Rates of Vessel Noise Exposure Are More Than AIS Data Predict for Narwhal in Nunavut, Canada

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Abstract

Increasing vessel traffic across the Arctic is modifying marine soundscapes and presenting a growing threat to vulnerable species. Among these are narwhals in Tasiujaq, Nunavut, where tourism and industrial-related vessel activity are increasing underwater noise levels during the lengthening open-water season. The impacts of vessel noise on narwhals are not well understood; thus, further investigation of the spatial and temporal pervasiveness of vessel noise is required.

This chapter focuses on vessel noise exposure, discussing common approaches to assessing and quantifying exposure, and presents a recent analysis of narwhal acoustic tag data as a methodological case study. Results from these animal-borne recordings indicate that narwhals are exposed to an average of 3.9 vessel noise events per day and that a minimum of 38.1% of all identified vessel noise events were not attributable to AIS-equipped vessels. Underscoring that AIS data are inadequate for quantifying vessel noise exposure, this work is key to developing a better understanding of how noise affects narwhal already contending with the consequences of a warming Arctic.

Keywords

Underwater noise · Arctic · Acoustic recording tags · *Monodon monoceros* · Marine mammals

Introduction

Driven by global commerce and facilitated by decreasing sea ice extent, the Arctic is experiencing a marked rise in ship traffic. Over the last decade (2013–2023), the total distance traveled by ships in Arctic waters increased 111%, reflecting a 37% increase in the number of unique vessels (PAME 2024). These increases, however, are not exclusively attributable to commercial shipping; the variety of vessels moving through the Arctic also includes fishing vessels, seismic vessels, research vessels, cruise ships, icebreakers, and an array of privately owned pleasure craft.

Studies aimed at describing the temporal and spatial scales of underwater vessel noise have predominantly used vessel information obtained from the automatic identification system (AIS), a VHF-based vessel reporting system implemented by the International Maritime Organization. Satellite AIS transceivers have enabled equipped vessels to be tracked globally with increasing accuracy, but importantly, AIS is only internationally mandated for large ships (>500 GT, or >300 GT for international voyages) and passenger vessels. Hence, studies which rely solely on AIS data are likely to underrepresent vessel noise (O'Hara et al. 2023; chapter ▶ "What Is Vessel AIS Missing, and Why Do We Care?" by Miksis-Olds; Nachtsheim et al. 2023).

Within Canadian waters, neither of the two fastest growing vessel classes—fishing vessels and pleasure craft—is mandated to operate AIS (PAME 2024). Though there is an increasing number of these vessel types that are voluntarily adopting AIS, the proportion of these vessels that remain unaccounted for in AIS datasets is largely unknown. This uncertainty is especially problematic for studies examining vessel impacts since fishing boats and pleasure craft are the vessel classes most likely to frequent ecologically important areas.

Narwhals (*Monodon monoceros*; Inuktitut: *tuugaalik*) are an iconic species of the Arctic, with an estimated global population of 170,000, distributed across three genetically distinct populations. The Baffin Bay population is the largest of these but is better described as a metapopulation comprising populations that share wintering grounds in Baffin Bay yet migrate to distinct coastal areas during summer (Doniol-Valcroze et al. 2020). Narwhals residing in Tasiujaq (Eclipse Sound; Fig. 1) are part of this larger metapopulation, moving into Tasiujaq's protected bays and fjords in early summer and staying until fall freeze-up prompts migration back to the deep waters of Baffin Bay.

Narwhals have historically been an important food resource for Inuit across Canada and Greenland, who have long been aware of narwhal's sensitivity to disturbance. Subsistence hunting continues to be important throughout Tasiujaq, and accordingly, there is growing concern that increased vessel traffic is negatively impacting narwhals in the region.

Situated at the eastern entrance to the Northwest Passage, Tasiujaq is adjacent to one of the most heavily trafficked waterways in the Canadian Arctic and, concomitant with the opening of the Mary River iron mine in 2014, has experienced a significant increase in ore carrier traffic over the last decade (PAME 2024; Fig. 1). During this same period, summer narwhal abundance in Tasiujaq has been estimated from aerial surveys: data from 2013 estimated 10,489 (CV: 0.24) narwhal (Doniol-Valcroze et al. 2020), surveys from 2020 and 2021 estimated 4381 (CV: 0.14) and 2081 (CV: 0.17) narwhal, respectively (NAMMCO 2022), and the most recent aerial survey estimated 10,492 (CV:0.05) narwhal (Baffinland 2024). The variability in these abundance estimates may suggest dynamic shifts in narwhal distribution in and around Tasiujaq.

To anticipate how future vessel noise is likely to impact narwhal in a changing regime, it is necessary to understand the consequences of noise in the present. This requires adequate knowledge of the direct behavioral effects caused by noise (i.e., response), as well as the spatial and temporal pervasiveness of the noise source eliciting the response (i.e., exposure). This chapter focuses on the latter, discussing approaches to studying vessel noise exposures, the role of acoustic recording tags, and ways in which exposure can be quantified. These topics are addressed with respect to recent work, presented herein, that uses acoustic data from animal-borne tags to describe in situ vessel noise exposure rates for narwhal in Tasiujaq.

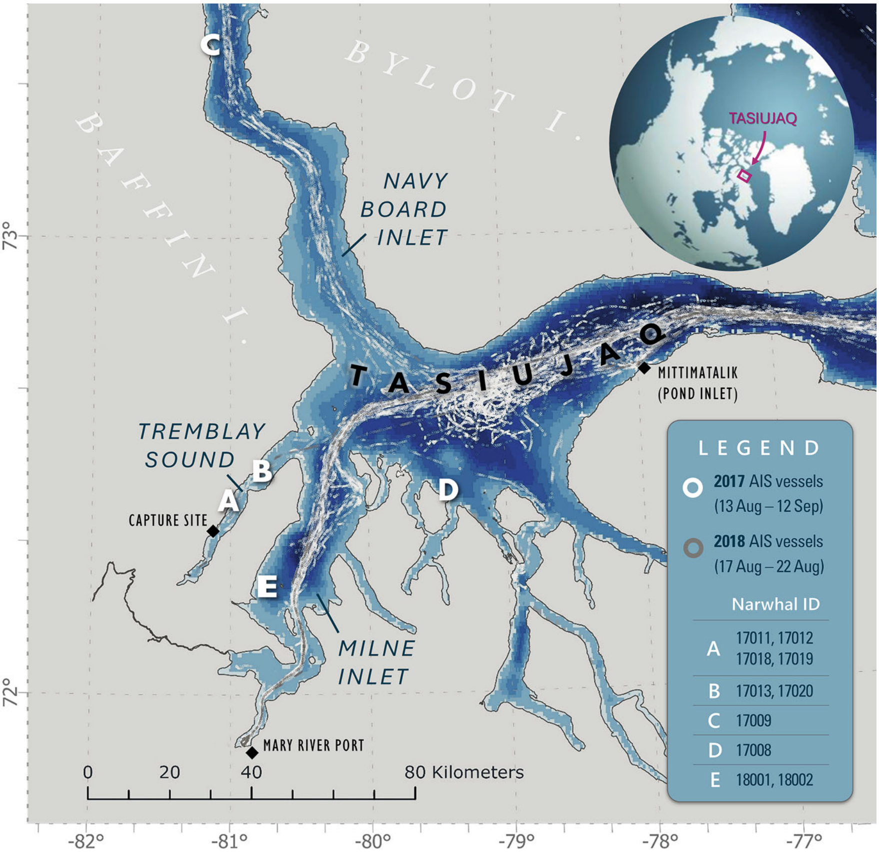

Fig. 1 Map displaying the extent of the Tasiujaq study area in Nunavut, Canada. Narwhals were captured along the western shore of Tremblay Sound. The Mary River iron mine is located at the head of Milne Inlet. AIS vessel locations, corresponding to the periods when animal-borne acoustic recording tags were deployed, are shown as white (2017) and light gray (2018) circles. Letters A–E indicate the furthest extent that narwhal moved from the capture site during tag deployment

Investigating Vessel Noise

Most marine mammal studies seeking to describe vessel noise exposures have done so by either (1) inferring noise exposure through the use of proximity analyses (e.g., Martin et al. 2024; Taylor et al. 2023) or else (2) by using a probabilistic approach whereby noise maps are integrated with species occurrence information to describe areas of exposure risk (e.g., Cominelli et al. 2019; chapter ► "Ship Happens: Mapping and Quantifying Impacts of the Noisy Neighbors of Marine Life" by Groenewoud et al.; Kochanowicz et al. 2021). While each of these approaches has value within the proper context, it is important to consider their limitations.

Proximity-based measures of exposure require calculating the distance at which vessels come within range of an animal, often termed the closest point of approach (CPA), then setting a distance threshold below which noise exposure is expected to have occurred. The strength of this method is that it is temporally relevant; whereas vessels and animals may overlap in space, yet this approach acknowledges that the two may not overlap in time. However, by using a simple distance metric to estimate uniform exposure zones, this method does not consider that the quality and extent of noise under water can fluctuate greatly, determined by the behavior and unique noise signature of the source vessel, as well as variability in the oceanographic features that influence sound propagation. Furthermore, distance thresholds are not always based on empirical data and can vary widely across studies, inhibiting comparisons across species and regions.

On the other hand, probabilistic approaches apply sound propagation models to vessel data and often account for vessel speeds, local bathymetry, and sound speed parameters. Additionally, they are typically computed across a variety of frequency bands and modeled outputs can be weighted to approximate the hearing capabilities of specific species. The drawback of this methodology is that it relies on averaging—sometimes across space, but most often across time—which limits its ability to accurately describe instances of nonconcurrent animal and vessel presence, thus undermining its ecological utility.

It should be noted that neither of the above approaches accounts for the vertical dimension: actual noise exposure rates are undoubtedly influenced by depth-dependent variation in sound propagation, yet animal diving behavior is rarely incorporated in these common approaches. However, some recent exposure studies (e.g., Jones et al. 2017; Trigg et al. 2020) have taken a more integrated approach: combining the spatial and temporal relevance of proximity-based methods with the acoustic realism of fully parameterized propagation models, while also using animal dive data to incorporate a depth component. The emergence of an integrated methodology that realistically approximates vessel noise exposure across time and three dimensions is unquestionably a promising step forward, yet its reliance on vessel location data means that it is currently limited to describing exposure from vessels represented by AIS datasets.

Finally, just as propagation models require empirical measurements for validation (see chapter ▶ "Validating Shipping Noise Simulations for the Red Sea Using Field Measurements" by Larayedh), methods that describe vessel noise exposure rates—either in the past or in the future—require empirical data to validate predicted outputs. This necessitates in situ measures of noise, ideally from the perspective of a free-swimming animal, which can presently only be achieved with animal-borne acoustic recording tags.

The Value of Acoustic Recording Tags

The first acoustic recording tag was deployed on the back of a northern elephant seal (*Mirounga angustirostris*) in 1995, in part to investigate the ambient sound levels experienced by seals at sea (Fletcher et al. 1996). Since then, rapid technological developments have increased the diversity and applicability of animal-borne acoustic recording tags, which remain especially valuable for noise studies. However, like all methodological approaches, these tags are not without limitations. Several known issues must be navigated by researchers to derive meaningful results.

- **Flow Noise**. Since acoustic recording tags are externally mounted on animals capable of high speed, flow noise is generated by hydrodynamic turbulence as the tag (and hydrophone) move through the water. This low-frequency noise is speed-dependent, with rapid swimming producing high-amplitude noise capable of masking other low-frequency signals. The upper frequency limit of flow noise is variable, depending on the tag's design, its placement on the body, and fluctuations in the animal's speed.
- **Bioacoustic Masking**. For bioacoustic research, acoustic recording tags are invaluable for recording the sound production of wild animals. For noise studies, however, high-amplitude vocalizations produced by tagged individuals, or even nearby conspecifics, can mask fainter noise signals of interest. This is especially true for echolocating species whose broadband click trains may reduce the detectability of subtler broadband noise.
- **Bias of Signal Detection**. In contrast to most stationary recorders, the detection zone of an acoustic recording tag is not omnidirectional. Onboard hydrophones have a directional bias that increases at higher frequencies, and once attached to an animal, shielding by the body further limits the detection field (Kastelein et al. 2024). This means that as an animal rolls, dives, and surfaces, the direction of best sensitivity is in flux, and the spectra and received levels of off-axis noise recorded by the tag may not accurately represent true conditions.

Given these constraints, it is crucial to recognize that acoustic recording tags, when used in vessel noise studies, are most effective at capturing high-amplitude noise from nearby vessel passes and are less capable of detecting noise from distant or quieter vessels. As a result, measurements of vessel noise obtained from these tags may not fully represent the noise levels of all vessels present.

Nonetheless, being the only practical way to measure the acoustic environment of an animal in situ, acoustic recording tags continue to be important for studying vessel noise and its effects. In particular, they are an invaluable tool for describing noise exposure because they allow both AIS and non-AIS vessel noise to be characterized (e.g., Mikkelsen et al. 2019; Nachtsheim et al. 2023).

Metrics for Quantifying Exposure

The primary goal of the current study was to describe narwhal exposure to vessel noise in Tasiujaq. To do this, 649 hours of acoustic tag recordings were manually reviewed for vessel noise signatures. Vessel noise generally consisted of flat, tonal components, sometimes accompanied by broadband noise (Fig. 2). Infrequently, vessel noise was solely comprised of a broadband component, lacking any tonal signal.

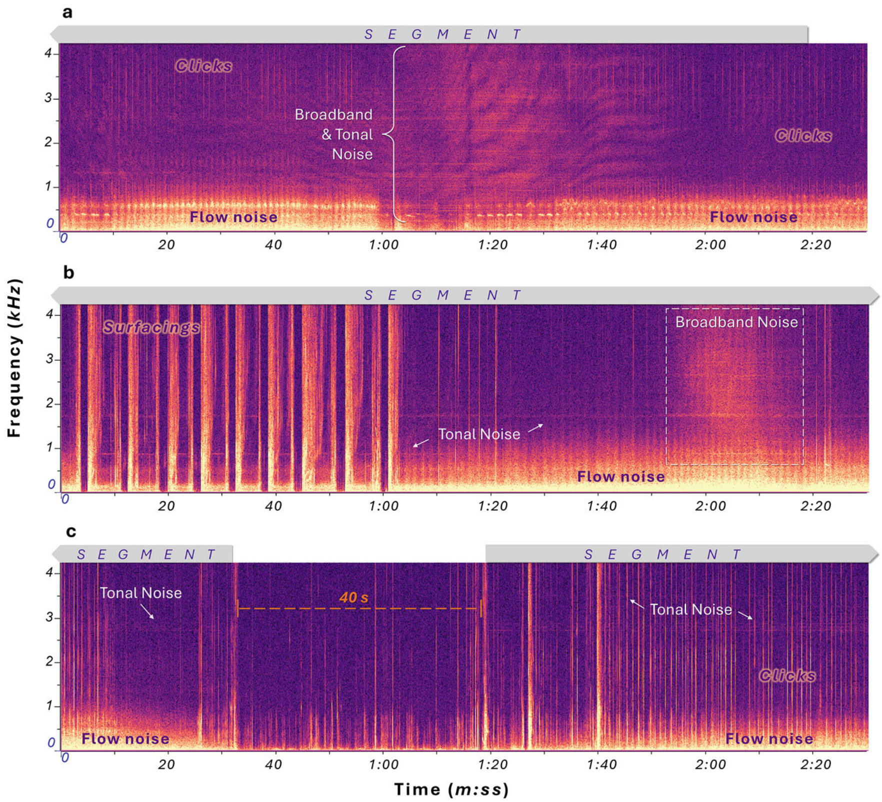

Fig. 2 Spectrographic examples of recorded vessel noise. Gray arrows above each panel indicate the parsing of noise signals into segments. (**a**) Vessel noise with both broadband and tonal components that are visible in the lowest frequencies only when flow noise subsides. (**b**) Vessel noise primarily consisting of tonal signals that are interrupted by narwhal surfacings. These brief gaps in the signal are included in the total segment duration. (**c**) Vessel noise is characterized by several weak tonals, partially masked by narwhal clicks. The signal is partitioned into two segments because it is undetectable for more than 30 s (*25.8 kHz sampling rate, FFT size = 4096, Hann window, 95% overlap*)

Once all vessel noise was identified, appropriate metrics for accurately and meaningfully characterizing noise were considered. Among vessel noise studies in the literature, measures used to quantify and report vessel noise have varied according to species, analysis approach, and the overarching goal of each study.

Sound Exposure Levels: An Energy-Based Metric

Noise exposure studies are most often implemented in a mitigation context, seeking to assess the level of noise which may induce some harmful effect. In these studies, the total amount of noise energy experienced by an animal is the primary concern, so exposure is calculated and reported as the cumulative sound exposure level (cSEL), or the total sound energy received over a defined period. For marine mammals, this metric is especially important for determining acute exposure events, which could cause severe effects such as temporary or permanent hearing loss.

The calculation of cSELs requires a means by which to accurately measure or approximate received noise levels. While this is methodologically possible using acoustic recording tags, it was not feasible for the current study. Narwhal recordings contained long periods of flow noise that masked the lower frequencies where vessel noise may have been substantial (Fig. 2). Additionally, episodes of near-continuous broadband clicking, produced by either the tagged narwhal or nearby individuals, often impeded the ability to measure even the higher-frequency parts of the signal (Fig. 2).

Exposure Rates: A Duration-Based Metric

For species which have low thresholds for disturbance, the proportion of time spent in the presence of noise may be a more relevant metric of exposure than an energy-based metric. Calculating these proportions, or exposure rates, is thus based on determining the length of time a noise signal persists in the environment, relative to the recording period. While ostensibly straightforward, this process can be more complicated using acoustic recording tags because they are unlikely to record vessel noise as a single, continuous signal. More commonly, noise is interrupted by surfacings, masked by vocalizations, or else fades in and out as the animal alters its depth and orientation to the vessel. The most objective way to account for these instances of discontinuous noise is to only measure the portions of the signal that are readily discernible in the spectrogram, referred to here as segments, while assuming that gaps in the signal represent cessations of noise. Although objective, this approach—basing exposure rates solely on the duration of intermittent noise segments—would yield unrealistic underestimates of exposure, especially in cases where flow noise caused lapses in detection, but the noise signal was presumably still audible in the environment.

Considering this, the current study instead assumed that vessel noise persisted in the environment throughout brief intervals when it was unrecorded and determined that including these intervals in measurements of vessel noise duration provides a more accurate representation of noise exposure (Fig. 2).

Exposure rates based on the duration of noise segments are reported in Table 1. Of the 13 narwhal deployments included in this study, all but the shortest (3.64 hours) contained at least one vessel noise segment. A total of 238 individual noise segments were identified, which ranged from 0.2 to 105.1 min and had a median duration of 2.1 min. To calculate exposure rates, segment durations were summed for each narwhal, then divided by the total recording time of each deployment (Table 1). For the 12 narwhal that encountered vessel noise, the average exposure rate was 1.69% but ranged from 0.17% to 5.89%.

Table 1 Summary of vessel noise exposure metrics for narwhal tagged with acoustic recording tags in 2017 ($n = 9$) and 2018 ($n = 4$). Vessel noise segments refer to visually discernible, nearly continuous noise signals. Vessel noise events are comprised of one or more segments, no more than 10 min apart, that are likely attributable to a single vessel transit

Narwhal ID	Start of tag recording (UTC)	Total recording (hh:mm:ss)	Vessel noise segments			Vessel noise events		
			No.	Total duration (mm:ss)	Exposure rate (%)	No.	No./24 hour	Total duration (mm:ss)
17008	2017-08-13 12:00:02	69:10:26	17	68:40	1.65	8	2.8	77:45
17009	2017-08-16 16:48:02	59:11:18	9	19:05	0.54	4	1.6	36:13
17011	2017-08-30 12:50:04	12:00:30	6	10:45	1.49	4	8.0	12:27
17012	2017-09-02 23:12:33	23:52:34	3	09:02	0.63	2	2.0	10:27
17013	2017-09-03 02:53:37	25:58:16	6	07:08	0.46	3	2.8	10:36
17014	2017-09-03 15:21:21	03:38:17	0	—	—	0	—	—
17018	2017-09-11 13:33:59	21:19:55	1	02:07	0.17	1	1.1	02:07
17019	2017-09-11 18:48:56	15:27:22	6	21:14	2.29	4	6.2	28:34
17020	2017-09-11 18:48:35	21:39:18	3	08:26	0.65	3	3.3	08:26
18001	2018-08-17 07:15:16	73:58:58	29	79:36	1.79	20	6.5	89:09
18002	2018-08-17 13:48:47	112:25:16	25	49:45	0.74	14	3.0	74:36
18003	2018-08-17 13:48:13	111:15:45	61	393:29	5.89	23	5.0	521:19
18004	2018-08-18 11:01:47	98:34:08	72	233:43	3.95	19	4.6	357:30

Events: A Vessel-Based Metric

Exposure rates are advantageous for quantifying noise when cSELS cannot be computed, or the length of exposure may dictate the degree of noise-induced response. However, for particularly sensitive species, the mere presence of vessel noise in the environment could initiate avoidance responses. In such scenarios, where the onset of noise is triggering, it may be more biologically relevant to express exposure in terms of individual vessel noise events.

Vessel noise events directly correspond to the number of recorded noise signals when vessel noise is recorded continuously. However, in cases with discontinuous recordings, like duty-cycled recorders or acoustic recording tags, noise from a single vessel may span several distinct segments. Correctly grouping noise segments into events requires an assumption that a vessel's noise may span across some—but not all—gaps in the recorded noise signal. To make this distinction in an objective manner, a threshold is needed.

For the current study, vessel noise events were defined as a grouping of one or more noise segments no more than 10 min apart. The chosen threshold aimed to ensure that each vessel noise event corresponded to a single vessel, striking a balance between extremes. While a too-short threshold might result in multiple noise events for one vessel, it was important to avoid an overly long threshold that could merge noise from consecutive vessels into a single event.

Vessel noise segments were grouped into 105 distinct vessel noise events (Table 1). For each event, the duration was calculated from the start of the first segment to the end of the last segment. In this way, event durations reflected the length of a vessel's passing, irrespective of narwhal behavior (e.g., swimming, foraging, and vocalizing) that might have interrupted the recording of the event.

The number of vessel noise events experienced by each narwhal was roughly proportional to the length of time the tag recorded (Table 1); to standardize this for comparison across individuals, and with other studies, the number of events was scaled to a 24-hour (daily) period. When considering all tagged individuals, narwhals were exposed to an average of 3.9 vessel noise events per day. While these exposure rates are below those reported for species in less remote regions (Jones et al. 2017; chapter ► "Vessel Noise Exposures of Harbor Seals Tagged in the Elbe Estuary" by Nachtsheim et al.; Wisniewska et al. 2018), it remains unknown if noise exposure at these levels could be impactful to narwhals already contending with the consequences of a warming Arctic.

Attributing Noise Events to Individual Vessels

Vessel noise exposure rates, as presented here, are key to developing a better understanding of vessel impacts on narwhal in Tasiujaq, but a more comprehensive understanding of how and to what degree narwhal alter their behavior in response to vessel activity is needed. Recognizing that AIS datasets do not represent all vessel activity in an area (see chapter ► "What Is Vessel AIS Missing, and Why Do We Care?" by Miksis-Olds), and that different vessel categories may elicit varying responses in narwhal, the secondary objective of the current study was to determine the proportion of noise events in Tasiujaq that might be attributable to non-AIS vessels.

Attribution of vessel noise events to either AIS or non-AIS vessel activity is, in essence, a process of elimination. Without the means to determine the vessel types, speeds, or positions of non-AIS vessels, attribution of noise to non-AIS vessels can only be inferred when AIS vessels are absent or otherwise unlikely to be the noise source.

To ascertain the vessel(s) responsible for individual noise events, studies have used a strategy in which the time of the CPA is determined acoustically, either from the center of a Lloyd's mirror effect or when received noise levels reach a maximum, and then compared against the timing of spatially derived CPAs from candidate vessels. However, this is not always achievable with data from acoustic recording tags. While Lloyd's mirrors are sometimes present in tag recordings, the intermittent nature of most vessel signals frequently hinders the acoustic identification of the CPA. Even when the point of maximum noise energy can be identified, it may relate more to depth-related acoustic properties, or the animal's orientation, than its proximity to the recorded vessel.

Alternatively, a proximity-based approach can also be used to attribute noise events to individual vessels. This method involves establishing a distance threshold within which vessel noise is presumed to be detectable, then subsequently attributing a noise event to the nearest AIS vessel within the selected radius. When no vessels are within range, the noise source is considered non-AIS. The accuracy of this method largely depends on the selected distance threshold, which can vary among studies (e.g., Mikkelsen et al. 2019; Nachtsheim et al. 2023). Moreover, choosing a single threshold fails to consider that a vessel's unique characteristics and behavior determine its source level and, consequently, the distance at which it can be detected. A single threshold is therefore unlikely to be a good predictor for determining AIS attribution across all vessel classes.

Even considering these issues, discontinuities in the recorded noise signals for the current study (discussed above) made it impracticable, in many cases, to acoustically determine a CPA for noise events. Thus, a version of the proximity analysis, which also incorporated the shoreline complexity of the region, was used to determine the provenance of vessel noise events.

Using linear interpolation, the location of all AIS vessels in Tasiujaq were determined at the beginning and end of all noise events for which narwhal location data were available. Given the coastal topography of Tasiujaq, candidate vessels for each noise event were mapped and excluded from consideration if they were stationary, or if a significant landmass obstructed noise transmission to the narwhal. However, because the class and speed of candidate vessels varied, no vessels were eliminated on the basis of their distance from the exposed narwhal.

A vessel noise event was only attributed to an AIS vessel if the vessel was the closest (or only) vessel within 10 km, and the CPA between the narwhal and vessel occurred during the noise event. This threshold, albeit conservative, is supported by a Tasiujaq soundscape analysis which indicated vessel noise propagates well at this distance (Jones et al. 2023).

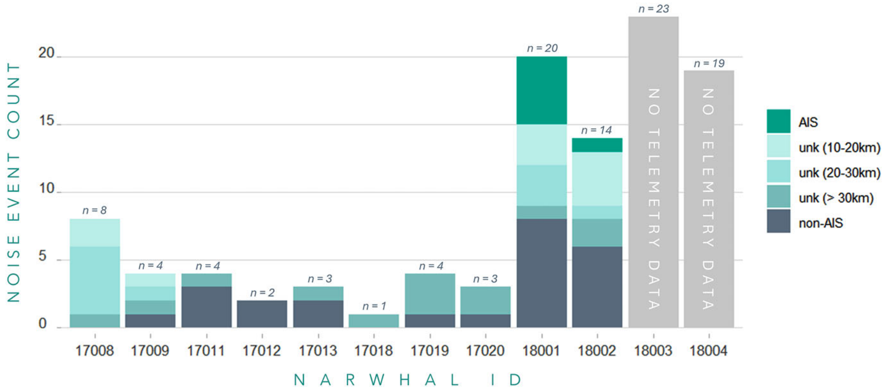

Fig. 3 Summary of vessel noise events, per individual narwhal, and their attribution to AIS or non-AIS vessel categories. Vessel noise events that could not be attributed to either group are labeled unknown (unk) and are categorized here according to the distance of the closest AIS vessel present during the noise event. No noise events were identified for narwhal 17014, so this animal is not included. No location data are available for narwhals 18003 and 18004, so their vessel noise events were not part of this analysis

Of the 63 noise events examined, 24 were attributed to non-AIS vessels (38.1%), and 6 were definitively attributed to an AIS vessel (Fig. 3). The provenance for the remaining vessel noise events ($n = 33$) remained unknown as they could not conclusively be attributed to either category using the described methodology. For unknown events, the distance to the closest candidate vessel ranged from 13.1 to 57.3 km.

The large number of vessel events with unknown attributions is directly related to the ambiguity in determining the appropriate distance threshold, especially given the slow speeds at which ore carriers generally travel within Tasiujaq. While it is acknowledged that much of this uncertainty could be resolved with a fully parameterized propagation model, this was beyond the scope of the current study.

All in all, the conservative analysis employed here concludes that 38.1% of recorded vessel noise events are unlikely to have originated from AIS vessels. This proportion is probably even larger, as roughly a quarter of unknown noise events were associated with slow-moving vessels that are unlikely to be recorded by tags at great distances. Furthermore, the difference in bathymetry between the main body of Tasiujaq and the surrounding inlets likely impedes noise from distant vessels reaching the shallow waters of Tremblay Sound.

Conclusions

- The analysis presented here represents the first time in situ noise exposure rates, derived from animal-borne recording tags, have been reported for narwhal, or any Arctic species.
- All 12 narwhal acoustically tagged for longer than 4 hours experienced at least one vessel noise event.

- Recorded exposure rates ranged from 0.17% to 5.89% of recorded tag deployment.
- Findings indicate that as few as 38.1% of recorded narwhal vessel exposures in Tasiujaq could not be attributed to AIS vessels. However, given the large number of events with unknown attribution, this figure could be as large as 90.5%.
- Along with other published research, the recent work presented here underscores that AIS data are insufficient for accurately describing the scope of vessel noise experienced by marine animals.

Cross-References

► Ship Happens: Advancing Life Cycle Assessment Methods by Integrating Impacts from Vessel Noise
► Underwater Shipping Noise in the Red Sea: Oceanographic Characterization and Modeling
► Vessel Noise Exposures of Harbor Seals Tagged in the Elbe Estuary
► What Is Vessel AIS Missing, and Why Do We Care?

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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