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Noise pollution from Arctic expedition cruise vessels: understanding causes, consequences and governance options

Fabienne Mannherz[1] ✉, **Maaike Knol-Kauffman**[2,3], **Vonintsoa Rafaly**[4], **Heidi Ahonen**[5] & **Bjørn Ivar Kruke**[6]

Significant increase in shipping in the Arctic has caught international and national attention. The rising presence of touristic expedition cruise vessels might describe a special case for noise as a marine pollutant while they seek exclusive opportunities to experience the Arctic first-hand. This interdisciplinary study develops a conceptual framework to investigate context-specific vessel noise cause-effect dynamics and how this knowledge can assist policymakers and industry in increasing environmental safety. The study comprehensively reviews noise-emitting activities from Arctic cruise expeditions and potential adverse consequences for Arctic endemic marine mammals. It further discusses governance options for mitigating these consequences. Internationally, legal adaptations in the shipping conventions MARPOL and SOLAS should recognise noise as harmful energy. This could facilitate the uptake of noise-level-based certification schemes in the Polar Code. These legal actions can be strengthened by extended collective self-governance and through introducing economic incentives at the port level.

In recent years, there has been an increasing concern about the implications of the changing soundscape of the oceans[1]. In the Arctic, where shipping activities are on the rise[2] and underwater noise has doubled within only six years[3], there is a clear need to assess and govern the risks related to underwater noise pollution[4]. Underwater noise features the characteristics of a pollutant which is understood as a substance or energy introduced to the *marine environment with the potential to cause harm (UNCLOS, article 1(1))*. The relatively pristine soundscape of the Arctic, combined with unique sound propagation characteristics, suggests that marine wildlife can detect vessels from greater distances and are more likely to react to individual ships than animals in other regions[3].

Climate change-induced warming and sea ice reduction enable vessels to go deeper into the Arctic. The so-called "last chance" tourism has led to rapid growth in cruise expeditions in the Arctic with new risks for humans and the environment[5–7]. The luxury cruise expedition icebreaker *Le Commandant Charcot* (Ponant) was the first passenger vessel to reach 90° North in 2021 and for the first time with passengers in 2022[8]. Substantial increases in cruise tourism have been documented for various Arctic regions, notably for Svalbard and Greenland[2]. For Svalbard, this increase has gone hand in hand with a lengthening of the operational season[2]. Further studies consider the cruise industry as one of the fastest-growing segments of polar tourism[5,9].

The spatial and seasonal increase in cruise shipping might well overlap with Arctic endemic marine mammal hotspots such as those identified by Hamilton et al.[10]. Hence, it is important to facilitate knowledge generation to better understand the causes and consequences of shipping noise in these extreme and vulnerable environments.

Among passenger and traditional cruise ships, expedition cruise operations differ from transiting maritime activities related to transport and cargo as expedition vessels spend prolonged time cruising and manoeuvring in the same area[11]. They engage in further activities such as driving with speedboats and utilising underwater remotely operated vehicles or helicopters that potentially cause more local noise disturbance. This is a concern, as single and combined noise from such shipping activities in the Arctic Ocean disturbs marine life, adding to cumulative pressures from climate change and other anthropogenic impacts[12]. Existing studies have mainly addressed global shipping noise emissions from vessels travelling between destinations with implications for larger areas, targeted species impacts, ship traffic trends, or ambient noise levels[13–21]. To our knowledge, this is the first study to examine context-specific shipping noise caused by cruise expedition vessels in the Arctic, which might reveal novel aspects for governance and future research.

[1]Department of Marine Sciences, Centre for Sea & Society, University of Gothenburg, Gothenburg, Sweden. [2]Norwegian College of Fishery Science, University of Tromsø - The Arctic University of Norway, Tromsø, Norway. [3]Norwegian Institute for Water Research, Tromsø, Norway. [4]School of Business, Economics and Law, University of Gothenburg, Gothenburg, Sweden. [5]Research Department, Norwegian Polar Institute, Tromsø, Norway. [6]Department of Safety, Economics and Planning, University of Stavanger, Stavanger, Norway. ✉e-mail: fabienne@agileowl.de

The objective of this paper is to develop a conceptual framework that can assist in exploring the sources and consequences of shipping noise from cruise expedition activities in the Arctic and to provide recommendations for policymakers and the industry to mitigate noise pollution and thus enhance environmental safety. The paper builds on a structured literature review and eight problem-centred expert interviews. Conceptually, data analysis was inspired by the safety-barrier model, developed in safety science and used in diverse industries to enhance safety and prevent incidents. As we will demonstrate, the model is highly relevant to better understanding the diversity of ways to deal with noise as a potentially hazardous energy[22]. First, we gathered contextual knowledge about the sources and consequences of shipping noise for endemic Arctic marine mammals. Second, we investigated possible mitigation measures and related governance options.

The following sections present background knowledge about cruise expeditions in the Arctic, known impacts of shipping noise on marine mammals, and the legal framework employed. The results and discussions will first consolidate and examine the main cause-effect relationships of shipping noise from Arctic cruise expedition vessels and potential impacts on endemic marine mammals. Consequently, we review safety barriers to mitigate noise impacts and propose a practical approach to precautionary governance of shipping noise from expedition cruises in the Arctic. The paper concludes with the key findings and implications for future action in research and regulation.

Polar cruise expeditions are characterised by adventure, wilderness, education and personal experience[9]. Modern cruise expeditions in the Arctic are rapidly increasing in number and geographical coverage. Climate-change-induced sea ice retreat facilitates extended navigation and urges people to visit the Arctic as *a last Frontier*[5,6,9,23]. Expedition vessels are categorised as passenger vessels, defined as any vessel carrying 12 or more passengers[24]. Expedition cruise vessels are smaller in size and passenger capacity than conventional cruise vessels (meaning coastal ferries and overseas destination cruises) and usually comprise 20 to 500 passengers[25]. However, expedition cruises do not travel on direct routes and do not spend the night at busy port sites like conventional cruise ships do. Instead, their purpose is to explore the landscape, encounter wildlife both on and off the vessel, access remote shorelines and sea ice, venturing into challenging waters, and seek exclusive opportunities on a relatively flexible itinerary to experience the Arctic first-hand[9,25]. Expedition cruises in the Arctic encompass a multitude of considerations concerning the vulnerable natural environment, the challenging safety hazards at sea and land, and the concern about lacking search and rescue infrastructure[5,26–28]. Arctic-bound expedition cruise vessels share similar requirements and characteristics with cargo and tanker vessels under international maritime regulatory frameworks, including the *International Code for Ships Operating in Polar Waters (the Polar Code)*[29]. In addition to global regulations, operators may address these challenges through a collective self-governance approach[25], such as membership in the *Association of Arctic Expedition Cruise Operators* (AECO) (https://www.aeco.no/). Its operational guidelines for members and recommendations are "dedicated to managing responsible, environmentally friendly and safe Arctic tourism and striving to set the highest possible operating standards" (AECO) and convey a close linkage of human and environmental safety for shipping in the Arctic. However, as of today, AECO's guidelines do not address underwater noise pollution.

Noise is invisible to the human eye and may be more challenging to grasp than other anthropogenic pollutants in the marine environment, such as plastic and oil pollution, bycatch, entanglement or ship strikes of marine animals. The known impacts of anthropogenic sounds on marine mammals comprise disruption of behaviour (e.g., feeding, breeding, resting, migration), masking of essential sounds, temporary or permanent hearing loss, physiological stress or physical injury, and changes to the ecosystems that result in a reduction of prey availability[30]. These impacts may lead to a displacement of marine mammals[4], with cascading effects on the local and global ecosystems and local communities[31].

From the perspective of a receiving marine organism, sound can be a *signal* that contains vital information about the environment and its inhabitants[30]. It facilitates critical functions such as acoustic sensing, communication, navigation and feeding by marine fauna, including marine mammals, fish and invertebrates[32]. *Noise* is any other form of sound that either does not provide any helpful information (background clutter), interferes with the biological relevant signals (masking), or causes stress, disturbance, temporal hearing loss, permanent injury, or death[30,31,33,34]. In addition to the growing number of studies investigating the acute consequences of shipping noise on marine mammals, Erbe et al.[35] developed a *population consequence of disturbance* (PCoD) model to identify long-term impacts. An example would be how noise affects foraging, leading to reduced energy intake or additional energy expenditure by the behavioural or physiological response, impacting maternal fitness, reducing the birth rate and pup health and potentially leading to pup or adult death. Despite the continuously growing research on the adverse effects of shipping noise on the marine environment within the Arctic, reaching legally binding agreements remains challenging[36–39].

Shipping noise is currently recognised as a pollutant in environmental discussions[31,33,36,40,41]. Looking at the general legal framework governing human activities at sea, the United Nations Convention on the Law of the Sea (UNCLOS) defines pollution as:

"Pollution of the marine environment means the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities." (UNCLOS, article 1(1)).

Hence, in defining pollution, UNCLOS makes an important distinction between substances and energies. International shipping, however, is mainly regulated through the International Maritime Organization (IMO), which, since its establishment in 1948, has focused on safety, environmental concerns, and preventing pollution from ships. Two main conventions negotiated through and adopted by IMO govern safety and the protection of the marine environment: *The Convention for the Safety of Life at Sea* (SOLAS), which entered into force in 1965, and *The International Convention for the Prevention of Pollution from Ships* (MARPOL), which entered into force in 1983.

SOLAS specifies the minimum standards for construction, equipment, and operations of ships concerning their safety. Regulations in SOLAS target "safety of life at sea, safety and efficiency of navigation and protection of the marine environment" (e.g. Regulations: 6—Ice Patrol Service, 10—Ships' routeing, 11—Ship reporting systems, 12—vessel traffic services, 34—safe navigation and avoidance of dangerous situations).

In contrast to UNCLOS, MARPOL defines pollution as a substance only and not as an energy:

Any substance which, if introduced into the sea, is liable to create hazards to human health, to harm living resources and marine life, […]. (article 2(2))

The six MARPOL Annexes are dedicated to preventing pollution by oil, noxious liquid substances, harmful substances carried by sea in packaged form, sewage from ships, garbage from ships and air pollution from ships. While MARPOL focuses on harmful substances, and SOLAS focuses on safety at sea, UNCLOS introduced the term "energy" as a source of pollution. Considering noise as harmful energy, noise pollution is implicitly addressed by UNCLOS but not by MARPOL or SOLAS[42].

In 2014, IMO introduced the *Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life*[43]. It comprises a set of non-mandatory guidelines that can be applied by any commercial ship to reduce shipping noise by focusing on primary sources associated with propeller hulls, machinery and operational aspects. However, the guidelines for reducing underwater noise lack practical advice on how certain elements, such as operational measures, should be implemented[37].

The Arctic Ocean poses a special case for shipping activities and related human and environmental risks. Shipping in the Arctic is strongly characterised by what Albrechtsen and Indreiter[44] define as the *Arctic Operational Context* and by what Chircop[45] refers to as the *Arctic Navigational Context*, such as cold and harsh weather conditions, remoteness, lack of infrastructure, lack of knowledge and the strong and unpredictable influence of climate change. In 2014, the growing concerns about risks posed to human operations and the Arctic environment by increasing shipping led IMO to adopt the Polar Code, a mandatory and legally binding regime for navigation in polar waters that is divided into safety-related measures (part I-A) and pollution prevention (part II-A). Further recommendatory provisions are made for both (parts I-B and II-B). The Polar Code addresses risks in polar waters and covers design, construction, equipment, operational, training, search and rescue, and environmental protection matters[29]. Its scope is mandatory for individual ships under SOLAS and MARPOL[46]. Ships intending to operate in polar waters must undergo a polar classification associated with the level of ice-infested waters their design will facilitate. The assessment involves identification of operational limitations and defining plans, procedures, and safety appliances necessary to mitigate incidents that might interfere with safety or lead to environmental consequences. In addition, vessels must carry a *Polar Water Operational Manual* (PWOM) regarding the operational capabilities and limitations to support decision-making. The Polar Code does currently not address underwater pollution, which has been identified as one of its implementation gaps[47].

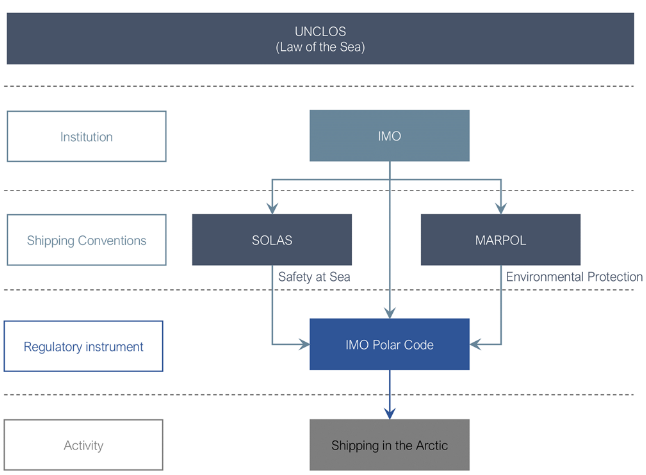

Fig. 1 | Legal framework for shipping in the Arctic.

Since maritime transport is transboundary and operates between areas within and beyond national jurisdiction, the introduced legal framework (Fig. 1) is relevant in discussions about policy-making for shipping noise in the Arctic[4,37,48].

Results and discussion

Sources and consequences of underwater noise in the Arctic

The contextualisation of results concerning causes, contributing factors and consequences of shipping noise in the Arctic have been inspired by the bow-tie model that has been developed in and adapted from safety science literature[22,49].

Considering sound as energy, a noise-emitting vessel describes the potential hazard to the very left of the bow-tie model (Fig. 2). Causes are the sources (yellow) and contributing factors (grey) that influence sound development and might lead to harm. To the right side, marine mammals are the vulnerable target that should be kept safe from a hazardous event—a situation where sound becomes harmful and develops adverse consequences that will affect marine mammals. The bow-tie model is a practical visualisation to discuss relevant causes and consequences for the in-situ activities.

This section builds on the model to understand the noise pollution risks from Arctic cruise expedition activities, considering sound as a potentially harmful energy. Rausand and Haugen[49] link harmful events to a specific location and time frame. This perspective on safety suggests that the duration of noise exposure within a local setting could be an important factor that increases the likelihood[50] and severeness[35] of adverse consequences for marine mammals. Contextuality of noise exposure has been demonstrated in different studies[11,51,52]. Efforts to reduce exposure to a harmful energy are labelled a barrier in the bow-tie diagram[22].

Hollnagel[53] finds an acceptably low number of harmful events important for ensuring safety. Repeated duration of noise emission, such as a popular landing or cruising site being visited by different cruise expedition vessels, should be factored in when assessing exposure time. Negative implications of prolonged and repeated noise disturbance were mentioned across the different potential consequences[54,55]. Cumulative temporary hearing loss (*temporary threshold shifts*), repeated consequences from sound masking, behavioural disturbance and physiological stress might lead to significant biological long-term population effects if there is too little time for recovery in between disturbance events[35,56].

The potential for harm depends on the area affected by the noise and the degree to which the signal overlaps with the communication or hearing capacities of marine mammals[49]. From a precautionary perspective, it is helpful to consider the auditory ranges since they comprise specific communication, acoustic sensing and other vital environmental cues[32]. Auditory

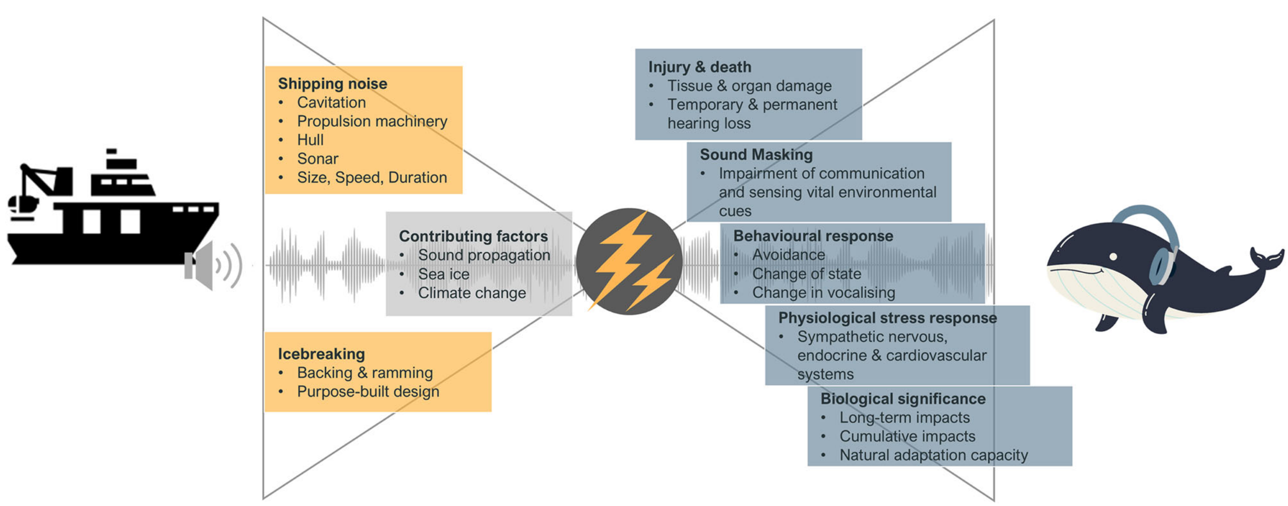

Fig. 2 | Causes of shipping noise and adverse consequences for Arctic marine mammals. Own illustration with Canva.

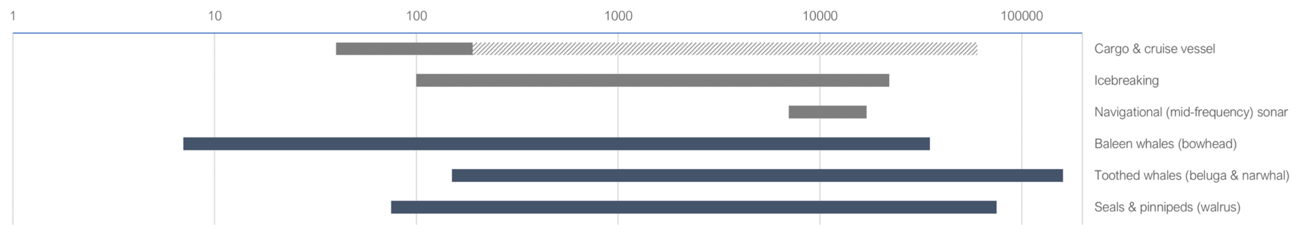

Fig. 3 | Shipping noise & marine mammal hearing frequencies in Hz, logarithmic scale.

masking can be described as the perceived interference of a signal (e.g., an animal sound) by another (e.g., a shipping vessel). The impact of the masking on the recipient depends on the spectral overlap, the intensity of the signal and the interfering noise. Moore et al.[30] describe masking as a chronic increase in sound that "degrades marine-mammal acoustic habitat much like fog or smoke obscures important visual signals for terrestrial animals" (p. 290)[30]. According to Weilgart[56], masking leads to the inability of marine mammals to locate widely distributed mates but also inhibits the detection of faint sounds of prey, predators and other navigation and orientation cues. There is an overlap of frequency bands of shipping, sonar and icebreaking activities and hearing frequencies assumed for Arctic marine mammals[3,17,21,30,52,57–59]. Figure 3 displays the approximate frequency bands of shipping[3,60], sonar[3,56] and icebreaking[58] activities in the Arctic relative to hearing frequencies used by Arctic baleen and toothed whales, seals and walruses (as cited in PAME (2019)[3]). The patterned stacked bar for cargo and cruise vessels represents the potentially higher frequency bands emitted from these vessel types, as Veirs et al.[21] reported. It is adapted from Moore et al.[30] and PAME (2019)[3] and modified using sources and frequencies relevant to this literature review.

A spatial signal overlap is a potentially unsafe condition[22] for marine mammals and these adverse consequences require a better understanding of the sources and contributing factors. Interview responses and literature[3,60] identify propulsion and cavitation as the primary source of shipping noise. Shipping noise is commonly considered low-frequency, with peaks at 50–150 Hz, but these signatures can be broadband, ranging from below 10 Hz and up to 60 kHz[3,21,52,60]. Veirs et al.[21] found that ship noise extends to higher frequencies and that ship noise across all types and sizes of vessels not only elevates background levels at low frequencies (20–30 dB re 1 μPa from 100 to 1000 Hz) and also at high frequencies (5–15 dB re 1 μPa from 10,000 to 40,000 Hz). Higher-frequency noise might, therefore, have greater or equal levels to the low-frequency noise within a kilometre of the vessel, making it an essential aspect for local or regional noise impacts such as those expected from cruise expedition activities.

An exceptional source of shipping noise in the Arctic stems from icebreaking[4,59], which is relevant to cruise expeditions towards the interior Arctic. A new era of expedition vessels such as *Le Commandant Charcot* (Ponant) and research expedition vessels like *RV Polarstern* (Alfred-Wegener Institute) and *RV Kronprins Haakon* (Norwegian Polar Institute) operate as icebreakers. Furthermore, in recent years several expedition vessels have started to venture into remote, ice-covered areas, escorted by icebreakers[31,61]. Roth et al.[61] investigated the noise of a research icebreaker in the Arctic Ocean. They measured high noise levels during backing-and-ramming manoeuvres caused by cavitation when operating the propellers astern or in opposing directions. Source levels were up to 200 dB re 1 μPa for the frequencies between 10 and 100 Hz, but the authors also mention a general increase in the noise signature between 20 and 2000 Hz. Cosens and Dueck[62] confirmed the presence of higher frequency (5 kHz band) components in the noise signal from an icebreaker. One informant for this study described extreme sounds caused by safety manoeuvres of breaking the ice with the help of the propellers from the stern, while another reported that the physical ice-breaking noises are accompanied by high noise peaks from the machinery during ramming and manoeuvring due to maximum engine loads. Erbe and Farmer[58] identified the bubbler system and the propeller cavitation during heavy load as the two main types of noise sources of an icebreaker, with median source levels of 192 dB re 1 μPa between 100 Hz–20 kHz for the bubbler system and 197 dB re 1 μPa between 100 Hz–22 kHz for the propeller cavitation. However, the loudest cavitation noise was 205 dB re 1 μPa during failed ramming.

Safety barriers

Results suggest that noise from cruise expeditions in the Arctic can affect endemic marine mammals. The highly contextual cause-effect relationships of a sound source and a vulnerable target can be considered "scientifically plausible but uncertain" (p. 14)[63]. A lack of baseline data on ambient sound levels and Arctic endemic marine mammal populations challenges precautionary action[3,59] (Intv.#1,#2,#6), difficulties in assessing actual thresholds for adverse consequences[35,52] (Intv.#2,#4,#7) and economic, navigational or safety constraints[4,37,48,59]. Still, this study investigated possible mitigation measures and adaptations to enhance the existing frameworks through which shipping noise is regulated in the Arctic (Fig. 4).

Haddon[64] suggests ten prevention strategies to deal with harmful energy that can be categorised into three main types of barriers (Table 1). The three barrier types of dealing with the energy source, separating the energy source from the vulnerable target and relating to the vulnerable target are also incorporated in Fig. 4. The following section will utilise selected strategies within Table 1.

Most of the technical and operational measures deal with the energy at the source. The spatial mitigations are best fitted into the safety barriers that separate in space and time. Monitoring, research and specific adaptation capacities can be considered safety barriers for the vulnerable target. Reducing the noise source levels is considered the most effective means of lowering actual and potential consequences for individual marine mammals and populations[35]. It virtually has an immediate effect[31]. Preventing the initial build-up of energy includes any design and technical aspects that lead to fewer noise emissions from the primary sources. Vessel slowdown or shutdown are examples for modifying the rate and distribution of energy. The literature and interview responses appear however to be divided on the pertinence of vessel slowdown or shutdown to reduce sound energy at the noise source[31,37,52,54,65] (Intv.#5,#6). Though speed reduction might come with reduced source levels and propagation of noise and decreases the risk of ship strikes, it leads to longer voyages[11,37,65]. Halliday et al.[17], McWhinnie et al.[37], and Pine et al.[52] doubt that reducing speed will have much impact on the overall noise risk since it will not reduce the number of disturbance events but cause prolonged disturbance due to longer travel time. Pine et al.[52] and one informant for this study added that travelling at sub-optimal speed might again increase noise emissions. Huntington et al.[65] highlight the need for a certain speed for safe manoeuvres. In general, potential benefits from speed reduction relate to vessels travelling at continuous, optimal speed, which is not feasible in all activities related to expedition cruises. Currently, no studies explore non-transit related noise sources or investigate the duration of the activity, related manoeuvres and sound signatures. Engineers who participated in the interviews suggested using hybrid propulsion solutions for peak-shaving related to ice-breaking. Further, they suggested the application of noise-reducing gear such as bubble curtains. This way of limiting the amount of energy[64] is also mentioned by Chou et al.[40] and Erbe et al.[35]. Some of these technologies would reduce noise levels overall. At the same time, others would be applied as an operational procedure to either prevent the release of (too much) energy, or modify the rate and distribution

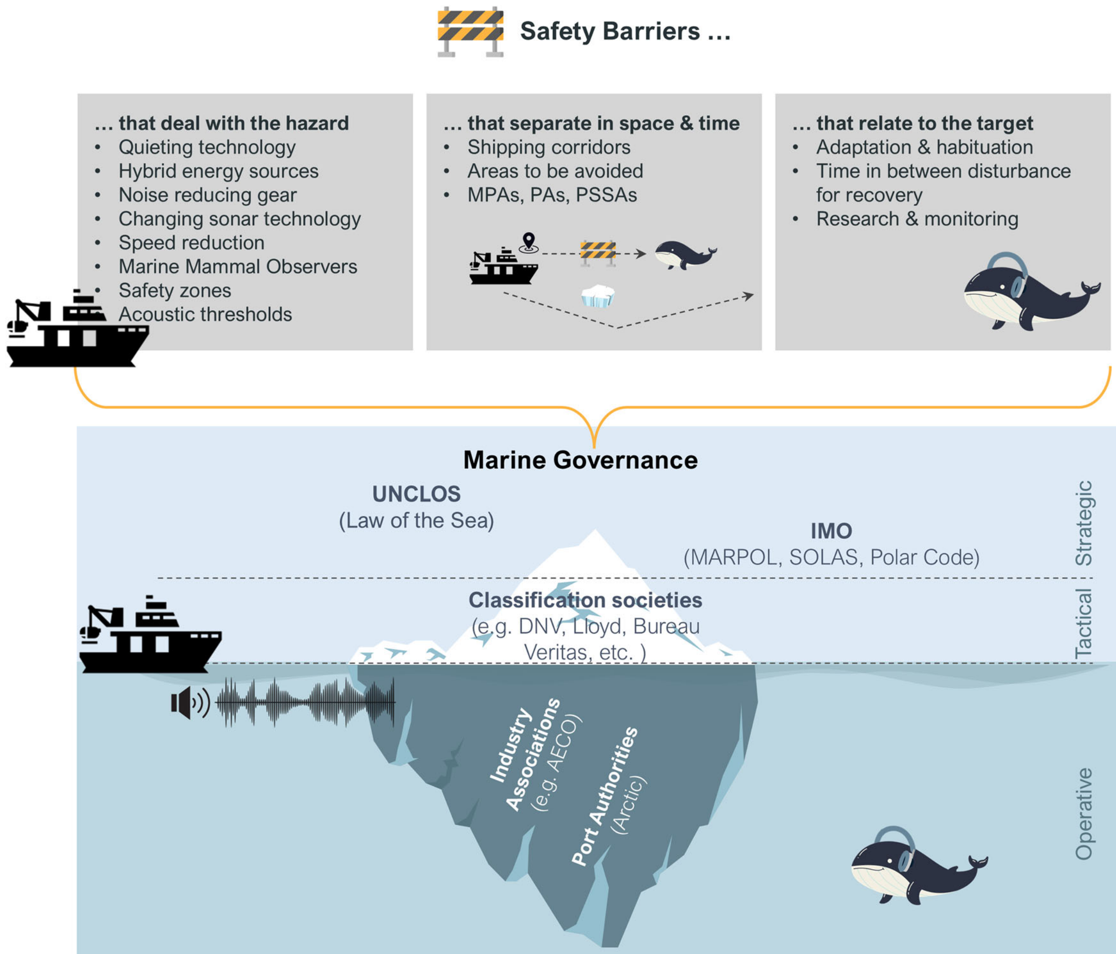

Fig. 4 | Summarised mitigation measures as safety barriers and the related governance framework for reducing adverse consequences of shipping noise for Arctic marine mammals. *Note*: Upper illustration—mitigation measures as safety barriers within the bow-tie model as applied categorization from Haddon's (1980) safety barrier strategies[64]. Lower illustration—multi-level marine governance for shipping noise during cruise expeditions in the Arctic. Own illustration with Canva.

Table 1 | Haddon's ten safety-barrier strategies

Safety-barrier strategies that…		
…deal with the energy source	…separate energy source from vulnerable target	…relate to the vulnerable target
1. Prevent the build-up of energy	6. Separate in time or space	8. Make the target more resistant to damage from the energy flow
2. Modify the quality of the energy	7. separate by physical barriers	9. Limit the development of loss (injury/damage)
3. Limit the amount of energy		10. Stabilise, repair, and rehabilitate the object of damage.
4. Prevent uncontrolled release of energy		
5. Modify the rate and distribution of the energy		

of the energy. Modifying the quality of the energy[64], appears in Weilgart[56] and Chou et al.[40] as alternate sonar techniques that are non-impulsive and low frequency. Comparing the noise levels of specific technologies and related frequencies and their overlap with marine mammal hearing capacities could also be applied to the other noise sources. However, this approach should be taken cautiously since altering frequencies might lead to adverse impacts for other marine organisms since there might not be something as "safe frequency bands" that can be applied to every marine organism.

Spatial separation by implementing shipping corridors, Marine Protected Areas (MPAs), Particularly Sensitive Sea Areas (PSSAs) or Areas to be Avoided (ATBAs) with special restrictions might be a local and seasonal option as soon as an overlap of landing sites, species hotspots, and adverse consequences have been identified. However, large-scale implementation is challenged by the highly migratory patterns of Arctic endemic marine mammals, the navigational constraints in Arctic waters and the wildlife-seeking, dynamic itineraries of cruise expeditions.

Lastly, we look at the third column of safety barrier strategies, which are the ones related to the vulnerable target (Table 1). These can be considered supportive elements or safety indicators of measures from the first two columns. Habituation could indicate a safe state[53], making the target more resistant—or resilient—to anthropogenic sounds. Ensuring maximum time of exposure and sufficient time of recovery between disturbance events[35,56] is a further relevant strategy that relates to the vulnerable target in the sense of stabilising, repairing, and rehabilitation. Finally, assessing and maintaining the adverse consequences requires research and monitoring of marine mammals, which could be achieved by monitoring the soundscape and marine mammal behaviour.

Governance recommendations

Based on the current knowledge and existing gaps outlined above, there is a demonstrated need to approach shipping noise in the Arctic by practical and precautionary actions at various levels. Due to the international dimension of shipping, there is a clear preference among interviewees and literature[4,65] (Intv.#3,#4) for governing noise through IMO and within the MARPOL and SOLAS conventions. A first step would be that shipping noise is explicitly recognised as a pollutant in these conventions. An update of MARPOL's definition of pollution, in line with UNCLOS, to include energies in addition to substances, would facilitate that noise is recognised as a marine pollutant. Since SOLAS relates to technological and operational safety aspects for human life and protection of the environment, recognising energy-related hazards to the environment could not only enhance the legal framework concerning shipping noise but also pave the way for the integration of other dangerous situations, such as vessel strikes (kinetic energy/motion). While *the IMO Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life*[43] (IMO, 2014b) describe a regulation on an international level, Arctic-specific regulations concerning shipping noise could be adopted in the Polar Code. Since expedition cruise vessels must comply with SOLAS and MARPOL, they must also comply with the Polar Code when operating in polar waters. It has been indicated in a previous study that the governance of shipping noise is a clear gap in the Polar Code[47]. The required classification process could be enhanced to include minimum technological and PWOM-related requirements for noise reduction—or, first of all, a noise emission assessment. Next, existing—or a new set of polar-specific—noise certification schemes could become part of the polar classification process. Hence, including such noise-reducing classifications would provide a practical yet adaptable governance solution.

To account for the special activities distinguishing expedition cruises from other vessels operating in the Polar Code region, more strict and targeted measures—such as expedition-related noise certification schemes or operational procedures—could be adopted through collective self-governance, such as through AECO. The association and its members could further benefit from studies investigating expedition-related noise levels and facilitating experience feedback about the effectiveness of procedures and technology. Port authorities are another set of actors that could have a larger role in the governance of shipping noise. UNCLOS Port state jurisdiction (e.g. *article 218(1)* and *article 219 UNCLOS*) provides the legal framework to adopt and enforce regulations regarding pollution prevention and vessels entering voluntarily in their ports. The Enhancing Cetacean Habitat and Observation (ECHO) programme by the Port of Vancouver aims to better understand and reduce the cumulative effects of commercial vessel traffic on at-risk whales. The initiative includes Passive Acoustic Monitoring (PAM) in multiple locations around the Salish Sea and achieved a decrease in sound levels through voluntary slow-down zones. Data from the ECHO programme has been used in multiple studies[17,19]. Informants of this study pointed towards the related EcoAction programme, an initiative to incentivise environmental and sustainable shipping activities. Within this programme, the port of Vancouver encourages operators by providing port fee discounts between 23% and 47% based on quiet notations and technologies[66,67] (Intv.#2,#6). Drawing inspiration from these initiatives, Arctic ports could provide economic incentives such as reduced port fees based on noise certification schemes. UNCLOS Port state jurisdiction (e.g. *article 218(1)* and *article 219 UNCLOS*) provides the legal framework to adopt and enforce regulations regarding pollution prevention and vessels entering voluntarily in their ports.

Towards governance and conservation research

This study has proposed a framework to understand the causes and consequences of noise pollution from cruise vessels in the Arctic. In addition, it has explored possible mitigation measures in terms of governance options. It has been beyond this study's scope to assess individual solutions' effectiveness or feasibility for cruise expedition vessels. It is our hope that the bow-tie model approach can inspire a more in-depth investigation of the available measures, including their implications for marine life. In terms of consequences, the focus has been on Arctic marine mammals; however, we acknowledge that noise pollution might also affect other species, such as fish and crustaceans.

A possible harmful impact for a marine mammal after noise exposure from an expedition vessel is specific to the particular species, the individual animal and the context. This study provides an interdisciplinary and contextual approach to address some of these uncertainties by designing and following up with targeted research to deepen and widen the elements of the proposed conceptual framework, including studies using high-resolution multi-sensor behavioural instruments[68–70]. To identify relevant study areas, one could further investigate the locations with the most frequent visits from expedition vessels around Svalbard by utilising AIS tracking data and mapping them to known and important hotspots for Arctic marine mammals such as the ones identified by Hamilton et al.[10]. Results could be used for more individual cause-effect scenario research and monitoring, such as long-term acoustic moorings and marine mammal behavioural studies.

This study suggests that enhancing environmental safety concerning shipping noise in the Arctic could be achieved by adapting the shipping conventions MARPOL and SOLAS to recognise noise as harmful energy. Strengthening the governance of shipping noise on the strategic level could facilitate and inspire momentum across the industry. Technical and operational measures to reduce noise at the source describe the most effective and precautionary mitigation options. Implementing noise-reducing measures could start through ship classification certification schemes. Mandatory compliance with minimum standards could be established as part of the Polar Code classification process. Voluntary compliance with more rigid and targeted classification levels could be established through collective self-governance, such as through AECO and economic incentive programmes at the port level. A future study should include interviews or workshops with related stakeholders at Arctic ports to assess the feasibility of reduced port fees for compliance with noise and potentially even further pollution prevention measures to enhance environmental safety for Arctic endemic marine mammals.

Methods

Research scope

To explore legal mitigation tools, this study investigates shipping noise from tourism-related cruise expedition activities around Svalbard and towards the interior Arctic. For adverse consequences, the study focuses on Arctic endemic marine mammals, namely the ice-associated cetaceans, narwhal (*Monodon monoceros*), bowhead (*Balaena mysticetus*) and beluga or white whale (*Delphinapterus leucas*), ringed seals (*Pusa hispida*), bearded seal (*Erignathus barbatus*), ribbon seal *(Histriophoca fasciata)*, spotted seal *(Phoca largha)*, harp seal *(Pagophilus groenlandicus)*, hooded seal *(Cystophora cristata)* and walrus (*Odobenus rosmarus*)[3,71]. The polar bear (*Ursus maritimus*) is not included in this study.

Interdisciplinarity and mixed methods

The lack of existing studies concerning shipping noise and Arctic expedition cruises and the urgent need for improved governance inspired the idea of conducting a study that would bridge knowledge between maritime law, social sciences, and natural sciences[72]. Palmer[73] suggests a research process that starts with policy needs, environmental problems co-identification, and relevant scientific research approaches. Cvitanovic et al.[74] emphasise the need for novel procedures to improve knowledge exchange between science and policy to facilitate adaptive governance of the marine environment. This study utilises theoretical models from human safety sciences in an environmental safety context to assist in sense-making for policy-makers.

Safety models

The anthropogenic safety view recognises and manages sound as potentially harmful energy that moves towards a vulnerable target[22]. It stems from traditional safety science, accident prevention and operational health, safety, and environment measures[22,49,50,75].

So-called safety-barrier diagrams are utilised to understand cause-effect relationships and generate new knowledge on preventative measures[22]. This section introduces the safety-barrier model approach and visualises its main elements within a bow-tie diagram. The safety-barrier model stems from the energy model, which understands hazards as potentially hazardous energy and harmful events as the loss of control of such energies[22]. This model is utilised to understand and prevent accidents or unwanted occurrences by identifying these potentially dangerous energies and how those can be reliably separated from a vulnerable target[64,76]. A hazard is "an energy source with the potential of creating injury to personnel or damage to the environment or material assets" (p. 34)[22]. Energy can be represented by gravity, motion (kinetic energy), mechanical or electrical energy, pressure, temperature, chemical, biological or radiation energy or sound. The concept of safety barriers applies barriers to prevent unwanted occurrences. A barrier "protects" a vulnerable target from this energy (Fig. 5). Formally, it can be defined as a set of system elements (human, technical or organisational) that as a whole provide a barrier function with the ability to intervene into the energy flow to change the intensity or direction of it" (p. 130)[22].

Bow-tie diagrams route in the safety-barrier theory[77]. According to Dianous and Fiévez[78], it provides a helpful overview of identified causes, consequences, and their logical relationships. The bow-tie model diagram (Fig. 6) can be simplified into five elements: (potential) hazards (1) which introduce one or multiple causes (2) that lead to a harmful event (3) with (adverse) consequences (4) to a vulnerable target (5)[22,49]. The diagram visually places the harmful event in the centre. The left side describes the hazards and initiating events or causes, called "fault tree". The right displays the consequences as sequences of outcome events, called "event tree"[79,80]. This study will not go deeper into the theory of fault and event trees but will use sequences of causing events (causes) and outcome events (consequences).

Fig. 5 | Visualisation of the safety-barrier theory. Own illustration with Canva.

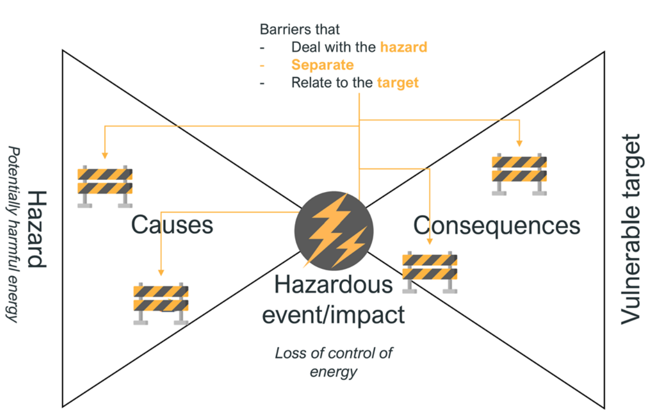

Fig. 6 | Bow-tie diagram with the integration of safety barriers. *Note:* Own illustration with Canva adapted from Kjellén and Albrechtsen[22] and Rausand and Haugen[49]. The shape of the diagram reminds the viewer of a classic bow-tie, which has lent the model its name.

Literature review

A structured literature review was conducted which resulted in a total of 44 papers considered for the study (Fig. 7, Supplementary material 1). Peer-reviewed papers have been sourced from *Scopus*, the supported and recommended literature database by the University of Gothenburg and *Google Scholar*. First, a primary query has been conducted targeting articles on shipping noise, governance, and marine mammals across the Arctic to get an overview of the overall research. The search was applied to the full-text level. *Scopus* retrieved 22 results. All results were screened for title and abstract—regardless of relevance, citations, and date. Results only included peer-reviewed articles in English. Hence, no language or source-related eliminations had to be made. Fifteen articles were selected to start the literature review, and five papers were added from *Google Scholar*. Two selected reports from environmental and governmental organisations have complemented results and relate to monitoring and assessing the impacts of underwater noise pollution in the Arctic. Four species-specific sub-queries followed the primary literature query to retrieve studies about the consequences of shipping noise for Arctic endemic cetaceans and pinnipeds. Ten papers were selected from the sub-queries in total. A further 12 articles were included through backward snowballing. These papers were not necessarily region-specific to shipping noise in the Arctic. However, they targeted a deeper understanding of the causes, consequences and mitigations of shipping noise and ensured that existing knowledge from other geographical areas was considered relevant.

Interviews

Döringer[81] introduced the problem-centred expert interview approach as a combination of theory-generated expert interviews which apply analytical and interpretative perspectives to outline and develop theoretical approaches[82] and the problem-centred interview approach that enables a process-oriented and joint refinement of the problem[83]. Problem-centred expert interviews can be applied in scenarios where the individual agency of experts contributes to a broader and more complex investigation, such as in policy analysis[81]. This combinatory approach inspired the conducted interviews. The study comprised three face-to-face and five remote semi-structured interviews with knowledge holders concerning the governance of shipping noise in the Arctic Ocean. The interviewees have been anonymised by reference IDs (Table 2).

Interview partners were selected across stakeholders within the SUDARCO project project and a related workshop in Tromsø, Norway in April 2023. In addition, relevant authors from the literature review were contacted. Sampling followed a snowballing approach to connect to further actors involved in the governance of shipping noise in the Arctic. The face-to-face interviews took place at Fram Centre in Tromsø in the respondent's office and a meeting area. The remote interviews were conducted via Zoom. The interview questions were slightly adjusted with relevance to the knowledge and background of the interviewee and shared in advance. The interviews lasted between 30 and 60 minutes and were adjusted to the availability of the interviewee and the volume of information that was shared. In addition to the idea of the problem-centred expert interviews, the interviews were conducted as a meaning-making conversation that actively forms and produces knowledge during a social encounter[84]. This approach was chosen in line with the study's aim as an approach to reduce and deal with epistemic uncertainty and create a fruitful atmosphere related to the different interviewees' backgrounds. Due to the data protection policies within the SUDARCO project, no recordings were made. Thus, transcription was impossible, and handwritten notes were taken during the interviews, which were converted into digital text straight after each interview.

Data analysis

A content analysis of the reviewed literature and conducted expert interviews facilitated the identification of patterns for the discussion. Results were

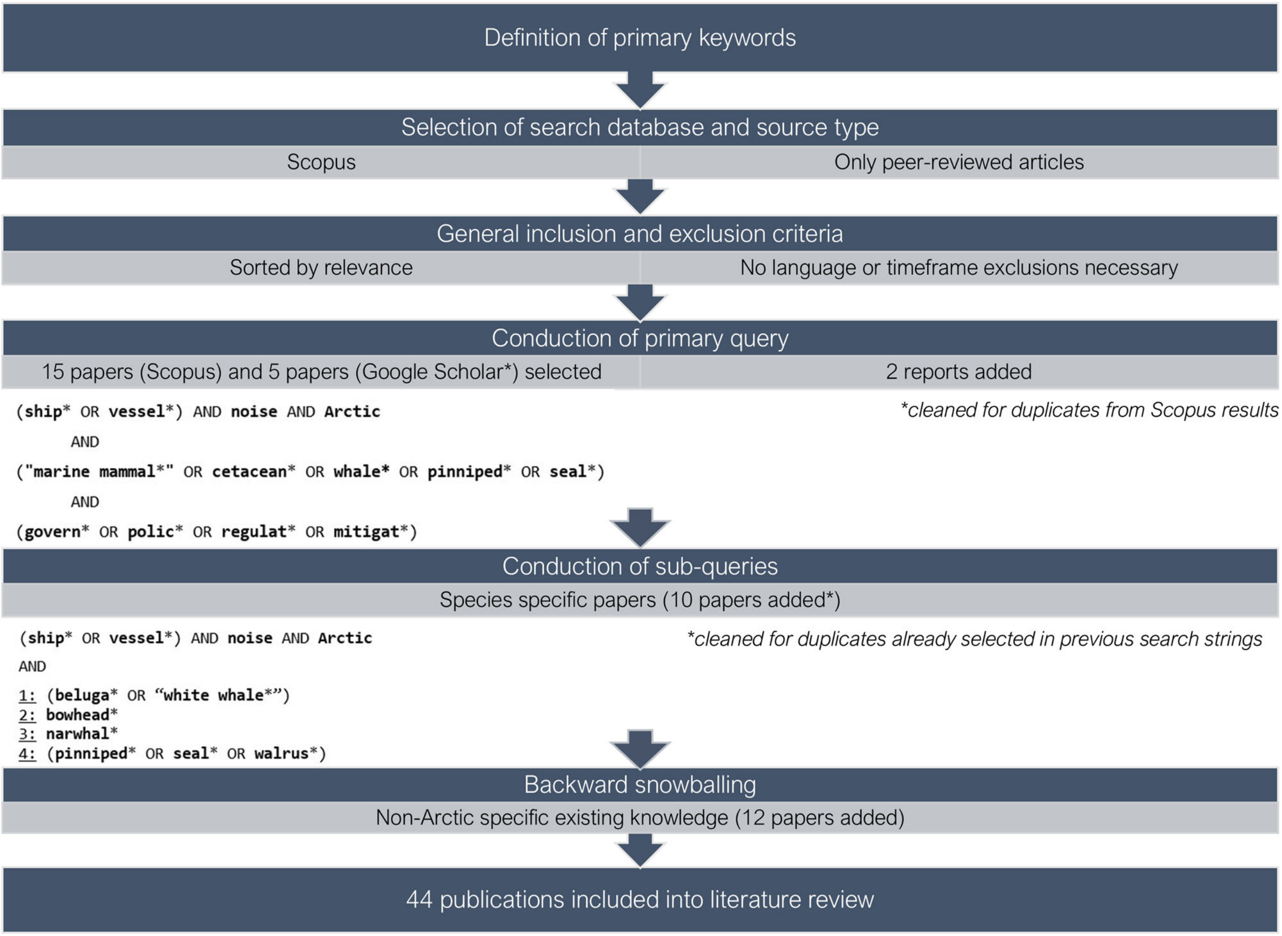

Fig. 7 | Visualisation of the methodical approach to the structured literature review and search parameters.

Table 2 | Overview of interviews with reference IDs

ID	Date	Type of expert/organisation	Interview location
Intv. 1	4/25/2023	Consultant Arctic Environmental Assessment	Fram Centre
Intv. 2	4/25/2023	Expert Ship Classification Association	Fram Centre
Intv. 3	4/28/2023	Engineer Arctic Research Vessels	Fram Centre
Intv. 4	5/4/2023	Researcher University & Environmental NGO	Zoom
Intv. 5	5/15/2023	Researcher Environmental NGO	Zoom
Intv. 6	6/1/2023	Arctic Cruise Expedition Industry	Zoom
Intv. 7	7/4/2023	Researcher Physical Oceanography	Teams
Intv. 8	7/17/2023	Engineer Arctic Cruise Expedition Vessels	Zoom

coded within the broader contexts of causes, consequences, mitigations, and governance aspects.

Data availability

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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Author contributions

F.M. developed the initial research questions, drafted the research approach, conducted the research, wrote the initial draft and designed visualisations. M.K.-K. and V.R. guided the research, conceptualisation and analysis. A.H. and B.K. contributed to and validated background, results and discussions. B.K. validated the conceptual framework. All authors contributed to the development and refinement of the ideas and the writing for the final version. All authors reviewed and edited the paper.

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Competing interests

The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to Fabienne Mannherz.