coast and the US coast (Figure 10a).

In modelling results for 2030, ship noise was louder than wind levels across more of the Bering-Chukchi, or around two thirds (65%) of the LME (Figure 10c). Across most of this area, ship noise was higher than wind levels for a quarter to half the month, with the exception of the Russian coastline south of the Bering Strait, where ship noise due to small (less than 100 m) fishing vessels at relatively slow speeds was higher than wind levels every day across the whole month (Figure 10d). Although shipping is still projected to be sparse in the Chukchi Sea in 2030, the model predicts observable changes to the soundscape from projected growth in traffic.

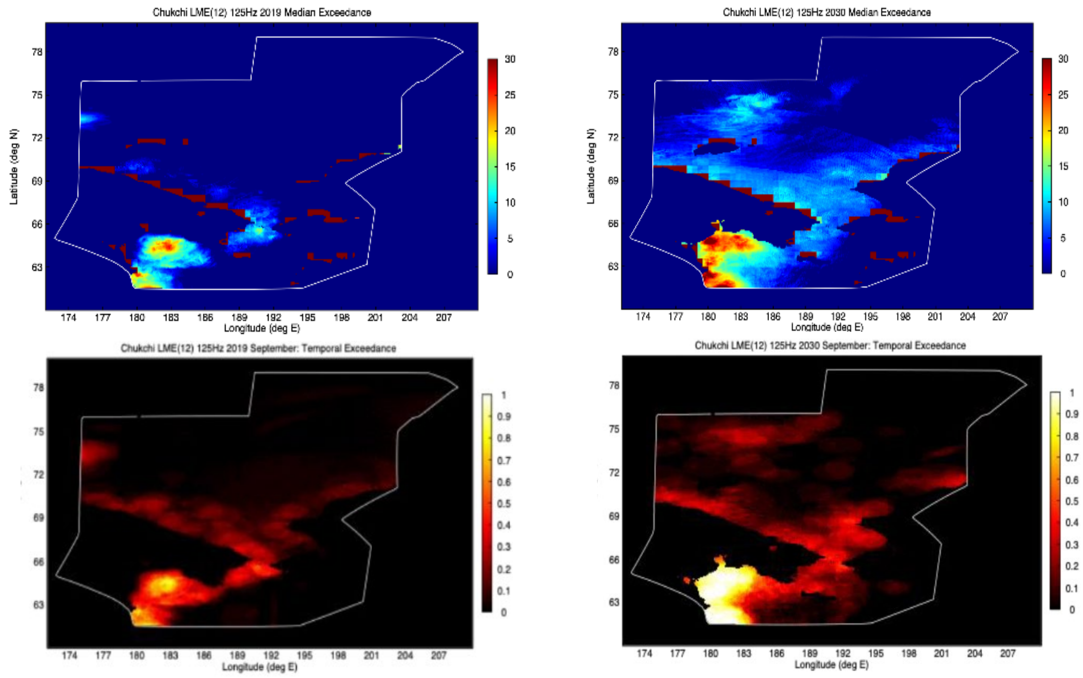


Figure 10: The intensity of ship noise above wind levels in the Northern Bering-Chukchi Sea LME in September 2019 (a, top left) and 2030 (b, top right), and the proportion of time ship noise was louder than wind levels in September 2019 (c, bottom left) and 2030 (d, bottom right, scale 0 – 1, where white is proportionally more time and black is proportionally less time).

Implications of vessel management strategies on underwater noise

Baffin Bay

There are several vessel management strategies proposed or in place in the Canadian Eastern Arctic–West Greenland LME. They have been proposed and/or implemented to address concerns, including from Arctic Indigenous communities, about the impacts of ship traffic on the LME's sensitive species. We chose three of these strategies to see how implementation of different measures would affect or are affecting the underwater soundscape of Baffin Bay. We selected which vessel management strategies to model through informal discussions with Fisheries and Oceans Canada, Transport Canada, Environment and Climate Change Canada, the Canadian Ice Service, and Scripps Institution of Oceanography.

Vessel management strategies

We applied three vessel management strategies in the Canadian Eastern Arctic – West Greenland LME, where Baffin Bay is located (Figure 11).

1. Speed reduction to or below 9 knots for all vessel traffic travelling along the shipping route from Milne Port to Baffin Bay.
2. Spatial restriction of all cruise ships to avoid Eclipse Sound.
3. Re-routing of all ships to implement an Area To Be Avoided (ATBA) surrounding the Wollaston Islands.

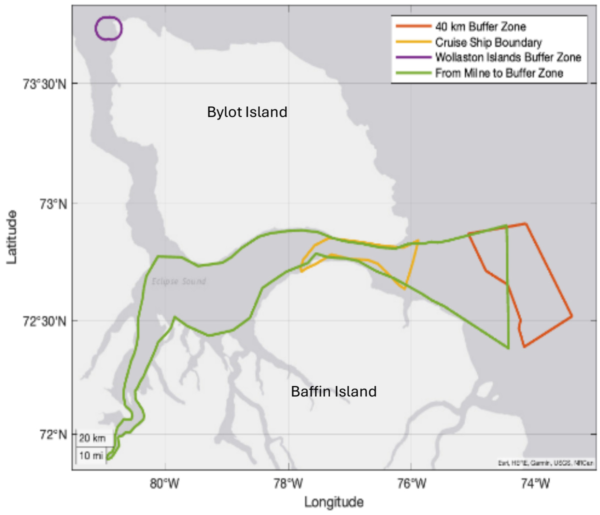


Figure 11: Three areas (purple, green and yellow bounded) where vessel management strategies were implemented in the Canadian Eastern Arctic – West Greenland LME, where Baffin Bay is located. Red boundary area delineates where Mary River mine cargo vessels waited before entering Eclipse Sound.

Speed reduction to or below 9 knots along the shipping route between Milne Port and Baffin Bay is a requirement that has been in place since 2019 for ships servicing the Mary River mine (Nunavut Impact Review Board Project Certificate No. 005). Here we modelled extending the measure to all traffic both for current traffic in 2019 and future traffic in 2030 supporting assessment of the role this could play in reducing disturbance to marine mammals, in particular narwhal, for which Milne Inlet and surrounding bays are important habitats in summer months.

The spatial restriction for cruise vessels to avoid entering Eclipse Sound has been in place since 2023 as a voluntary measure taken up by the Association of Arctic Expedition Cruise Operators (AECO) to reduce disturbance to narwhals and their habitat. It is observed by AECO members, which represent the majority of expedition operators in the Arctic.

Finally, the area to be avoided surrounding the Wollaston Islands has been proposed to protect walruses and their habitat from disturbance, but is still subject to community consultations and approvals, as of 2023. That area has been awarded Zone 1 protection in the Tallurutiup Imanga National Marine Conservation Area (NCMA) and once approved, would prevent shipping within a 5 km buffer zone surrounding the island.

Vessels affected by the management strategies

In our existing 2019 dataset, most traffic along the shipping route between Milne Port to Baffin Bay was travelling at or below 9 knots (43 ships, Figure 12). This was not surprising as the majority of vessels are associated with the Mary River mine and were subject to a 9-knot maximum speed restriction. Of the 43 ships on the route, 13 bulk carriers, four passenger/cruise ships, and two pleasure craft exceeded 9 knots and thus were adjusted in our model to be slower. In 2030, despite much of the Mary River mine traffic having been rerouted out, 53 vessels were present in the Milne Port/Baffin Bay shipping route, and 35 of these were subject to the modelled reduction in speed.

Keeping cruise ships out of Eclipse Sound required rerouting four vessels in 2019 and two vessels in 2030. Ship traffic within the 5 km buffer around the Wollaston Islands was similarly sparse in both years, with two ships and seven ships rerouted out of the buffer zone in September 2019 and 2030, respectively (Figure 13).

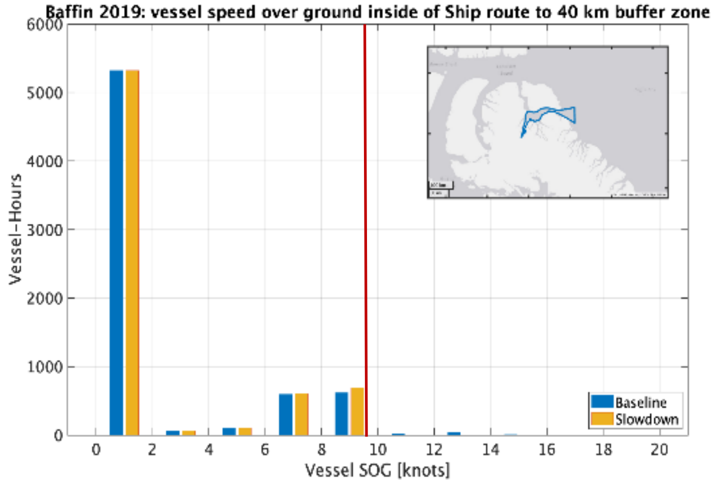


Figure 12: Speed of bulk carrier ships (in vessel hours) travelling through designated speed reduction area between Baffin Bay and Milne Port in the Canadian Eastern Arctic – West Greenland LME, in September 2019. The red line denotes speeds at or below 9 knots.

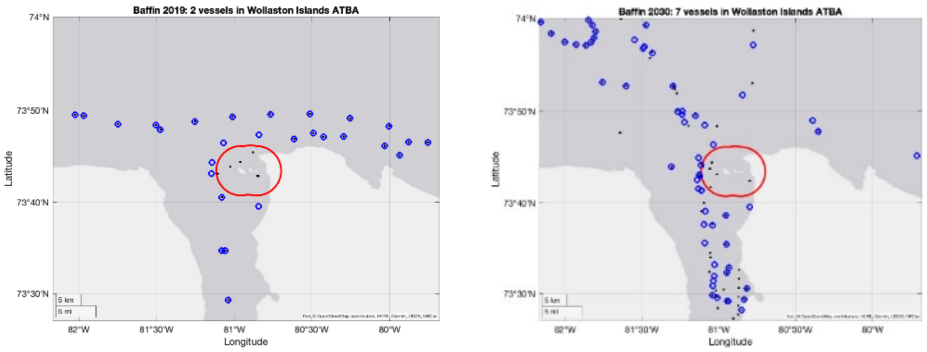


Figure 13: Vessel locations (blue, black circles) relative to the 5 km buffer zone (red) around the Wollaston Islands in the Canadian Eastern Arctic – West Greenland LME in 2019 (a, left) and 2030 (b, right). Vessels rerouted are black circles.

Effects of vessel management strategies on underwater noise

In 2019, reducing the speed of Mary River mine bulk carriers transiting between Baffin Bay and Milne Port resulted in no more than a 0.5 dB decrease in underwater noise along the route. In 2030, slowing down vessels resulted in little to no change in noise levels. Irrespective of the slowdowns, the level of underwater noise along this transit route in 2030 was significantly lower (by 10 dB) than in 2019, despite more vessels being present (53 compared with 43 in 2019). This was due to the removal of 20 ore carriers servicing the Mary River mine for re-routing through Steensby Inlet.

Restricting cruise ship traffic to be within the designated area (Figure 11) produced little to no change in overall noise levels because of the small number of cruise vessels in the area over the month (4 in 2019, 2 in 2030) and the presence of other ships without modified behaviour. However, the restriction changed the transit patterns of the cruise ships so that they entered and exited from the same side, instead of passing through the designated area and via the interior waterway of Bylot Island. This nearly doubled the number of vessel hours in that area.

Finally, excluding vessels from within the 5 km buffer around the Wollaston Islands had no discernible effect on underwater noise levels within the buffer, due to continued incursion of underwater noise from the surrounding area.

Barents Sea

Vessel management strategies

Given the high levels of underwater noise from shipping in the Barents Sea LME both in 2019 and 2030, the implications of vessel management strategies on noise were explored through spatial measures (with a focus on important areas for noise-sensitive species) and by exploring additional noise reduction at the source for the growing fishing fleet. The measures we developed are hypothetical and not currently or planned to be in place.

To develop vessel management strategies to be modelled, we consulted informally with the Norwegian Coastal Administration and researchers in the sub-region with acoustics and underwater noise expertise, including from the Norwegian Defence Research Establishment (Forsvarets forskningsintitutt).

Two strategies were applied:

1. Speed reduction to 10 knots for all vessels in important habitats for marine mammals (selected to represent a noise-sensitive group).
2. Reduction in noise levels at the ship's source by 6 dB for 25% of the fishing vessel fleet, where 6 dB is within the 5 to 10 dB noise reduction range achievable from various retrofitting options (Vard, 2023).

Speed reduction

Reducing ship speed is recognised as an effective operational measure for reducing underwater noise (Findlay et al. 2023; IMO, 2023). We selected a speed limit of 10 knots because it represents a speed below which propeller cavitation – the main source of underwater noise – occurs for many ships (Leaper and Renilson, 2013), and at which the risk of fatal collisions between ships and large whales is significantly reduced (Vanderlaan and Taggart, 2007). For these reasons, it is a speed limit required or recommended in several important marine mammal habitats around the world (World Shipping Council, 2024).

The spatial boundaries for modelled speed reductions were derived from Hamilton et al. (2021) and represent important summer/autumn areas for Arctic marine mammals identified as Focal Ecosystem Components (FECs) by the Conservation of Arctic Fauna and Flora working group of the Arctic Council (CAFF, 2016). The areas include important habitats for bowhead whales, narwhals, beluga whales, walruses, ringed seals, bearded seals and hooded seals, as well as for species present in the Arctic in summer: blue, fin and humpback whales, harbour seals and harp seals.

Reduction in underwater radiated noise source levels

Source level reduction was applied randomly to 25% of fishing vessels in 2019 and 2030, without regard to ship characteristics (e.g., operational speed, vessel size). This assumes that such a reduction could be achieved in those 25% of vessels, independent of their other characteristics. This is a simplified assumption meant to summarise the potential application of wide-ranging technical modifications to reduce fuel consumption, greenhouse gas emissions and/or underwater noise from ships (Vard, 2023). Noise reduction through new build or retrofit-based modifications to fishing vessels was modelled rather than speed reduction or rerouting, recognising operational requirements for vessels that are actively fishing. Further, many fishing vessels have controllable pitch propellers, which are not necessarily quieter at slower speeds/power.

Vessels affected by the management strategies

There was overlap between vessels and important areas for marine mammals in 2019 and 2030 (Figure 14). Of these, approximately 16.9% of cruise/passenger vessel hours, 18% of cargo traffic vessel hours and 11.7% of fishing vessel hours (4539, 3249, and 29875 vessel hours respectively) were at speeds greater than 10 knots (e.g. Figure 15) and thus were affected by invoking a 10-knot speed limit in the management scenario.

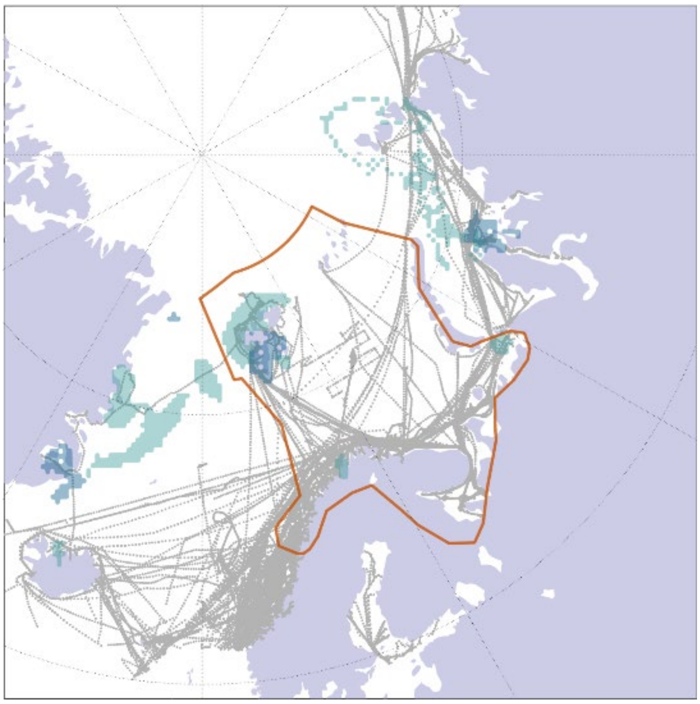


Figure 14: Cargo ship traffic (grey lines) in important areas for marine mammals (blue, blue/green shaded areas, based on 70%+ hotspots in summer/autumn) in September 2030 (2019 not shown) in the Barents Sea LME (orange).

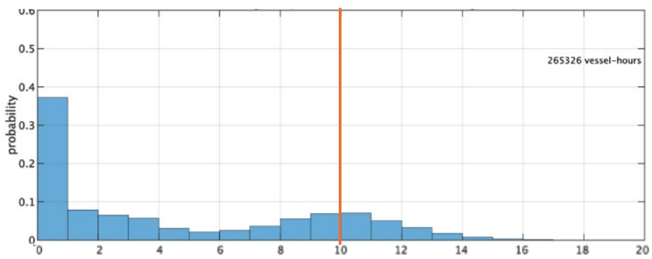


Figure 15: Ship speed distribution in 2030 for cargo vessels within important areas for marine mammals in the Barents Sea LME, with threshold speed of 10 knots as red line. Vessels to the right of the red line had the speed reduction measure applied.

Effects of vessel management strategies on underwater noise

Noise intensity in important areas for marine mammals was lower than that of the whole Barents Sea (Table 1). Reducing the speed of all vessels within these marine mammal areas to 10 knots achieved median underwater noise reduction in those areas of less than 0.1 dB in both 2019 and 2030 relative to modelled baselines. This small change is two-fold. One, the source level reduction due to the slowdowns has a relatively small effect on the total source level distribution in the area. Secondly, and more importantly, these marine mammal areas are quite small, so nearby ships exhibit unmodified behaviour, and their vessel noise permeates into the slowdown areas.

Similarly, source level noise reductions in a proportion of the fishing fleet resulted only in very modest noise reductions of 0.5 – 0.8 dB in 2019 and 0.2 – 0.5 dB in 2030. Because fishing activity is spread across much of the Barents Sea LME, the scale at which underwater noise was compared before and after the measure was the entire LME. For this reason, the influence of reducing source levels in only a quarter of this fleet, when evaluated at the scale of the LME, rather than in a more localised area of concentration, was not strong.

Table 1: Ship noise levels (displayed as percentile quantities of sound in dB) in the Barents Sea areas important for marine mammals (MMA) and after vessel slowdowns to 10 knots (M1); and in the LME (LME) and after noise reduction at the source for 25% of the fishing fleet (M2).

Percentile	**2019**				**2030**			
	MMA	**M1**	**LME**	**M2**	**MMA**	**M1**	**LME**	**M2**
5th	53.7	53.6	63.7	63.1	62.3	62.6	67.5	67.3
25th	67.0	67.2	78.6	78.1	72.3	72.6	84.9	84.6
50th	75.8	75.8	85.8	85.2	85.0	85.2	91.3	90.8
75th	84.7	84.8	94.4	93.6	92.5	92.6	97.5	97.0
95th	99.4	99.6	104.8	104.0	104.2	104.3	106.5	106.1

Chukchi Sea

Given the LME's importance for fish, seabirds and marine mammals, several vessel management strategies have been evaluated and/or proposed to increase navigation safety and to protect specific areas of biological importance in this ecosystem. We used these as a basis for exploring effects on the underwater soundscape. During development of vessel management strategies, we consulted documentation from the US Coast Guard, the US Maritime Administration, US Marine Mammal Commission, comments on the US Coast Guard Port Access Route Study process from the Alaska Eskimo Whaling Commission and had informal discussions with subject matter experts and members of academia.

Vessel management strategies

We applied four vessel management strategies (Figure 16):

1. Rerouting ships travelling along the coast of Alaska from east of Red Dog Mine to Kaktovik into an offshore corridor with slope-transiting port destination routes.
2. Adding a speed limit of 10 knots for rerouted ships under #1, in the “E-shaped” area just north of the Bering Strait encompassing corridors to Point Lay, Point Hope, and Kivalina
3. Rerouting ships around Areas to Be Avoided (ATBAs): King Island, Nunivak Island, and St. Lawrence Island.
4. Routing ships around a walrus haul-out zone on Little Diomede Island.

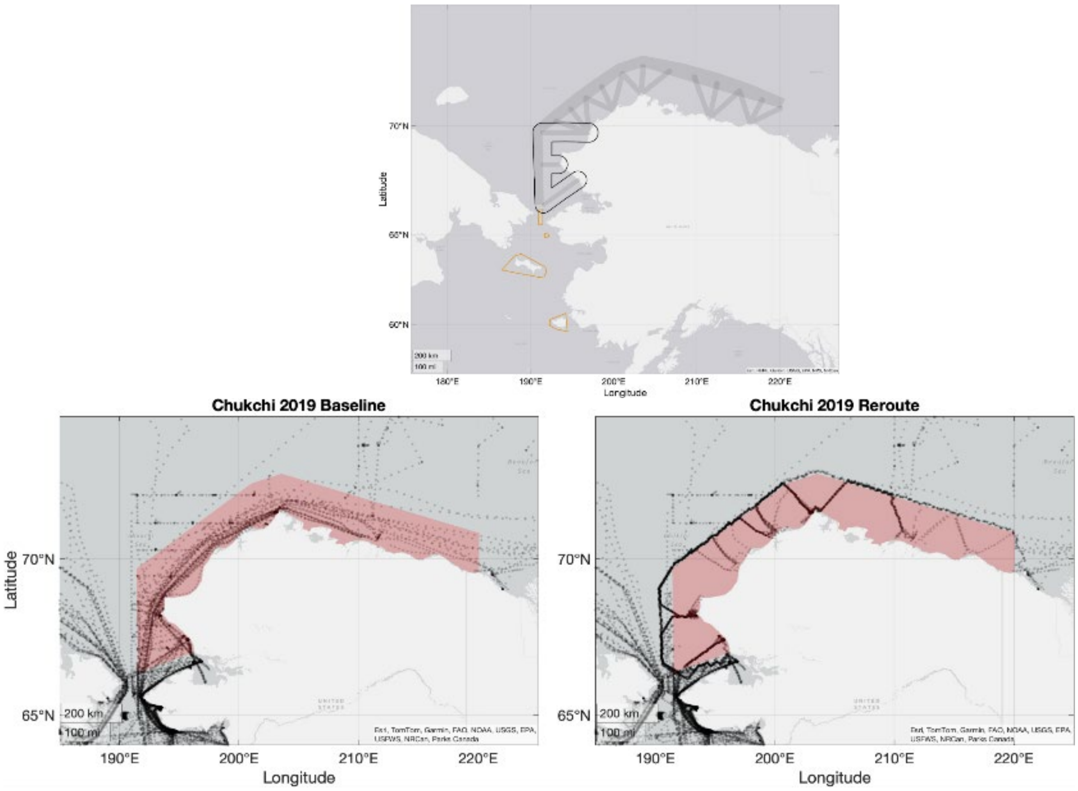


Figure 16: (top) Locations in the Northern Bering-Chukchi Sea LME where vessel management strategies were simulated and underwater noise statistics calculated. The grey highlighted region shows the modelled routing for ships travelling along the coast of Alaska. Orange areas show the ATBAs, including the walrus haul-out zone on Little Diomede Island. The black "E" represents the area additionally assessed as a slowdown area of 10 knots. (bottom) Distribution of traffic changes modelled for 2019 with red area indicating mitigation zone used to evaluate change in noise.

Vessels affected by the management strategies

Routing ships into an offshore corridor and slope-transiting destination/resupply corridors

In 2019, 48 vessels (4390 vessel hours) on the North Slope, were rerouted into an offshore corridor and destination/community resupply slope-crossing corridors. In 2030, 80 vessels (7613 vessel hours), were rerouted (see red polygon area in Figure 16). The proportional breakdown of the types of vessels affected by the rerouting was almost identical in both years and was approximately 30% fishing vessels, 25% cargo vessels, 8% tankers, and 6% passenger vessels.

Additional speed limit of 10 knots in a portion of the new offshore Alaskan routing

In the 2019 re-routed condition, 53 unique vessels transited through the modelled corridors just north of the Bering Strait, for a total of 2225 vessel-hours. Vessels were approximately 40% fishing and towing, 7% passenger, 24% cargo, and 12.5% tankers, and 84% of their speeds were below 10 knots. Similarly, in the 2030 baseline conditions, 85 unique vessels transited through these new routes, for a total of 4387 vessel-hours, comprised of approximately 30% cargo, 26% fishing and towing, 8% tanker, and 1% passenger, and 90% of their speeds were below 10 knots.

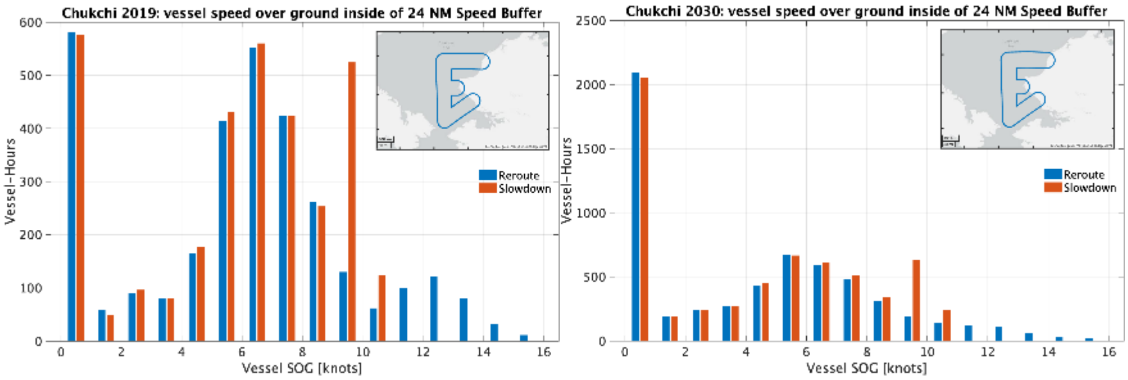


Figure 17: Ship speed distribution in 2019 (left) and 2030 (right) showing number of vessel hours affected by modelled 10 knots or less threshold (note difference in vessel hour scales).

<u>Rerouting ships out of Areas To Be Avoided (ATBAs)</u>
Relatively few vessels were within the ATBA boundaries in 2019 and 2030. For the King Island ATBA, five vessels (nine vessel hours, primarily fishing vessels) in 2019 and 11 vessels (12 vessel hours, cargo and passenger vessels) in 2030 were affected. For the Nunivak Island ATBA, 11 vessels (206 vessel hours, primarily fishing, two cargo and one passenger vessel) in 2019 and 43 vessels (1354 vessel hours, fishing and cargo vessels) in 2030 were rerouted. Finally, rerouting around the St. Lawrence Island ATBA affected 11 vessels (230 vessel hours) in 2019 and 18 vessels (460 vessel hours) in 2030. In both years, these were mostly cargo vessels and tankers.

<u>Rerouting ships around a walrus haul-out zone on Little Diomede Island</u>
In 2019, eight vessels (80 vessel hours), which were a mix of passenger and cargo and fishing vessels were affected. In 2030, 21 vessels (58 vessel hours) were affected on their transit through the Bering Strait.

Effects of vessel management strategies on underwater noise
The objectives for the routing measures evaluated here are avoidance of designated areas of environmental sensitivity and waters with safety or navigability hazards. Thus, the performance of each vessel management measure relative to noise is evaluated by comparing each target area prior to and after a routing or speed adjustment.

Routing ships into an offshore corridor and slope-transiting resupply corridors
For the corridor appraisal, we assessed the difference in noise results over the shallow coastal areas of the North Slope between baseline and when vessels were concentrated into bands of traffic to transit the slope, entering and existing a new offshore corridor. The new offshore corridor was not included in this comparison as it was acknowledged that the objectives of the proposed measure resulted in proposals to concentrate community resupply traffic within slope waters into bands, and to shift transiting vessels away from shallower waters and into deeper waters.

Most of the time (5th through 50th percentiles Table 2), sound from the new offshore corridor (now placed in deeper water with better propagation conditions for noise) permeates onto the slope, and, in aggregate over the entirety of the slope, noise levels were equal to or higher than when traffic was more coastally distributed. However, the variability in noise conditions on the slope also became markedly greater, and 5-25% of the time, it was quieter across the slope (3-4 dB reduction), representing significant reductions in noise that did occur, likely in areas farthest away from the corridors.

Table 2: Ship noise levels (displayed as percentile quantities of sound in dB) in the Chukchi Sea reroute area (red zone in Figure 16) under baseline and reroute conditions in both 2019 and 2030.

	2019		2030	
	Baseline	Reroute	Baseline	Reroute
5th	8.6	13.2	11.1	11.7
25th	28.2	32.5	31.9	33.3
50th	44.2	45.2	46.9	47.7
75th	58.5	57.0	61.6	60.6
90th	77.5	73.4	82.6	79.9

Additional speed limit of 10 knots for ships north of the Bering Strait
Adding a slowdown area to Point Lay, Point Hope, and Kivalina to the rerouted ships north of the Bering Strait affected only 10-16% of vessel speeds in both the new offshore corridor and the port routes. Assessment of the distribution of these speeds (Figure 17) also shows relatively low speed variance above 10 knots. These are likely drivers for the finding that imposing this 10-knot threshold had a relatively minimal influence on noise reduction in that portion of the corridor (Table 3). However, the overall trend towards decreasing noise levels is more pronounced in the 2030 prediction (2 dB noise reduction), with a larger number of vessel-hours slowed down compared to that in 2019.

Table 3: Ship noise levels (displayed as percentile quantities of sound in dB) in the Chukchi Sea speed reduction area ("E" shaped zone in Figure 16) under baseline and reroute conditions in both 2019 and 2030.

	2019		2030	
	Reroute	Slowdown	Reroute	Slowdown
5th	15.5	15.4	18.0	18.4
25th	35.1	34.5	39.3	39.2
50th	47.8	47.5	52.2	51.8
75th	60.4	59.9	65.0	64.4
95th	78.2	77.7	86.0	84.0

Evaluating the North Slope reroute and slow down at the scale of the LME
Because the LME is so large, with plenty of open sea, evaluations at the scale of the LME (Table 4) are not effective to evaluate noise reduction in the specific areas targeted by the management strategies, reported above. What such assessment does show, however, is that as many ships are moved farther offshore, from shallow to deeper water, the resulting noise propagates further, resulting in slight increases in median noise levels in the region under most cases, and/or elimination of the benefits seen at the local scale under the higher traffic conditions predicted for 2030 (Tables 2, 3).

Table 4: Ship noise levels (displayed as percentile quantities of sound in dB) in the Chukchi Sea LME under baseline, North Slope reroute, and North Slope reroute + speed reduction conditions in both 2019 and 2030.

	2019			2030		
	Baseline	Rerouted	Slowdown	Baseline	Rerouted	Slowdown
5th	8.3	9.1	9.27	16.6	17.4	17.7
25th	28.2	29.2	29.2	39.6	40.4	40.2
50th	41.8	42.3	42.5	55.2	55.5	55.3
75th	55.6	56.1	56.2	70.0	70.0	70.1
95th	70.9	71.2	71.1	86.5	86.4	85.7

Routing ships around Areas to Be Avoided (ATBAs) (King Island, Nunivak Island, and St. Lawrence Island), and a walrus haul-out zone on Little Diomede Island

The ATBAs around King Island, Nunivak Island, and St. Lawrence Island are all relatively small and heavily influenced by vessel noise from outside their boundaries. In general, in both 2019 and 2030, rerouting produces only small reductions within the avoidance zones because there were very few large vessel passes. Similarly, the proposed ATBA around Little Diomede only represents 0.04% of the pixels in the model, likely too small for robust statistical power and change was insignificant due to routing when evaluated for such a small area so heavily affected by noise from outside the area (see Appendix C, tables C1, C2).

Discussion

The implications of underwater noise from shipping on marine life are of global concern (Harding and Cousins, 2022; International Maritime Organisation, 2023), and the Arctic Ocean is acknowledged as a special case (PAME, 2019, 2021, Lancaster et al. 2021). This project explored Arctic shipping and associated underwater noise in open water conditions (September) at two timepoints: 2019, to represent the present, and 2030, to represent the near future based on a modelled shipping scenario reflecting growth in shipping sectors. In three Arctic sub-regions, a variety of ship traffic management measures previously identified as having potential to reduce underwater noise were applied and their effects assessed.

1. **Projected increases in Arctic shipping will add more underwater noise to the region's marine environment, and even relatively modest increases in vessel traffic can have large effects**

Under the 2030 shipping projections, underwater noise from shipping across the Arctic and in the Baffin Bay, Barents Sea and Chukchi Sea sub regions all increased. This was due to a combination of more ship traffic and ice-free conditions, including the continued northward recession of the ice edge.

Increases in underwater noise have been observed or deduced to have a variety of behavioural, physiological and even genetic effects on marine species (e.g., Erbe et al., 2018; Weilgart, 2023). High levels of ship noise can cause a phenomenon known as masking, which is caused by acoustic interference and results in a shrinking of listening space for animals that use hearing as a key way to sense their environment (Clark et al., 2009 and references within). Masking can result in animals having a lower chance of detecting an auditory signal of importance, for example, a predator, prey, a member of the same species or an environmental cue. The degree of masking that Arctic animals experience as a result of rising ship noise depends on several factors, including the frequency and intensity of background noise relative to those signals of importance. We can assess human-caused loss of listening space by understanding how much acoustic interference animal auditory signals encounter due to natural conditions (wind) compared with the addition of ship noise. The implications of added noise are coarsely proportional to the contractions in listening space: an increase in 3 decibels of noise represents a doubling of sound pressure level and a quartering in the space over which overlapping signals are detectable.

At the scale of the whole Arctic Ocean, underwater noise is projected to increase by an average of 5 dB by 2030, although there is much variation across the region. The Chukchi Sea on average is projected to experience up to a ten-fold (15 dB) increase in sound pressure levels, while in

Baffin Bay and the Barents Sea, changes in shipping activity are projected to result in an approximate doubling (2 dB and 4 dB respectively) of sound pressure. The large increase in the Chukchi Sea, despite only a modest increase in vessel traffic, illustrates the vulnerability of the Arctic Ocean's undisturbed and naturally quiet areas to the addition of noise sources. In contrast, the Barents Sea is one of the most shipped sub-regions of the Arctic, and the contribution of ship noise to the soundscape was already sizeable in 2019. Although louder baseline noise environments are less affected by future increments of traffic change (either growth or decrease) than quieter baselines, if they are supporting acoustically sensitive animals, their current or higher overall noise conditions may highlight the need for management. More shipping projected in 2030 would leave few areas of the Barents Sea free from ship noise. Further, ship noise would spread farther north, including into the central Arctic Ocean. Finally, despite projected increases in fishing and other ships in Baffin Bay by 2030, increases in underwater noise were offset by a rerouting plan to take vessels servicing a large iron ore mine out of Baffin Bay. This demonstrates how concentrated shipping to support resource extraction projects can affect the underwater soundscape at the sub-regional scale.

2. **Vessel management measures, whether directed to reduce underwater noise or with indirect noise consequences, can be modelled to inform and support policy- and decision-making**

Vessel routing, speed reductions, and technological modifications were explored to reduce vessel noise levels in the three sub-regions to see how underwater noise was affected. Several measures modelled were already in place on a voluntary or mandatory basis, while others were hypothetical. Of the real-world examples, most were not developed specifically to address underwater noise from ships. For example, measures around walrus haul-outs were in place to reduce disturbance to walruses primarily when they were on land.

Speed reduction has significant environmental benefits that can make it an attractive option for underwater noise management, including reducing carbon dioxide emissions and the risk of fatality for large whales if struck by a ship (Vanderlaan and Taggart, 2007; Leaper, 2019). In Baffin Bay, the Barents Sea and Chukchi Sea, baseline operational speeds for many ship classes in selected areas with aggregations of noise-sensitive species were mostly below 12 knots. Therefore, applying speed reductions at a threshold of 10 knots in those areas did not affect a large proportion of vessels or had a muted influence on their speed-dependent source levels. This is the main driver of the results, which showed mostly small reductions in underwater noise levels in the areas assessed once speed restrictions were invoked. It was also likely that noise from vessels adjacent to these areas, which were not subject to speed restrictions, permeated into these areas of concern, thus diluting any positive effects of the slowdown.

When considering applying speed restrictions in the Arctic, it is important to know existing baselines of vessel speeds in areas of concern to determine how slowing down could improve underwater noise levels. It is also critical to evaluate the feasibility of slowing down relative to navigation and safety thresholds in Arctic weather and ice conditions. Finally, it is important to consider including buffer zones around important areas when implementing vessel management measures to reduce underwater noise. This consideration is not limited to speed restrictions but rather reiterates the ocean's permeability to sound and the need to account for that when addressing underwater noise.

A reduction of noise at the ship's source was applied to one quarter of the fishing fleet in the Barents Sea through changes in vessel design or propulsion. Given the operational requirements and behaviour of fishing vessels, this approach seemed to be more fit for purpose than a speed restriction or rerouting. However, likely due to a combination of the size of the fishing fleet (over 3000 vessels), the source level reduction amount, the application of the measure to a random subset of vessels, and (most importantly) the spatial scale assessed and its pre-existing level of noise, this measure did not have a discernible effect on estimates of underwater noise levels over the entire sub region. Next steps could invoke a more targeted approach, for example, assessing the dominant vessel types in a soundscape to determine which, if any, design approaches might be effective, and matching technological measures for quieting to specific vessels based on characteristics such as engine, propulsion, size and operational parameters. Further consideration could be given to whether the goal is to reduce noise at the scale of an ecosystem, or more locally in specific areas, so as to evaluate opportunities for technical modifications in vessels that have a dominant influence in the area of concern.

3. Spatial scale is important when assessing underwater noise effects and solutions

This project assessed underwater noise from shipping at multiple spatial scales – the whole Arctic Ocean, the sub-region (based on Large Marine Ecosystem) and locally within a sub-region. The pan-Arctic assessment provides regional noise statistics for comparison with other oceans in the world, as well as an overview of how Arctic shipping and underwater noise are distributed across the Arctic, including in the central Arctic Ocean. The sub-regional assessments give insights into shipping noise baselines for three marine ecosystems and both scales account for connectivity among habitats and shipping patterns, thus allowing exploration of sub-region- and region-wide solutions.

Further assessing underwater noise at local, sub-regional scales was particularly important when exploring noise results under different vessel management measures. Measures that were effective at reducing underwater noise in a local area of concern can result in increases in noise elsewhere. For example, in the Chukchi Sea, moving ships away from shallower slope waters resulted in the ships being re-positioned over deeper water, where underwater noise can spread farther. The goal – reducing underwater noise levels in important slope habitat – was partially achievable through this routing scheme, however the resolution of this benefit was lost when evaluation also included deeper sub-regional waters. Similarly, excluding cruise ships from an important summer habitat for narwhals in Baffin Bay (Eclipse Sound) by restricting them to a designated area doubled the shipping activity in that area, likely leading to a higher sub-regional noise footprint.

The trade-offs of shifting underwater noise from one place to another can be assessed but require comprehensive spatio-temporal information on biodiversity features at quite fine scales. Such data have not been collated across the Arctic. Assessing trade-offs is also challenged by range shifts and changes in migratory behaviour across populations of Arctic species in response to climate change (e.g., Seger et al., 2020), making it difficult to know with certainty how effective measures will be over time. Indeed, vessel management measures modelled here used knowledge of current important habitats for species, since future important habitats are not known. This underscores the importance of shipping measures being dynamic enough to keep up with the pace of change in the Arctic marine environment.

4. Given projected growth in Arctic shipping and consequences for marine species and ecosystems, it is important to build towards regional-scale management of underwater noise from shipping

The Arctic Ocean contains some of the planet's remaining most biologically important and least human affected acoustic environments (Jalkanen et al., 2021). Prospects of shipping growth in the Arctic are being counterweighed by a growing body of scientific literature on the effects of underwater noise and Indigenous knowledge and long-standing concern from coastal Indigenous peoples about such effects on marine mammals central to their cultures, livelihoods and food security (e.g., PAME, 2019, Duarte et al., 2021, MEPC.1/Circ.907). Thus, there is a need to build and contribute to management that supports safe growth in ship traffic that also preserves the health of Arctic marine species and ecosystems.

Next steps towards this could include sharing the work of the Arctic Council on underwater shipping noise with broader relevant communities and governance fora such as the International Maritime Organization (IMO). The IMO is hosting an Experience Building Phase after updating guidelines for the reduction of underwater noise from commercial shipping. The Organization also finalized an Underwater Radiated Noise Action Plan in 2023, which includes action to develop specific guidance for Arctic waters.

Further work by the Arctic Council and Arctic states could build on expertise of other regional bodies that have advanced regional-scale initiatives with strong monitoring programs and management objectives for underwater noise, such as the European Commission's Marine Strategy Framework Directive and associated monitoring programs in the North Sea (Joint Monitoring Programme for Ambient Noise North Sea - JOMOPANS), Baltic Sea (Baltic Sea Information on the Acoustic Soundscape - BIAS) and Atlantic seas (Joint program for Ocean Noise in the Atlantic - JONAS).

Open access digital archives of ocean sound data representing time periods and spatial scales relevant for collective decision making have been highlighted as important tools to support regional management. Such archives have also been recommended to implement the role of Ocean Sound as an Essential Ocean Variable within a Global Ocean Observing System (GOOS) (Tyack et al. 2023). Several States maintain such underwater recording archives inclusive of Arctic measurements, and present opportunities to further coordinate and track measured noise status as well as more effectively ground-truth regional predictive models such as those presented here. Indeed, the Arctic and Antarctic are highlighted by GOOS as priority regions to advance common data practices, due to both heightened difficulties in collecting underwater sound recordings and rapid changes in acoustic conditions in both polar regions. The Arctic Council could play a role in advancing linkages among existing repositories as well as encourage access to other long-term listening assets maintained by States. Such efforts are increasingly trackable as standard data management and measurement practices are advanced internationally.

Matching measurement resources to PAME's Arctic Ship Traffic Data (ASTD) database could support more continuous status and trend evaluation, as well as provide Arctic Council capacity to evaluate underwater noise impacts associated with proposed vessel management approaches. As noted in this report, the transboundary nature of underwater noise requires transparent and collaborative resources for evaluating management decisions over multiple scales. Such cross-disciplinary, inclusive approaches are critical tools for advancing shared stewardship of the Arctic region.

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Appendices

Appendix A: Modelling Approaches

Modelling the natural Arctic Ocean soundscape

Wind

Wind noise that ensonifies the oceanic acoustic environment can be calculated if wind speed over the ocean surface is known. Modelled wind speed across the Arctic Ocean is provided by The National Centers for Environmental Prediction (NCEP) in 6- and 12-hour intervals. Using the NCEP output, wind speed data were fit (interpolated) for every grid point in our LMEs of interest and for 3-hour intervals, creating a mapped (gridded) wind speed time series. Using these wind speed measurements, as well as wave action and a wind-speed-to-noise model developed by F. C. Felizardo[1] (who used the Weather Observations Through Ambient Noise [WOTAN] method[2]), the sound pressure levels at 125 Hz were calculated for the whole Arctic Ocean, Baffin Bay, the Barents Sea and the Chukchi Sea.

Wind models assumed an ice-free ocean, because current understanding of the physics and modelling of ice-generated sounds and the effect of ice coverage on wind sound are quite poor. This means that ambient sound levels in parts of the Arctic Ocean may have been overestimated, because sea ice coverage would reduce the amount of sound penetrating the water column.

Sea ice

The fidelity of oceanographic modelling in the Arctic is severely limited by both sparse *in situ* observations and few surface satellite measurements. Acoustic data of the ocean below the sea ice are restricted to a handful of specialized moorings from the Ice-Tethered Program (ITP; https://www2.whoi.edu/site/itp/), and from a collection of other studies[3,4,5,6]. There is therefore high uncertainty in how much sound ice contributes to the soundscape since there is so little data to corroborate the models. To avoid this uncertainty in the acoustic models, sound from sea ice forming and calving was not included.

Sea ice was included in the acoustic model as being a dampener of sound propagation. For 2030 models, sea-ice extent was taken from the Consortium model for Sea Ice Development (CICE)[7] and hindcasts of the Pan-Arctic Ice-Ocean Modeling and Assimilation System.

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Estimating spread of sound underwater

Sea ice extent and location of ice edge

HYCOM and ICESAT models were used as starting points in this project, but some caveats must be understood.

Arctic sea ice thickness is poorly parameterized in both climate models and in coupled ocean-ice models such as Global HYCOM-CICE (Ge Peng, Joe Metzger; personal communication). Although sea ice thickness is available from merged satellite products (e.g., ICESAT-2, CRYOSAT-2, SMOS) there is large uncertainty owing to the paucity of in-situ measurements. Thickness data, unlike ice edge, is not assimilated into ocean-ice models. Climate models, or General Circulation Models (GCMs), calculate energy exchange in Earth processes, and are useful to make projections of future changes provided different emissions scenarios. However, these models have coarse resolution, and have difficulty capturing many of the feedbacks that occur during sea ice melt and formation.

Ultimately, as sea ice is decreasing, it is transitioning from multi-year to seasonal ice, which changes composition and reduces coverage and makes it more navigable by more vessels in the global shipping fleet[8]. To make predictive acoustic models of the soundscape of the Arctic Ocean in 2030, ice thickness and ice coverage models needed to be generated out to 2030, and it was assumed that as long as the thickness and coverage were both decreasing, the effect of less sea ice was being captured in the acoustic models. Due to the uncertainties mentioned, three ice models were evaluated: CESM, MIROC, and HYCOM. The HYCOM ice forecast model was chosen as it displayed median ice extent and thickness and retained realistic ice edges at the small scales necessary for vessel routing.

Transmission loss and calculation of ship noise

Acoustic transmission loss (TL) models and maps were made from the shipping models. To calculate TL of each ship in the shipping models, only longitude, latitude, and draught values were required. One TL model was run per ship per unit time (1-hour interval). Speeds, length, and class of the ships at each hourly interval were subsequently used to calculate their unique source levels using the JOMOPANS-ECHO model[9].

The TL model uses a parabolic equation model (based on[10]) to calculate how much sound levels decrease with range from the sound source. Key environmental variables that play a role in how sound propagates include temperature and salinity (a.k.a. the sound speed profile) and bathymetry. These variables were input to the model calculations using the World Ocean Atlas database for sound speed profiles and the General Bathymetric Chart of the Oceans (GEBCO) database for bathymetry. The first result of an acoustic model run is a TL map, or a “noise field”, of all the ships’ sound energies summed together. From these noise field maps, many other calculations can be made, such as combining ship noise with wind noise, comparing ship noise levels to wind noise levels, tallying when and where ship noise is at or above certain levels in time and space.

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The TL models were run for every ship position every hour only if the ship was in water at least 3 m deep. This was based on the assumption that if a ship was in less than 3 m of water it was either docked or stationary, and therefore either not producing noise or the noise would not propagate far (it would get readily absorbed into the ocean bottom). Since every sound source is emitted at a certain depth in the ocean, and that depth is important for the model, the ship draught was used as the sound source depth. If no draught was listed in the MMSI database, 3m was used as it is the deepest a ship could be in the water of our ≥3m threshold.

When sound travels through the oceanic environment, it spreads out in all directions and across all depths, but it is very computationally expensive and storage intensive to calculate the amount of sound at every grid point for the entire volume of the ocean region. Therefore, these models calculated how much ship noise was received in all directions across four layers of the ocean: 10, 30, and 100 m from the surface, and 10m off the bottom. The models were run out to 500 km from every ship source.

Calculating TL using parabolic equation modelling becomes increasingly computationally expensive as the frequency of the sound source increases. Therefore, all TL models were run for only the decidecade band (a.k.a. “pitch range”) centred at 125 Hz (range of 112 - 141 Hz) because that is a commonly loud frequency band for ship engines and an important frequency range for certain marine mammal species. To be more computationally efficient, the TL models were calculated just for 125 Hz, but then to add the sound energy contribution from the full frequency range, an adjustment factor of 14.6 dB of sound pressure level (SPL) was added. The grids over each area of interest needed to be standardised so that comparing acoustic model results across scenarios was consistent and eliminated the need to interpolate between grid values. Therefore, the output resolution of each area of interest was fixed to a maximum of 800 pixels (in a single direction). The TL code automatically calculated the longitude x latitude grid to form square pixels.

The specific propagation areas and grid resolutions for each area were:

Baffin Bay Propagation area: SW corner 259°E, 59°N ; NE corner 316°E, 79°N
Output grid resolution: 799 x 783 pixels

Barents Sea Propagation area: SWcorner -2°E, 63°N ; NE corner 69°E, 83°N
Output grid resolution: 800 x 770 pixels

In summary, all TL maps in this report show how much ship noise (in the frequency range around 125 Hz), from their hourly positions averaged over the month of September, cumulatively spread across the respective domains. The actual received levels of sound across the LMEs (as if an animal was hearing the noise while swimming) were then calculated by taking the source level (SL) of each ship at each position given its speed (i.e., ships are louder when they are faster), subtracting the amount of noise lost during transmission (i.e., the TL model calculation), and adding the amount of wind sound(W; representing the contribution of natural, or ambient sound) at each grid spot in the map.

This means, the variation of the SONAR equation we used was:

$SL - TL + W = RL$ or, ship noise - ship noise loss + wind sound= the amount of sound (in decibels [dB]) at each grid point in the map.

The grids of wind sound and shipping noise were then masked (spatially constrained to include data only in the area of interest) to only contain valid values inside the chosen LMEs.

Note that areas of interest in vessel management analyses also had masks applied to them. Removing data outside of the area of interest allowed for later statistical comparison of the noise in only the areas of interest.

With these RL values, comparisons of how much ship noise is contributing to the environment compared to the natural wind sound can be quantified over specific regions of interest. Comparisons can also be made for how much ship noise in a region existed in 2019 versus how much ship noise is modelled to exist in our 2030 projections or in various other shipping scenarios. Finally, statistical measures of noise levels in each region of interest, like medians and probability distributions, are calculated.

Appendix B: Arctic shipping datasets

2019 shipping dataset

The Arctic Shipping Traffic Data (ASTD) AIS dataset was provided to project consultant Applied Ocean Sciences (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. AIS data is known 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 as monthly files. The entire dataset was 335 GB with over 1.37 billion ship positions. 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.

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 snapshots for acoustic simulations. The filtering applied by Dr. Verlinden to obtain a clean set of ship tracks for 2019 is provided below. Each ship kept for this analysis must have:

- 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.

Modelling a 2030 shipping dataset

A variety of factors will influence future Arctic vessel traffic patterns. While changing ice and weather conditions play a role, political and socioeconomic factors are the dominant drivers, and these factors can vary significantly depending on the scenario. Because of this uncertainty, rather than offering a specific "forecast" of Arctic vessel traffic—which would depend on unpredictable political and economic conditions—we instead present multiple potential future "scenarios." Each scenario is built on clearly defined assumptions and parameters based on the likely factors discussed earlier. These scenarios are intended as a qualitative sensitivity analysis, providing insights into how factors such as resource extraction, trans-Arctic shipping, and sea ice conditions might shape the future Arctic soundscape. The methodology used in this study is designed to be reproducible, allowing for analysis of numerous future scenarios and the potential to evaluate the effects of future policy decisions or suggest mitigation strategies.

We chose to model two scenarios using the extrapolated HYCOM ice forecasts, with two different economic projections for shipping.

The HYCOM ice forecast for 2030 represents an approximate median between the CESM and MIROC forecasts, and the small scale features which drive vessel behavior were captured in a way that influenced the cost function in our shipping model in the most realistic way.

The economic model parameters vary regionally, so the Arctic was divided into five economic regions: the central Arctic, the Canadian Arctic, US Arctic, Russian Arctic, and the Baffin-to-Barents region. Within each of these regions, an approach mirroring the approach taken by the US Committee on the Marine Transportation System (CMTS), during the preparation of the Ten-Year Projection of Maritime Activity in the U.S. Arctic, 2020-2030 report released in September 2019. We began with the parameters produced for the US Arctic and estimated similar but coarser parameters for each of the other four economic regions. When possible, parameters for 2030 were extrapolated from trends seen from 2013 to 2019.

The Ten-Year projection produced for the US Arctic described four potential shipping scenarios:

(1) reduced activity scenario,
(2) most plausible scenario,
(3) optimized growth scenario, and
(4) accelerated but unlikely scenario

We define our "high ship traffic" conditions as the "accelerated but unlikely" scenario, which assumes that all operational risks in the region are fully mitigated and includes all potential sources of growth, even those considered improbable based on the best available data. Similar scenarios were developed for each of the four other Arctic regions. Notably, the actual increase in vessel traffic since the report's publication in 2019 has already far surpassed even the most aggressive scenario outlined. This suggests that even the most ambitious shipping projections modelled for 2030 may be conservative. It's also important to highlight that, like the CMTS study, this analysis focuses only on large commercial vessels equipped with AIS, excluding smaller recreational vessels. As a result, vessel counts in the region could be underestimated by as much as 40% (CMTS).

For each economic region and vessel type, a limited set of driving factors, or "forcing functions," was selected to determine the number of vessel hours each class of vessel would spend in that region. Experts were consulted to map these forcing functions to vessel activity. Transarctic shipping was projected at the cumulative level, with iterative parameterization in each sub-region to match the projected overall vessel-hours.

In Arctic waters subject to U.S. jurisdiction, fishing activity was expected to be driven by regulatory decisions, while coastwise bulk carrier traffic would depend on the growth and development of coastal facilities in the U.S., Canadian, and Russian Arctic. Tanker activity was linked to anticipated oil and natural gas leases. Tourist vessel activity was projected based on an extrapolated linear trend from the previous seven years, with variations between aggressive and low-traffic scenarios. Passenger vessels were expected to remain relatively constant, except for cruise ships, which were also projected based on past trends due to the absence of new ferry routes in the region. Military, survey, and research vessels were similarly expected to follow an extrapolated linear trend. Comparable forcing functions were applied to other economic regions with some exceptions. In the Canadian Arctic, specific proposed regional projects were factored into traffic forecasts. In the Barents Sea, fishing vessel activity was assumed to align with anticipated fishing quotas in Nordic countries and was adjusted proportionally. In the Russian Arctic, the low-traffic scenario assumed three new leases for natural gas exploration, while the high-traffic scenario assumed six. Cargo vessel traffic along the Northern Sea Route was extrapolated linearly in the low-traffic scenario using trends from the past seven years, whereas the high-traffic scenario relied on official projections from the Russian government.

After estimating the number of vessel hours and transits for each route under the two economic scenarios, the next step was to predict the likely routes vessels would take. We assumed vessels would generally adhere to the Polar Code, meaning they would transit outside of territorial seas when possible and respect international laws governing transit and innocent passage. Additionally, all scenarios assumed it would not be economically viable to operate large fleets of Panamax-size container ships under Polar Code regulations for at least the next 15 years. The Polar Code imposes stringent requirements on vessel design, crew training, and operational procedures, making year-round compliance prohibitively expensive for fleets that would only transit the Arctic during a few ice-free months. As a result, even our most aggressive 2030 projection does not anticipate significant trans-Arctic Panamax container vessel traffic.

Vessel routes were generated using a combination of approaches. For cargo vessels transiting between ports, including tug-in-tow, bulk carriers, and tankers, it was assumed that these vessels would transit approximately along the most efficient routes considering on-scene conditions. A least cost path tool was created with inverse-vessel-speed representing the “cost-to-go”. The 2030 HYCOM extrapolated ice model was used to predict ice conditions. Non-ice capable vessels were assumed to avoid the ice entirely, while ice reinforced and ice breaking vessels were allowed to transit through ice according to their class and rating, at substantially reduced speeds. The result was that vessel paths predominantly avoided sea ice where possible across nearly all classes of vessels. Track lines were slightly perturbed from optimal using a simple Gaussian weighting function to spread vessels along some nominal distances from “optimal”. Vessel speeds were taken to follow local speed restrictions where applicable, but otherwise consistently followed vessel class and conditions. A Gaussian distribution random perturbation was applied to vessel speed to generate more diversity in vessel tracks.

For survey, research, and fishing vessels, a simple route optimizer was not appropriate. Instead, vessel tracks were created by determining the number of vessel-hours expected in each of these classes and then selecting the appropriate number of actual historical tracks from previous years, modifying the time and vessel ID, and placing them in the 2030 model. The vessel tracks were picked to reflect the 2030 ice conditions. For the noise modelling work in this phase, only the high traffic model was used.

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Appendix C: vessel management strategies

Chukchi Sea:

Table C1: Ship noise levels (displayed as percentile quantities of sound in dB) in the Bering Strait ATBAs under baseline and reroute conditions in both 2019 and 2030.

	2019			**2030**	
	Baseline	**Reroute**		**Baseline**	**Reroute**
5th	3.9	3.7		4.9	5.0
25th	15.9	15.6		19.6	19.7
50th	27.9	27.5		33.3	33.4
75th	42.4	41.5		50.0	49.6
95th	64.7	63.5		73.8	72.4

Table C2: Ship noise levels (displayed as percentile quantities of sound in dB) in the walrus haul-out zone for Little Diomede Island under baseline and reroute conditions in both 2019 and 2030.

	2019		**2030**	
	Baseline	**Reroute**	**Baseline**	**Reroute**
5th	29.1	35.6	31.5	32.7
25th	48.7	50.6	54.2	53.0
50th	60.2	61.6	65.8	65.3
75th	71.2	71.6	76.2	76.1
95th	85.2	85.1	93.9	92.8